Numerical and Experimental Design of Coaxial Shallow Geothermal Energy Systems

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ABSTRACT

Geothermal Energy has emerged as one of the front runners in the energy race because of its performance efficiency, abundance and production competitiveness. Today, geothermal energy is used in many regions of the world as a sustainable solution for decreasing dependence on fossil fuels and reducing health hazards. However, projects related to geothermal energy have not received their deserved recognition due to lack of computational tools associated with them and economic misconceptions related to their installation and functioning.

This research focuses on numerical and experimental system design analysis of vertical shallow geothermal energy systems. The driving force is the temperature difference between a finite depth beneath the earth and its surface stimulates continuous exchange of thermal energy from sub-surface to the surface (a geothermal gradient is set up). This heat gradient is captured by the circulating refrigerant and thus, tapping the geothermal energy from shallow depths.

Traditionally, U-bend systems, which consist of two one-inch pipes with a U-bend connector at the bottom, have been widely used in geothermal applications. Alternative systems include coaxial pipes (pipe-in-pipe) that are the main focus of this research. It has been studied that coaxial pipes have significantly higher thermal performance characteristics than U-bend pipes, with comparative production and installation costs. This makes them a viable design upgrade to the traditional piping systems.
Analytical and numerical heat transfer analysis of the coaxial system is carried out with the help of ABAQUS software. It is tested by varying independent parameters such as materials, soil conditions and effect of thermal contact conductance on heat transfer characteristics. With the above information, this research aims at formulating a preliminary theoretical design setup for an experimental study to quantify and compare the heat transfer characteristics of U-bend and coaxial geothermal piping systems. Based on the simulations and experiments, the effect of parameters on the overall operating costs is studied.

Finally, with the results obtained, the economics and return on investment behind coaxial geothermal energy systems are discussed. Government policies on renewable energy are explained, highlighting the energy incentives associated with geothermal energy in the United States. The findings of this research provides a platform for further shallow geothermal energy system studies with an immense potential to revolutionize the energy industry in the future.
DEDICATION

First, I would like to dedicate this thesis to God, who has offered me the strength and belief to succeed with flying colors at every juncture of my life. I would also like to dedicate this work to my parents, K. N. Raghavan and Mythrayi Raghavan, and my sister Nivedita Raghavan for providing moral, motivational and monetary support whenever I needed the most, and encouraging me to go the extra mile in achieving whatever I desired. Finally, I would like to dedicate this thesis to every person in this world who is striving to make our earth a cleaner and greener place to live in.

कर्मण्येवाधिकारस्ते मा फलेषु कदाचन।
मा कर्मफलहेतुर्भुधं ते सङ्करस्त्वकर्मणि॥ २-४७

“Do your duty and be detached from its outcomes. Do not be driven by the end product, but enjoy the process of working towards your goal.”

—Bhagawad Gita (2-47)
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CHAPTER 1

INTRODUCTION TO GEOTHERMAL ENERGY SYSTEMS

1.1 WHAT IS GEOTHERMAL ENERGY?

Geothermal energy is often associated with energy obtained from cracks, crevices, volcanoes and geysers at large depths under the earth. This interpretation is highly skewed, which is the single biggest reason for investors and public’s hesitation to move towards geothermal energy. In July 2009, the definition stated in the EU legislative framework; EU Directive 2009/28/EC on Promotion of Renewable Energy Sources (Article 2) read: “Geothermal energy can be defined as the energy stored in the form of heat beneath the surface of the solid earth.” This energy can be obtained even at depths of 100 feet, which brings shallow geothermal energy into picture. Estimations have shown that the total heat content of the Earth are calculated above average surface temperature of 15 °C, is of the order of 12900 MJ, and that of the crust is of the order of 5500 MJ. This energy can be easily extracted using present state-of-the-art equipment, thus proving an immense capability of this energy resource to be used independently, or in combination with other renewable sources of energy. [34]

1.2 WHY GEOTHERMAL ENERGY?

According to 2015 Annual US and Global geothermal power production report published in January 2015, geothermal energy has sustained a growth rate of 5% for three consecutive years.
The U.S. industry had about 3.5 GW of installed nameplate capacity and 2.71 GW of net capacity at the end of 2014. The current established geothermal power production graph (in MW) in comparison with other countries is as follows:
Since 2005, the United States has built over 38 geothermal power projects adding nearly 700MW to the U.S. electricity capacity. The global energy production market has reached 13GW of operating capacity as of January 2015, spread across 24 countries, with the United States contributing to one fourth of the total energy production. It is interesting to note that this energy production is more than the annual energy consumption of some countries. [60]
In order to heat and cool homes across the United States, including commercial buildings, shallow geothermal systems are already in use, utilizing steady temperatures just beneath the ground, cleanly and inexpensively. By 2030, these numbers are expected to grow two fold, showing positive results competing against well-established renewable energy sources like solar, wind and hydroelectric power. The international geothermal energy production trend is as follows:
Figure 4: Projected growth of geothermal energy capacity until 2021 by Geothermal Energy Association (GEA). [60]

Based on the above graph, we can infer that this trend shows a positive indication for geothermal energy as a sustainable energy source for the forthcoming years and with proper technology and subsidies, it can compete with the likes of solar and wind energy production.

1.3 TYPES OF GEOTHERMAL ENERGY SYSTEMS

There are different classifications to the geothermal energy systems which are as follows.

Based on the refrigerant loop in the borehole, systems can be classified as:
1. Closed Loop system: Refrigerant is allowed to flow in closed loop pipes without any interaction with the environment, other than through heat transfer between the pipe and the soil.

![Closed Loop Systems](image)

**Figure 5: A closed loop geothermal energy system.** [1]

2. Open Loop System: This type of system circulates the refrigerant (typically water) from a reservoir (usually a large water body, a water well or any catchment area) to the geothermal energy system.
This research primarily focuses on closed loop systems, and further classification based on orientation of the piping systems is as follows:

1. Horizontal geothermal energy systems: These systems have pipe configuration running just beneath the surface of the earth in the form of horizontal loops.
2. Vertical (or borehole) geothermal Energy systems: These systems have boreholes for the pipe setup to be inserted. This creates a vertical heat transfer loop that occurs across the length of the pipe. Since heat transfer occurs along the full length of the pipe, their heat transfer characteristics are better than horizontal geothermal energy systems.

![Closed Loop Systems](image)

*Figure 8: A vertical closed loop geothermal energy system. [1]*

Based on the depth of operation, there are four types of geothermal energy systems:

1. Horizontal loop: They typically operate at 1-5m depth.
2. Vertical (Borehole or Shallow) energy systems: They typically operate at 10-400m depth.
3. Energy piles (Pile foundations to provide support to the building, as well as act as a heat source and a heat sink): They typically operate at 10-50m depth.
4. Ground wells of Water: Their maximum depth is 50m.

In this research, shallow, closed loop, vertical geothermal energy system is used for the experimental analysis and numerical simulation purposes.

1.4 SOIL STRUCTURE

In the case of vertical geothermal systems, boreholes are drilled into the ground for pipe installation. Hence, the soil structure plays an important role for effective heat transfer characteristics between the outer walls of the pipe and the soil. The level of the water table underneath the earth or the presence of any waterbody next to the drilling site is an important parameter for geothermal drilling in a particular location. An ideal soil structure for drilling will be moderately porous, less connected with adequate cracks between the rocks.

In general, the geological factors which affect the geothermal wells drilling site are as follows:

1. Rock Type, history of rocks and regional rock types: Categorizations underlying reservoir rock are given by:
   - Granitic/higher-grade metamorphic – Saprolite Layers
   - Volcanic Rocks
   - Sedimentary basin
Ideally, for a shallow geothermal energy drilling situations, the underlying saprolite layers are targeted and tested for green strength and heat transfer characteristics.

2. Impact of Saprolite layer: Saprolite is a chemically weathered rock formed in the lower zones of soil profiles and represent deep weathering of the bedrock. This layer is very crucial when drilling in hilly areas which have potential threats for landslides and earthquakes. Saprolite layer can be identified using seismic refraction techniques.

3. Presence of wet soil: The presence of wet soil might increase/decrease the rate of heat transfer. Wet soils are not related to submerged soil, which is found near surface water bodies.

4. Porosity and Permeability of the soil: Porosity determines how much water the rock or soil can retain. Permeability is also a parameter which measures how easily water can travel through porous soil or bedrock. Soil and loose sediments, such as sand and gravel, are porous and permeable. Although clay and shale are porous and can hold a lot of water, the pores in these fine-grained materials are so small that water flows cannot through them.

5. Location of subsurface water table: Water table has a cooling effect on the underground pipeline system. Also, it is critical to understand where this water table is located. If it is at depths less than 10m, water resistant concrete additives have to be used to prevent water based corrosion and water-refrigerant interactions in case of leaks. Hydrogeology and seasonal fluctuations of water table should also be
taken into consideration. Water table depths vary considerably by landscape position. The water table in upland areas fluctuates as much as 4 m in a given year, typically increasing in the late spring following spring rainfall and slowly declining through the growing season despite additional rainfall. The water table depth typically ranges from 3-4 m in upland regions. In the floodplain, the water table exhibits minimal variation.

6. Casing of the well after drilling: Material and thickness of the concrete walls which can increase or decrease the heat transfer coefficient.

7. Possibility of contaminants interacting with the well: Ammonium compounds and Nitrates interacting with the walls or refrigerant used in the system should be minimized.

8. Potability of water if the refrigerant leaks: This is important in densely populated areas where there is a high risk of water contamination in case of leaks from geothermal pipes. The refrigerant should not be hazardous or cause any impact on the neighbouring localities or water bodies.

9. Frost Line: The frost line, also known as frost depth or freezing depth, is the depth to which the water in the soil is expected to freeze. The frost depth depends on the climatic conditions of an area, the heat transfer properties of the soil and adjacent materials, and on nearby heat sources. The freezing layer of the soil in cold months can be up to few metres. On an average, the frost line layer for United States in winter occurs at 1m-1.5m depth.
10. Number of wells and spacing between each well in the particular area: In a densely populated area, this is a parameter to consider for effective heat transfer between two adjacent columns and the number of wells which can be drilled in a particular area. Space between two wells must be optimized so that there is no heat build-up in the soil. [74]

1.5 HEAT TRANSFER CHARACTERISTICS

There are three fundamental modes of heat transfer. They are conduction, convection and radiation.
**Conduction:** It is the transport of energy in a body due to the temperature difference between two points, due to molecular activity in the body. It is characterized by Fourier law:

\[ Q = k \cdot A \cdot \frac{dT}{dx} \]

where \( k \) is the thermal conductivity of the body (W/mK), \( A \) is the area of cross section (m²) and \( \frac{dT}{dx} \) is the variation of temperature with respect to distance. Conduction is associated with the thermal conductivity of refrigerant, soil and grouting materials, and so, it is a key parameter in this research.

**Convection:** It is the process of heat transfer between a surface of a body and a moving fluid which are at different temperatures. Convection can be of two types: Natural, when there is a fluid moving without any external influence, and Forced, when the fluid is moving under an external influence like a pump or an air fan. The general relation for the amount of convective heat is given by,

\[ Q = A \cdot H \cdot (T_{\text{body}} - T_{\text{fluid}}) \]

where \( A \) is the area of cross section, \( H \) is the heat transfer coefficient of the body (W/m²K) and \( \Delta T \) is the temperature difference between the body and the fluid (\( T_{\text{body}} \) and \( T_{\text{fluid}} \)). Convection occurs between the brine and the inner walls of the pipe. It can also occur when there is an underground aquifer close to the geothermal pipe. The temperature of ground water in the aquifer can influence the temperatures of refrigerant at the depths of the geothermal pipes. However, this is beyond the scope of this research.
**Radiation:** The electromagnetic energy emitted from the surface of a hot body because of its surface temperature is called radiation. The radiation energy emitted by a body is represented by Stefan Boltzmann equation:

\[ E = \sigma \cdot T^4 \]

where \( \sigma \) is the Stefan Boltzmann constant of \( 5.670 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4} \) and \( T \) is the temperature of the body. Radiation comes into play in geothermal systems at the interface between layers of materials through the contact conductance behavior. However, it is negligible for all practical purposes. [27]

With respect to fundamental movement of heat through different materials in a geothermal system, there are three properties which are key aspects of this research. They are:

**Thermal Conductivity:** It represents the ability of a material to transfer heat by conduction methods. The SI unit of thermal conductivity is W/m.K. Thermal conductivity is an important parameter to test the efficiency of heat transfer of different soils and grouting conditions in this research.

**Specific Heat:** It is the amount of heat per unit mass required to raise the temperature by 1 degree Celsius. (J/Kg.K) The relation can be represented as follows:

\[ Q = m \cdot C_p \cdot \Delta T \]

Where \( m \) is the mass of the body (Kg), \( C_p \) values varies with different material conditions, and this plays an important role in heat distribution in the system and \( \Delta T \) is the temperature difference between initial and final states.
Thermal Diffusivity: It is the ratio of thermal conductivity to the thermal heat capacity of the system (m²/s). It is represented as follows:

\[ \alpha = \frac{k}{\rho \cdot C_p} \]

Since thermal conductivity and density varies with different material types, thermal diffusivity is a realistic property to measure how well heat is being distributed in a system.

[27]

The above mentioned properties are used extensively in Chapter 8 of this thesis.

1.6 GEOTHERMAL PIPE DESIGN

There are several pipe combinations which have been tested and used, but the two common designs which are widely used are as follows:

1. U-Bend pipes: They consist of a pair of straight pipes, connected by a 180°-turn at the bottom. Multiple (One, two or three) such U-pipes can be installed in one hole. The advantage of the U-Bend pipe is low cost of the pipe material, resulting in double-U-Bend pipes being the most frequently used in borehole heat exchangers.

1. Coaxial Pipes: They consist of two or more pipes with varying diameters placed inside each other. Complex configurations are also possible with multiple pipes within a pipe of large diameter.
This research primarily focuses on coaxial pipes. The aim of the outer walls of a coaxial geothermal pipe is to dissipate maximum energy to the surrounding soil, and to maintain minimum heat transfer from the inner pipe. In a vertical geothermal energy system, standard pipes used in these applications are made of Poly-vinyl chloride (PVC), High Density Polyethylene (HDPE) and Poly-propylene.

Coaxial pipes, assembled with turbulators and spacers, are installed in the ground as sections of specific lengths and fused together at different depths. Turbulators are vortex generators which shifts the flow regime of the fluid in the annulus from laminar to passive turbulence region. Based on fundamental heat transfer knowledge, turbulent regimes have higher heat transfer tendency than laminar flows, thereby enhancing the thermodynamic properties of coaxial pipes.
Figure 11: Variation of Reynolds number for different flow rates in inner and annulus pipes. [76]

Spacers are used to prevent the pipe sections from collapsing. The remaining space between the pipe and the soil is pumped with grouting material, which is a combination of cement and bentonite. Further, the heat transfer of these pipes can be enhanced by using internal fins, vortex generators, riblets and creating a rough surface on the inner wall of the pipe.
1.7 GROUTING

Grout or concrete, is generally a mixture of water, cement, sand, and fine gravel (if it is used to fill the cores of concrete blocks). This prevents the interaction of water with other refrigerants. An ideal grout will be high thermal conductivity, with low moisture content and consisting of non-corrosive materials. It is applied as a thick emulsion and hardens over time, like mortar. The general factors to be considered when making the cement shell casing (grout) include:

1. Thickness of the cement layer shell.
2. Composition of metal aggregates present in the shell.
3. Composition of cement and Bentonite.
4. Composition of Ca-Al cements which can provide different thermal conductivities.

Grout design is critical component of heat transfer in geothermal systems. The grout layer is susceptible to four modes of damage namely:

1. Axial tear- tearing at pipe joints due to tensile stresses.
2. Collapse- extensive pressure gradient between grout’s outer wall and pipe’s inner wall.
3. Burst- Damage due to high internal pressure and low external pressure.
4. Concrete damage- Damage due to pressure difference and high moisture content.

Therefore, care must be taken while making the grout composition. The grout mixture is a key component for effective heat transfer between the pipe and the soil. Modifications can
be made to increase the heat transfer, like using steel fibres and meshes along with concrete and bentonite, using polymer concretes and use of Silane/silica fumes admixtures. [84] [86]

1.8 HEAT PUMP CHARACTERISTICS

Pumps deployed in geothermal applications are called ground source or geothermal heat pump (GSHP): They tap and transport the heat extracted from the earth’s crust.

GSHP systems consist of three parts: the ground heat exchanger, the heat pump unit, and the heating/cooling system by ductwork, radiant heating and cooling or water heater. The heat exchanger is a system of pipes called a loop, which is buried in the shallow ground underneath the building. The size of the pump system is chosen based on the size of the conditioned space and is measured in tons.

Figure 12: Illustrative representation of heat transfer in coaxial shallow geothermal energy system for summers and winters. [2]
Ground source heat pumps usually use earth as a part of the heat exchanger for heating and cooling needs. The good efficiency of GSHP is characterized by constant temperatures associated with the ground at finite depths, thereby leading to good coefficient of performance (COP) of the system. A geothermal heat pump usually operates at nearly 400% efficiency (COP 4), meaning that for every unit of energy given to the system, four are received. The only requirement is that electricity is needed to run the pump, which can be provided with other renewable sources of energy like Solar and wind. This makes geothermal energy with GSHP an environmentally friendly addition to energy efficient homes. [46]

1.9 REFRIGERANT

A refrigerant is a fluid used in heat pumps for transferring and circulating heat. An ideal refrigerant will have good thermodynamic properties, be non-corrosive to the pump and other mechanical components, non-toxic and non-flammable during its working cycle and non-hazardous when disposing of it. The fluid, which is water for open-looped and a brine mixture of glycol and antifreeze for close-looped systems, passes through the geothermal energy system under the ground and takes or dissipates heat based on the ground temperature. In winter conditions, the refrigerant circulating in the heat pump takes heat from the ground (through the heat exchanger) and carries it to the heat pump unit. In the summer, the process is reversed, where the heat is carried from the heat pump unit into the ground.
CORACON GEKO E bio-refrigerant is used in many practical geothermal energy systems. The frost protection of the biological heat carrier fluid CORACON GEKO E is based 100% on renewable raw materials, while conventional brine fluids are based on Monoethylene glycol or Monopropylene glycol. Biodegradable materials, which have been approved for food use, are one of the constituents of CORACON to prevent corrosion. This brine can be used with a proportion of as little as 10 Vol-%, as it contains sufficient anti-corrosion agents. In this research, basic brine properties are used in all analytical and numerical simulations. [2]

1.10 KEY OBJECTIVES

The key objectives of this research are as follows:

1. To create numerical models of steady state and transient analysis on Abaqus software.

2. To vary the independent parameters of the system and establishing a relation between the parameters and heat generated in the system. This relation can be directly linked with the overall operating costs of the system.

3. To design an experiment for a coaxial and U-bend piping system and measure the temperature at different points in the soil and grout.

4. To develop a cost analysis report of the working of a typical geothermal energy system, and calculate the return on investment and savings of a residential coaxial geothermal energy system.
CHAPTER 2  

LITERATURE REVIEW

Over three billion years, the temperature of the mantle has reduced between 300 to 350 °C, which remains at about 4000 °C at its base. Estimations have shown that the total heat content of the Earth are calculated above average surface temperature of 15 °C, was of the order of 12.6 x 1024 MJ, and that of the crust was of the order of 5.4 x 1021 MJ.

Geothermal energy is used in many regions of the world as an affordable and sustainable solution in case of decreasing dependence on fossil fuels and the global warming and public health risks which was because of use of fossil fuels energy. The United States with more than 3,000 megawatts in eight states has more energy in terms on geothermal capacity in comparison to other countries. In order to heat and cool many places across the United States, including thousands of homes and buildings, geothermal heat pumps also use the steady temperatures just underground, cleanly and inexpensively.

Geothermal energy is cheap, clean, abundant and renewable. Twenty percent originates from the original formation of the planet while eighty percent comes from radioactive decay of minerals. The difference in temperature between the core of the planet and its surface is (geothermal gradient) stimulates continuous exchange of thermal energy, heat from the core to the surface. [34]

Jake Brown provided a full understanding of the necessity for alternative energies, the science behind geothermal power and the various ways of harnessing it. It led into a background on various design considerations for ground source heat pumps. An analysis
of the economics of operation, a lifecycle analysis of the costs, issues and procedures
during installation, operation and after a set buyback period of time, provided an insight
into how much cost benefit there was in installing a ground source heat pump system.
Finally he concluded the feasibility of geothermal energy in both large scale and small
scale applications, which is the foundation of this thesis. [47]

2.1 GEOLOGY
Trevor Halfhide explored the feasibility of geothermal technologies on Colgate
University’s campus. He concluded that geothermal heating and cooling was a very
feasible option for Colgate and that vertical, closed-loop shallow systems have the most
potential because of the restrictions associated with the underlying geology and the
concerns held by the Village of Hamilton about drinking water contamination. Multiple
cost-benefit analyses were conducted, comparing the possible economic costs of
installation with the potential economic, social, and environmental benefits, which gave an
idea on formulating the chapter on cost analysis of coaxial shallow system. [80]

Another independent study concluded that geothermal energy was a low-operating-cost,
low-carbon, base-load, renewable energy resource that has been exploited for electric
power production for more than a century. As at end-2011, the world’s total installed
geothermal electric power generation capacity stood at more than 10,700 MWe (Megawatt
electrical) and, despite a considerably lower public profile, in 2010 produced twice the
electricity output of solar sources. It was observed that geothermal power offers a steady
base-load source of electricity, not subject to the intermittent nature and risks of most other
renewable energy sources such as solar or wind. Geothermal energy was used for electricity generation in 24 countries worldwide; many more countries use lower-temperature geothermal sources for heating applications, which further validates the advantages of geothermal energy. [78]

Maureen McCorry studied that Ground Source Heat Pumps make an important contribution to energy saving and emission reduction and have the potential to make a greater contribution in the future. Research in Europe showed that one of the barriers to a sustainable and growing geothermal market was the lack of appropriately skilled personnel. The objective of this project was to develop a professionally-oriented European education program to support the geothermal heating and cooling market. The chapter on ground source heat pumps was of great importance in the understanding of commercially available geothermal pumps. [37]

Tatjana Brkic defined three main geothermal energy sources based on its occurrence as:

- **Shallow ground** - upper three to ten meters of ground maintain the same temperature throughout the year in spite of the changes of surface temperature. The temperature difference between the surface and underground can serve as a heat exchange mechanism that can heat and cool residences and commercial buildings.
- **Hot Springs**
- **Hot rock** – this source found a few miles beneath the Earth's surface, and down even deeper to the extremely high temperatures of molten rock called magma. This
this type of energy was called dry geothermal heat and it can be accessed by drilling, and enhanced with injected water to create steam.

The main focus of this research is on type 1 geothermal source. The most popular geothermal application in the modern world was geothermal heat pump that was used for heating and cooling buildings – a heat pump that uses earth or groundwater as heat source (in winter) and heat sink (in summer). New techniques have been developed all over the world to maximize the efficiency of heat exchange mechanisms and their applications vary depending on the geothermal energy source in geographic areas. Shallow ground heat and hot water are generally used for heating and cooling of residential and commercial buildings while hot rock represents a resource mainly used for large scale geothermal energy generation. [79]

2.2 HEAT TRANSFER

Yekoladio studied the thermodynamic design and optimization of a downhole coaxial heat exchanger for an enhanced geothermal system. The optimum diameter ratio of the coaxial pipes was determined for minimum pressure drop in both limits of the fully turbulent and laminar fully-developed flow regimes. It was observed to be nearly the same irrespective of the flow regime. Performing an entropy generation minimization analysis, the entropy generation rate was found to be due to both heat transfer and fluid friction irreversibility. The coaxial pipes dimensions and fluid circulation flow rate were optimized to ensure minimum pumping power requirement and maximum extracted heat energy from the Earth’s deep underground. It was deduced that a higher underground temperature gradient
minimize both the geometry size of the downhole heat exchanger and the geothermal mass flowrate required to be continuously circulated through the Earth. The concepts related to flow regimes and their impact on pressure drop was useful in the understanding of fluid behavior inside coaxial pipes. [66]

Another independent study showed that grouting material used for BHEs must satisfy several hydraulic, mechanical and thermo-physical requirements. It provided a wide investigation on various admixtures including laboratory tests and a comprehensive evaluation of the performance of BHE probes made of different types of grout materials operated in a sandbox. Test results showed that slow no-flow condition of materials caused difficulties during the pumping process of the grouting material, mainly for silica sand-based materials and some homemade admixtures while the ability to flow of bentonite-based material was comparatively better. Both compression strength and hydraulic permeability of each material showed satisfactory results, excepted for the mixture with expanded graphite. In terms of thermo-physical properties, it was concluded that even a small amount of graphite addition (5%) had a great influence on the thermal conductivity of grout. This research proved vital for studying thermal properties and independent parameters influencing the heat transfer characteristics of the system. [75]

Marcia Karr worked on the functioning of a shallow geothermal heat pump for residential buildings. The basic concept was that a geothermal pump sends water through pipes placed in the ground where the soil and rock rather than the outside air as it will either absorb or add heat to the water. This system took advantage of the higher conductivity of soil and
rock, as well as the relatively constant underground temperature of 68°F-70°F opposed to the variable air temperature above ground to transfer the heat. Once the heat transfer occurs, the water flows back up into the home, where it heats or cools the air. Geothermal heat pumps efficiently move water through pipes in the surrounding ground to transfer heat from the home to the rock, or vice versa. The conductivity studies and concepts were widely implemented in this research. [49]

2.3 CEMENTS AND GROUT

L. Wadsoa proved that it was possible to increase the volumetric heat capacity and the thermal conductivity of concrete by at least 50%. The results also showed that it was possible to predict the thermal conductivity using the Hashin-Strikman composite model, and that the volumetric heat capacity was correlated with the density for dry concrete. Further study of how thermal mass of buildings influenced such factors as their peak power consumption and their thermal comfort. It was studied if it was possible to improve the thermal properties of concrete for buildings with high thermal mass by using aggregates with high heat capacity and/or materials with high thermal conductivity. It was found that both volumetric heat capacity and thermal conductivity was increased by at least 50% compared to standards concrete, which is one of the key studies related to concrete properties. [52]

Xu studied that Silane and silica fume together are effective admixtures for increasing both the specific heat and the thermal conductivity of cement paste. Silica fume alone increased the specific heat but decreased the thermal conductivity. Silane provided a network of
covalent coupling among the silica fume particles, thereby increasing both the specific heat and the thermal conductivity, in addition to increasing the compressive strength and modulus and decreasing the compressive ductility. The further addition of silane increased the thermal diffusivity by up to 27%, further increased the specific heat by up to 35%, slightly increasing the density, and increased the thermal conductivity by up to 78%. The overall effect of addition of both silane and silica fume was a decrease in thermal diffusivity by up to 18%, an increase in specific heat by up to 50%, and an increase in thermal conductivity by up to 38%. This research was particularly useful to improve the thermal conductivity of grout. [86]

2.4 REFRIGERANTS AND TRANSPORT PHENOMENA

Bu compared the different refrigerants available on an Organic Rankine cycle/vapor compression cycle (ORC/VCC) system for air conditioning and a thermodynamic model for the geothermal pump was developed. Six working fluids, R123, R134a, R245fa, R600a, R600 and R290 were selected and compared in order to identify suitable working fluids which may yield high system efficiencies. The calculated results show that because of high system pressure for R290 and R134a, R600a was the more suitable working fluid for ORC in terms of system efficiency and system pressure. In addition, R600a was also the most appropriate working fluid for VCC in terms of pressure ratio and coefficient of performance. R600 and R600a are more suitable working fluids for ORC/VCC in terms of overall coefficient of performance, refrigerating capacity per unit mass flow rate and chilled water yield from per ton hot water. It can be inferred that R600a was the most suitable working fluid for ORC/VCC system through comprehensive comparison of ORC
efficiency, expander size parameter, pressure ratio, coefficient of performance, system pressure and chilled water yield from per ton hot water for six different working fluids. However, the primary concern will be the flammability of R600a. Although this study dealt with air based geothermal pumps, it provided vital information regarding refrigerants and their applications. [24]

The mechanism of solid particles transported in the wellbore by the moving fluid during geothermal fluid production was thoroughly explained by Salazar using concepts from fluidized state and particle suspension, fluid particle interaction, drag forces and terminal velocities undergone inside the geothermal pump pipeline. The results observed were, for fluids flowing in the wellbore at higher velocities, it can carry relatively bigger diameter solids. For denser fluids like water, more drag and buoyancy force contribute to the upward push of the particle and thus, even at relatively lower velocities, it was capable of transporting bigger size particles. The particles smaller than the calculated particle diameter at given terminal velocity was expected to be transported to the surface. [72]

2.5 NUMERICAL ANALYSIS

Kaldal focused on casing failures such as collapse which was a result of combined loads and impurities in the casing and the surrounding concrete. In this paper a simple case of collapse caused by a geometric defect in the casing was analyzed using the finite-element method (FEM). The collapse of an impaired casing and its resulting shape was investigated with respect to the external supporting concrete. A specific load history for the production casing was used in the analysis. The load history represented the fundamental loads which
occur during the lifetime of a typical well. The magnitude of the external pressure and its stimulus for later collapse was also analyzed. The collapse shape obtained in the FEM analysis was similar to collapse shapes that have been observed in geothermal wells. [42]

Nabiha aimed to evaluate the Tunisian geothermal energy and second to test the performance of horizontal ground heat exchanger. An experimental set-up was constructed for climatic condition of Borj Cedria located in the north of Tunisia for space cooling. The ground temperature at several depths was measured, the overall heat transfer coefficient was determined. To evaluate the system efficiency, the energy analysis was applied; the energy efficiency was found to range from 14% to 28%. The heat exchange rate was quantified, the pressure losses were calculated. The total heat rejected by using the ground heat exchanger (GHE) system was compared to the total cool requirements of a tested room with 12 m$^2$ surface. The results showed that the GHE, with 25 m of length buried at 1 m depth, covers 38% of the total cool requirement of the tested room. This study showed that the ground heat exchanger provide a new way of cooling buildings, it also showed that Tunisia have an important thermal potential. [64]

Aparna Kanth studied the heat transfer and thermo-mechanical analysis of geothermal tunnels using a 3-D models. The model was analyzed for finding out thermal stresses, temperature and displacements on concrete lining, embedded pipes and the soil in which tunnel was being constructed. Results were generated in the form of various plots after running the analysis for a duration of 8 years. The ABAQUS numerical model was used to assess this transfer. The model was calibrated against periods with TES heat extraction.
rates of 30W/m² and 10W/m² for sandy soil. It was known that compressive strength of steel was 250-500 MPa and that of concrete was 15-20 MPa depending upon the grade of concrete and that of sand was 0.2 to 0.6 MPa. This research provided critical information about stress and thermal analysis of geothermal pipes on Abaqus. [21]

Cvetkovski evaluated that the performance of ground source heat pumps relied greatly on the heat transfer efficiency throughout the ground loop configuration. It was suggested that vertical ground loops could employ a U-Bend or a coaxial pipe configuration which could generate vortex structures and turbulence, enhancing the heat transfer process. For the U-Bend, the Dean Number (radius of curvature) and the Reynolds Number (inlet velocity) are tested. For the Coaxial, the inner pipe offset, and the Reynolds Number (inlet velocity) are tested for improved configurations. For the U-Bend, it was found the Reynolds Number dominates. In the Coaxial system, it was found that inner pipe offset destroys the heat flux of the system. Comparing the two systems, the coaxial pipe showed both lower pressure loss and increased heat flux at equivalent inlet flow rates, which is critical for designing the experiment setup. [33]

Yang simulated the temperature distribution in the soil around the underground heat exchangers by a two-dimensional model based on the column heat source theory, with the help of partial differential equation tool of Matlab software. Through single-tube model, temperature distribution around heat exchangers and thermal radius under such conditions were obtained. To find out heat coupling effect among adjacent boreholes and temperature distribution in the soil, multiple boreholes were simulated on the basis of single-tube
model, the coupling degree between tubes was obtained, from which a concept (heat affected public area) was proposed. To eliminate or decrease the heat imbalance of heat emitted to soil in summer and absorbed from the soil in winter, water heater was added to the GSHP system. Experimental results of the hybrid system show the highest EER of the system could raise to 4. [84]

2.6 U- TUBE AND COAXIAL PIPES

Guillaume’s study was on a component of a GSHP system - an annular pipe in pipe Coaxial Borehole Heat Exchanger (CBHE). This design presented interesting characteristics compared to the traditional U-pipe borehole heat exchanger, and it was tested during heat pump operation. Its performance was analyzed experimentally and with the finite element software COMSOL. The simulation results were compared to temperature measurements collected using fiber optic cables installed along the borehole depth. Further, two cross sections of the CBHE used were modeled, enabling to see the effects of the insulation and of the position of the central pipe on the borehole thermal resistance. The studies showed that up to 40% more heat from the ground can be extracted by using an insulated pipe in a CBHE instead of a non-insulated pipe. It has been concluded that the borehole thermal resistance of an annular CBHE was very small compared to the borehole thermal resistance of a U-pipe. It was also found that the borehole thermal resistance remains constant whatever the position of the central insulated pipe was, and it was not the case for a non-insulated central pipe. Finally, the borehole thermal resistance decreased when the central pipe got close to the borehole wall. This research triggered the need to study about borehole resistance and thermal contact conductance between interfaces. [41]
Wang’s research presented the results of comparative heat transfer efficiency study based on in situ full scale tests conducted on conventional U-loop borehole heat exchangers (BHE) and a coaxial BHE. The results showed that the coaxial BHE has considerably higher heat transfer efficiency, while consuming less pumping power than the U-loop’s. The implication of a high efficiency BHE on reducing borehole loop length and initial investment cost was also discussed. It was concluded that the higher efficiency coaxial BHE has the potential to reduce borehole length 30% to 50%. The single coaxial BHE performance can reach 94%-96% of the twin U-loop’s. On the other hand, the single U-loop BHE performance was only 78% of the twin U-loop’s. When pressure dropped of the two types of BHE are compared, the coaxial pipe showed a 17% average lower head loss, resulting a 40% higher flow rate at the same pumping force. This research is critical for the experimental design for comparing the heat transfer characteristics of U-Bend and coaxial systems. [82]

Acuna’s thesis provided a better understanding of the function of U-pipe BHEs and investigated alternative methods to reduce the temperature difference between the circulating fluid and the borehole wall, including one syphon and three different types of coaxial BHEs. Field tests were performed using distributed temperature measurements along U-pipe and coaxial heat exchangers installed in groundwater filled boreholes. The measurements were carried out during heat injection thermal response tests and during short heat extraction periods using heat pumps. Various power levels and different volumetric flow rates were imposed to the tested BHEs and used to calculate local ground thermal conductivities and thermal resistances. Forced convection in the groundwater
achieved by injecting nitrogen bubbles was found to reduce the local thermal resistance in U-pipe BHEs by about 30% during heat injection conditions. This research proved key to compare thermal characteristics of U-Bend and coaxial systems. [15]

Jasmin Raymond indicated that the coaxial pipe configuration was advantageous than the single U-pipe configuration to reduce the total borehole length of a system. A decrease of the borehole thermal resistance and an increase of the thermal mass of water contained in the coaxial exchanger helped to reduce borehole length by 23% for a synthetic building load profile dominated by cooling. The decrease of the borehole thermal resistance was achieved with an outer pipe made of thermally enhanced high-density polyethylene, where the thermal conductivity was 0.7 W m\(^{-1}\) K\(^{-1}\). Calculations suggested that at a high flow rate, the borehole thermal resistance of the proposed coaxial GHEs can be below 0.05 m KW\(^{-1}\), which was significantly below single U-pipe GHEs but remains above double U-pipe GHEs. Another possible configuration to reduce the borehole thermal resistance was a coaxial GHE made with a flexible liner which was shown to have a measured resistance that was 40% smaller than the lowest resistance of coaxial GHE considered. The drilling depth was an important factor for balancing flow rate of both double U-pipe and coaxial GHEs. [46]

2.7 ENVIRONMENTAL AND OTHER ISSUES

Kevin Rafferty argued that water quality was a frequently overlooked issue in the application of geothermal heat pump systems. In residential open loop applications, water was supplied directly to the heat pump’s refrigerant-to-water heat exchanger. If the water
had a tendency to form scales, fouling of the heat exchanger may occur. This fouling reduced the effectiveness of the heat exchanger and compromised the performance of the heat pump. The objective of the work was to identify areas where scaling might occur based on the water quality. With this information, installers and system owners could plan for the regular maintenance that will be necessary to address the scaling and preserve system performance. Alkalinity was characterizing the type of hardness (carbonate or non-carbonate) and whether it was of the variety that will cause scaling. [68]

2.8 ECONOMICS
Angrisani analysed a case study in which an existing low-enthalpy geothermal well (96°C), located in Ischia, Italy, was used to drive the geothermal system. Results showed that the performance of the proposed system was significantly affected by the utilization factor of Domestic Hot Water. In fact, considering a range of variation of such parameter between 5% and 100%, Primary Energy Saving increased from 77% to 95% and Pay-Back Period decreased from 14 years to 1.2 years, respectively. The simulations proved the technical and economic viability of the proposed system. The results of the calculations also showed that the performance of the system was especially sensitive to the thermal demand, which is a key consideration in the cost analysis of the system. [39]

When we take the economics behind Geothermal Energy into consideration, Nathanaël Hance Cédric reviewed the entire analysis on how variable most cost components of geothermal projects were. With regard to capital costs, the site and resource characteristics (e.g. site geology, access, spread and weather conditions, resource temperature, chemistry
and depth, etc.) were the most important factors affecting geothermal power development costs. Geothermal plants typically had a capacity factor around 90%, which was higher than most other power production technology. That meant that geothermal power plants typically delivered power at full capacity during 90% of the time, while outages (planned and unplanned events) prohibited power delivery during the remaining time. This advantage, along with the remarkable price stability of geothermal power, made geothermal power highly valuable as a price stabilizer which buffered the dependency and high volatility of power markets against fossil fuel prices. [26]

Róisín Goodman researched on identifying the optimum way for electricity production purposes. Based on their different flow rates and temperatures, their potential net power outputs and annual energy production were calculated. The aim of this research was to identify how low-enthalpy geothermal sources could meet a part of the industrial, commercial and residential energy demand in an area chosen from the local community to meet its needs. It was found that approximately 45.43 GWh per year could be covered using electricity produced from geothermal energy in total. For the case study selected, it was found that approximately 10% of the total electricity demand could be met from the Geothermal Energy. It was also found that on an average, the needs for geothermal energy contribution were increased significantly when the usual grid production was low. This could be very beneficial for the grid because during the wintertime, geothermal energy can be used for heating, while during the summertime, it could assist in electricity production when heating was not needed. [40]
CHAPTER 3

DESCRIPTION OF COAXIAL GEOTHERMAL ENERGY SYSTEMS

In this section, the manufacturing processes involved in coaxial pipes are discussed in length. Ideal installation locations, procedures and codes are explained for proper grouting and placement of geothermal pipes. The cost for drilling and installation is also discussed in this section.

3.1 MANUFACTURING

Manufacturing of pipes is generally done by extrusion- hot and cold. The basic concept behind extrusion is that a cylindrical billet is forced through a die in a manner similar to squeezing toothpaste from a tube, in various cross sections from a press. A wide variety of solid, hollow and coaxial pipes can be produced by extrusion. The key characteristic of extrusion is that, large deformation of plastic material can be done without fracture because the material is under high axial compression. Since the die geometry remains unchanged throughout the process, extruded pipes have a constant cross section.

Coaxial pipe manufacturing widely uses PVC, HDPE and PE for extrusion. Depending on the ductility of the selected material, the extrusion process is carried out at different temperatures. When the extrusion process is carried out at room temperatures, it is known as cold extrusion. For polymers which do not have sufficient ductility at room temperature, or in order to reduce the forces required, extrusion is carried out at elevated temperatures. Since they operate in hot working conditions, this process is called hot extrusion. Pipes are however, not extruded for long lengths such as 10m. Extrusions are cut into different
shorter lengths and made into discrete parts, which are then fused together. This is the most economical process for manufacturing, storage and transportation of pipes. Since pipes are extruded into discrete numbers, this process is a batch and semi-continuous process. This process is economical for small as well as large batch productions. Tool and die costs are low, particularly for producing coaxial pipes. [48]

In coaxial extrusions, coaxial billets of polymer material may be extruded together, providing compatible strength and ductility of inner and outer pipes. Stepped extrusions can also be achieved by extruding the billet partially in one die and then in one or more larger dies. In this type of manufacturing, cold working conditions are employed for polymers because:

1. Mechanical properties improve upon work hardening, as long as the heat generated from plastic deformation and friction does not damage the pipe.

2. Good control over dimensional tolerances, eliminating the need for subsequent machining and finishing processes.

Production rates and costs are competitive. [48]

In this research, coaxial pipes are assembled using 10 feet length flexible PVC pipes of different diameters with turbulators that act as vortex generators, and spacers which holds the pipe from collapsing. The sections of pipes are fused together to produce the entire pipe as one piece. This pipe is then inserted into the borehole using a crane.
3.2 LOCATION SELECTION FOR GEOTHERMAL DRILLING

Based on different parameters mentioned in the previous section, the location for setting up geothermal energy systems have to be optimized for effective system working conditions. The Department of Energy has provided an extensive geothermal technical report on the presence of aquifers and their soil structure for drilling and installation of geothermal systems.

Based on geological studies, there are two major aquifers in the United States – Piedmont Aquifer and the Northwestern aquifer. The crystalline-rock aquifers that underlie the Piedmont and Blue Ridge physiographic provinces in east-central Alabama, northwestern Georgia, and western South Carolina are collectively called Piedmont and Blue Ridge aquifers. Similar aquifers extend northward throughout a large area from North Carolina into New Jersey. The Piedmont and Blue Ridge aquifers consist of bedrock overlain by unconsolidated material called Regolith. Included in the Regolith are saprolite, which is a layer of earthy, decomposed rock developed by weathering of the bedrock. The saprolite is by far the largest component of the regolith, and has a thickness of 150 feet in some places. Presence of saprolite layer, which is found in close proximity to aquifers, considerably enhances geothermal drilling and installation. [32]

Large areas of the eastern, northeastern, and north-central parts of the United States are underlain by crystalline rocks. Spaces between the individual mineral crystals of crystalline rocks are microscopically small, few, and generally unconnected; therefore, porosity is insignificant. These igneous and metamorphic rocks are permeable only where they are fractured, and they generally yield only small amounts of water to wells.
The following map of aquifers in the United States (obtained from United States Groundwater information) shows the shallowest principal aquifers:

![Map of aquifers in the United States](image)

**Figure 13: Pacific and Piedmont aquifers in the United States.**

Piedmont and Pacific Aquifers. Piedmont Aquifer passes through South Carolina at a region north of Columbia. These regions are porous and ideal for shallow geothermal energy drilling.
Figure 14: Piedmont Aquifer from South of Pennsylvania to East of Alabama.

We can see that the inner Piedmont aquifer runs through western South Carolina, which is roughly located to the north of Columbia. Inner Piedmont aquifer is characterized as perforated from 1187m to 1227m (3895 ft. - 4026 ft.). The temperature of water at the level of perforation was 56°C and at the surface the discharge temperature was 51°C. Under high production for an extended period of time, it is expected that the temperature difference between the well head and aquifer would be less.

This aquifer consists of fractured metamorphic rock inlands with Coastal Plain (Silt and Clay) extending into the Atlantic Ocean. The water flow rate downstream is close to 10 gal/min in the areas north of Columbia. However due to the slope tending towards the Atlantic Ocean, there is a higher flow rate in south east of Columbia. [32]
3.3 INSTALLATION OF GEOTHERMAL ENERGY PIPES

Geothermal piping installation is one of the critical processes for effective setup and running of the system. Adequate care must be taken for proper installation and maintenance of these boreholes.

Prior to installation, all existing underground utilities, piping, etc. must be located and marked. During pipe installation, all ground piping on the plot plan must be accurately marked as an aid to avoid potential future damage in the installation process.

All earth piping materials should be limited to only polyethylene fusion below ground (buried) sections of the loop. Galvanized or steel fittings should not be used at any time due to its tendency to corrode by galvanic action. All plastic to metal threaded fittings should also be avoided due to the chances of potential leak in earth coupled applications; a flanged fitting should be substituted.

For vertical earth loops, boreholes should be drilled using an appropriate size drilling equipment. Regulations which govern water well installations also apply to vertical ground loop installations. Vertical applications typically require multiple boreholes for effective power generation. The space between boreholes should be between 10-15 feet apart. However, large scale commercial installations may require more distance between bores. Larger diameter boreholes can also be drilled if adequate space is available. Each coaxial pipe section must be assembled carefully, and then filled with water to perform a hydrostatic pressure test prior to insertion into the borehole. [3]
3.4 SITE PLAN

Site plan is a location description of the buried underground utilities that constitutes a given area. The location description and sketch should include:

1. The location of all buried utilities.
2. The location of the ground heat exchanger should be established from two permanent points in case of future excavations.

The owner of the system should be aware of the site plan and be consulted to determine if:

1. Special areas are to be avoided. Trees, shrubs, and gardens that are not to be disturbed should be identified.
2. Acceptable locations for entry and exit of heavy equipment.
3. Services like underground water sprinklers should not be known or easily identified. Hence, the owner should uncover these buried systems. [44]

3.5 INSTALLATION EQUIPMENT TO BE USED

The most common equipment used for borehole digging are:

1. Chain trenchers: Trenchers are the most economic choice since the amount of soil or dirt removed is minimal when compared to other methods, and trenching productivity is usually very high. The most common size chain trencher is in the depth range of 3 to 5 feet.
2. Bulldozers: Using a bulldozer will be appropriate only if excavation is carried out for a large header system.
3. Backhoes: Backhoes are used where there is a presence of rocks, cobbles, or boulders which are too large or too hard to be removed by a chain trencher. Backhoes are also used where more than one pipe is placed in a single trench, either stacked vertically. The biggest disadvantage is that the soil removed by a backhoe tends to be lumpy and can leave air pockets around the pipes, greatly reducing the heat transfer.

4. Vibratory plows: Vibratory plows are commonly used at depths not greater than 3 feet. To facilitate rapid burial, a vibrator or vibratory plow is used to improve the speed of placement. Loose or unstable soils are also amenable to this type of pipe placement and they work better than a chain trencher. However, the shallow depth results in larger seasonal soil temperature swings and longer lengths of pipe.

5. Drilling Machines: They are used for depths greater than 50 feet as ground temperatures fluctuate near the surface of the earth. They are used in such a way that, if 500 feet of bore hole is required, two 250 foot vertical bore holes are acceptable and are more cost effective. Soil and rock conditions will determine drill rates and consequently determine an economical borehole depth. [44]

3.6 INSTALLATION PROCEDURE

The standard installation procedure for coaxial geothermal energy system takes place as 4 key steps given as follows:
1. PRESSURE TEST

- The pipe is laid horizontally as a single finished piece and connected to a proper pressure testing equipment.
- All ball valves are closed. (deaeration of pipe black Ø 25 mm and return pipe black 40 mm) The water is pumped into the coaxial ground heat exchanger, until a pressure of 4 bar (58.016 psi) is reached.
- Valve of the pressure pump is closed and a stand time of 15 minutes is given. The circumference of the coaxial ground heat exchanger will extend up to 3 mm (0.12 inches) and the pressure will fall to approximately 2.5 bar (36.26 psi).
- Again the system is built up to a pressure of 4 bar (58.016 psi) and provided a stand time of 15 mins. The pressure will fall slower than before.
- Finally, the pressure is built up once more to 4.0 bar (58.016 psi) by pumping in water. Immediately, the pressure is released to 2.0 bar (29 psi). The valve is closed again and in that condition, the pressure remains stable. The average variation is about 0.2 bar (3.5 psi). When the pressure remains steady for 15 minutes, the pressure test is successfully terminated. (Tolerance range 0.2 bar (3.5 psi))
- A test with air pressure is done to control the welded seams prior to the lowering of the probe into the borehole. It is helpful to use a leakage-spray around the seams. Also here, the pressure it built up to 4 bar (58.016 psi). It is advisable to avoid direct radiation from the sun on the probes.
2. FILLING OF PROBES AND CONNECTION TUBES

- With multiple pipe strands in the system, each strand is filled and deaeriated (air exhausted) individually. All other strands are closed at the distribution shaft.
- The deaeriation pipe in the distribution shaft or in the building has to be closed. The ball valve at the return pipe has to be opened.
- Brine is pumped through the feed pipe until brine exits through the return pipe and air stops to escape.
- Then ball valve of the return pipe is closed and brine through the feed pipe into the system is pumped.
- The ball valve of the deaeriation pipe is closed so that brine can exit from there. The ball valve is closed when no more air bubbles escape from the deaeriation pipe.
- The above procedure is repeated two to three times to ensure that there is no air inside the system. All valves are closed when no more air escapes out.
- The process is repeated for the other pipe strands.

3. CONNECTING THE COAXIAL GROUND HEAT EXCHANGER

- Each coaxial ground heat exchanger is filled with approved brine through the return pipe (black Ø 40 mm).
- It is observed that heavier brine pushes the lighter water through the feed pipe (blue Ø 40 mm) and the deaeriation pipe (black Ø 25 mm).
When the brine is in level with two openings (feed pipe and deaeriation pipe), the coaxial ground heat exchanger is completely filled.

After filling, each coaxial ground heat exchanger is connected to the distribution shaft and/or into the building. Connections should not be started before all ground heat exchangers (probes) are filled.

It is a general recommendation that coaxial ground heat exchangers with a maximum total length of 100 m (328 feet) can be connected in a row (for example 3 x 32 m or 2 x 48 m) instead of a single depth, thus saving cost for distribution shafts.

It is observed that with an in-row-connection each single coaxial ground heat exchanger has to be filled individually before being connected. A filling of the exchangers after being connected leads to a differing dilution ratio.

4. PREPARATION

The ball valve is closed and attached at the end of the return pipe (black Ø 40 mm) and at the end of the deaeriation pipe (black Ø 25 mm) of the coaxial ground heat exchanger.

The pressure pump is attached with manometer at the end of the feed pipe (blue Ø 40 mm) of the coaxial ground heat exchanger.

The ball valve of the return pipe is opened (black Ø 40 mm).

The water is pumped through the feed pipe (blue Ø 40 mm) of the coaxial ground heat exchanger until water is ejected from the return pipe (black Ø 40 mm). After that ball valve at the return pipe (black Ø 40 mm) is closed.
• The ball valve is opened at the end of the deaeriation pipe (black Ø 25 mm).

• Water is pumped through the feed pipe (blue Ø 40 mm) again until the water is ejected from the deaeriation pipe (black Ø 25 mm).

• Finally, the ball valve of the deaeriation pipe is closed.

Additional considerations that are required when closed vertical loops are used in limited site areas are as follows:

1. Soil Conditions will determine the type of drill bit to be used and whether any mud additive for effective heat transfer is required.

2. The depth and number of boreholes for vertical loops depends on the heating and cooling load, the drilling rate, the site area, soil and rock types, and moisture level.

3. Each pipe should be fused, assembled, and tested for leaks and flow before it is assembled into the borehole, so that it can be lowered before it caves in or the mud settles to the bottom of the hole.

4. The hole should be 5 - 10 feet deeper than the length of the pipe to accommodate expansion of the loop. The pipe should be filled with water prior to insertion.

5. If the hole is to be grouted in place, it should be filled with water and pressured to a level that will prevent the pipe from being crushed by the denser backfill material.

6. Taping short lengths of scrap steel rebar on the end of the pipe will hold the bottom end straight and offsets buoyancy of the plastic to make insertion easier and faster.

Grouting is an important aspect of the installation of a vertical closed-loop ground heat exchanger when used with a ground-source heat pump system. Not only will it provide the proper heat transfer between the grounds necessary for the most efficient operation
of the ground-source heat pump system, but it will also provide effective groundwater protection.

The Environmental Reasons for Grouting is that it prevents leakage downward along the pipe from surface or near surface contamination sources, prevents the migration of water between aquifers, seals off formations which are known to be contaminated, preserves the hydraulic characteristics of artesian formations and prevents leakage upward along the pipe. The economic choice of right equipment and practices to follow depends on local site conditions and the competitive cost situation. [44]

3.7 OVERVIEW OF COST ANALYSIS IN GEOTHERMAL ENERGY SYSTEMS

Before installing any new heating or cooling system in a home, it is necessary to reevaluate and reduce the energy load of the home. A more energy efficient home will not only reduce the cost of a new system and utility bills, but it may improve comfort. Because of the upfront cost for installing geothermal heat pump systems, it is very common to finance these systems. Monthly payments for financing a geothermal system are very reasonable and can actually save a homeowner money as soon as the system is installed. [4]

In order to analyze the costs involved in procurement and installation of geothermal energy systems, there are several factors which influence the overall cost of running the system. They are as follows:
1. **Equipment cost:** This includes the cost of any equipment used in the system, like probes, pipes, ground source heat pump, grouting materials and the refrigerant. Additional costs are involved if any of these materials are not manufactured locally, and have to be shipped from afar.

2. **Time and Cost to install:** This involves drilling and installation of the pipe. This cost is directly proportional to the depth of the system and heating/cooling capacity. Also, installation time plays an important role as complex assemblies and fittings can add to the labor costs.

3. **Installation complexity:** Complex assemblies, soil conditions fittings and equipment in drilling and installation add on to the installation complexity of the system. Hence, it is advisable to keep the assembly simple and fast and efficient to reduce installation costs and time.

4. **Operating Costs:** The costs involved due to day to day running of the system is calculated under operating costs. A system with high operating and running costs is economically not viable for commercial use. Hence, this cost must be as low as possible so that the customer can financially save in the long run.

5. **Savings:** Savings can be calculated compared to traditional heating and cooling systems which uses electricity from non-renewable sources of energy. Although the expenses incurred due to installation and equipment in a geothermal energy are high, the long term savings are generally significantly higher than traditional heating and cooling systems.
6. **Observed efficiency:** The coefficient of performance for Ground source heat exchangers of 4, minimum electricity has to be provided for maximum heating and cooling efficiency. Added to that, the average lifetime of a geothermal system is 40 years. This factor further strengthens the fact that geothermal energy can be a reliable and consistent energy source in the future generations.

7. **Tax Rebates:** The Department of Energy (DoE) and US Environment Protection Agency (EPA) have made radical changes to energy policy of renewable energy. Massive subsidies and tax cuts have been provided to encourage customers to invest in geothermal energy. The DOE has been actively involved in promoting geothermal heat pumps in residential applications. The elaborate energy policies of Federal and South Carolina have been elaborated in the following chapter.

8. **Return on Investment:** Return of investment is calculated based on the time taken to overcome the initial investment costs incurred and the start point of savings due to the technology. Ideally, installing a geothermal heat pump for a residential application, the average return of investment is about 3 to 5 years. [5] [6]
CHAPTER 4

ANALYTICAL AND NUMERICAL HEAT TRANSFER MODELING

Analytical and numerical HT modeling has been generated for in-depth understanding and simulation behind the structure and functioning of geothermal energy systems. This chapter presents the analytical methods for modeling thermal contact resistance (or thermal contact conductance, which is the inverse of thermal contact resistance) between the contact surfaces, namely Refrigerant-PVC, PVC-Concrete and Concrete-Soil. In coaxial geothermal systems, the thermal resistance of inner pipe is required to be as low as possible, to allow for more heat to be collected along the path of the fluid flow; whereas in pipe where the fluid flows out, the opposite applies. The grout is required to conduct heat when the fluid goes down along the inner pipe, and resists heat when the fluid goes out. Therefore, in designing a borehole heat exchanger, a careful optimization of the thermal resistivity is essential for obtaining high efficient geothermal systems. However, not many works have been found which takes into account the effective contact resistance on heat transfer at different pipe interfaces in geothermal piping systems. Hence, this chapter deals with the analytical modeling of effective contact resistance between interfaces, under certain assumptions.

4.1 INTRODUCTION

The analytical solution in coaxial geothermal energy system deals with the radial heat transfer from the fluid to the boundary, in a Gaussian distribution (spatial domain). Therefore, this model deals with the setup at infinite time, that is at steady state condition.
Since heat flux variation along the cross section of the pipe is of prime importance, we take a 2-Dimensional model for working. The modeling is Axisymmetric because it is a 3-dimensional system with a rotational symmetry about an axis. This will make the analysis simpler, considering the number of boundary conditions required to solve the problem. The input is 2-dimensional, but because of the rotational symmetry, the analysis is a symmetric 3-dimensional problem. The model consists of a coaxial pipe with a circulating refrigerant, flowing with a temperature $T_{\text{ref}}$, having a constant thermal capacity $C_p$, and emitting a constant heat flux $Q_{\text{net}}$. This refrigerant is in contact with the inner wall of PVC pipe, having thermal conductivity $\lambda_p$ and thermal diffusivity $\alpha_p$. The PVC pipe is surrounded by a layer of grout, having a thermal conductivity of $\lambda_g$ and a thermal diffusivity of $\alpha_g$. This grout layer is surrounded by a 10m radius region of soil, having a thermal conductivity of $\lambda_s$ and a thermal diffusivity of $\alpha_s$. The heat flux passing through each layer should be $Q_{\text{net}}$ at each boundary. [47]
The resulting radial heat transfer problem can be represented as follows:

**Figure 15: The top view of a coaxial pipe with different connected interfaces.**

Based on the figure, we can see that there are three contact surfaces where the heat transfer to the subsequent layer is not perfect. An analysis from the microscopic point of view reveals that all connected surfaces have certain imperfections or deviations from perfect contact. So, based on these imperfections, only at a few discrete points do the surfaces actually touch each other and heat transfer occurs, when the bodies are in contact. As pressure between the surfaces increase, the surface asperities on the topmost layer deform, creating regions where the heat flux can flow by conduction. In the regions where the physical contact is not effective, the heat is transferred by conduction, through gases that fills the gaps. Hence, this study takes into consideration the thermal contact conductance between each material layer.
The process of heat transfer across a joint is complex because the thermal resistance can depend upon many geometric, thermal, and mechanical parameters, which are listed as follows:

- Geometry of the contacting solids (surface roughness, asperity slope, and waviness)
- Gap thickness
- Type of interstitial fluid or material (vacuum, grease, foil, etc.)
- Thermal conductivities of the contacting solids and the interstitial substance
- Hardness or yield pressure of the contacting asperities (which affects the plastic deformation of the highest peaks of the softer solid)
- Modulus of elasticity of the contacting solids (which affects the elastic deformation of the wavy parts of the interface)
- Average temperature of the interface (which affects material physical properties)

4.2 MATHEMATICAL BACKGROUND

Macroscopically, the thermal resistance effect can be obtained by measuring the temperature profile of the contacting bodies along their centerline, and extrapolating the resulting one-dimensional line to the contact interface. The contact resistance at the interface, $R_i$ is then defined as the ratio between the temperature drop, and the heat transferred,
\[ R_i = \frac{\Delta T}{A_i Q_i} \]

where \( Q_i \) (in W/m²) is the heat flux that crosses the joint and \( A_i \) (in m²) is the interface cross-section area.

Now, the relation for contact conductance from literature works is be given by:

\[ C_i = \frac{1}{R_i A_i} \]

The radial conduction in a multi-layered cylindrical wall from the PVC wall to the far field soil boundary, assuming 1 Dimensional, steady state, constant conductivity, no heat generation and perfect interface contact is given by:

\[
R_{\text{total}} = R_{\text{cylinder}_1} + R_{\text{cylinder}_2} + R_{\text{cylinder}_3}
\]

\[
= \ln \frac{r_2}{r_1} \frac{2 \pi L \alpha_1}{2 \pi L} + \ln \frac{r_3}{r_2} \frac{2 \pi L \alpha_2}{2 \pi L} + \ln \frac{r_4}{r_3} \frac{2 \pi L \alpha_3}{2 \pi L}
\]

### 4.3 EFFECTIVE THERMAL RESISTANCE FOR CONTACT NETWORK

This joint conductance is equal to the sum of three heat conductance in series: the conduction through the contacting points, the radiation through the gaps between the surfaces, and the gas conduction through the gas that fills these gaps, or

\[ h_j = h_c + h_r + h_g \]

Therefore, the net heat flux through a boundary can be given by:

\[ Q_x = \frac{\Delta T}{(1/\lambda_1 + 1/c + 1/\lambda_2)} \]
4.4 ANALYTICAL MODEL OF THE SYSTEM

Analytical models are heat conduction and heat transfer problems designed to find the exact solutions of partial differential equations and Eigen functions using initial and boundary conditions, mathematically. After the boundary conditions are applied to Eigen functions, the solutions are expressed as Fourier series, Fourier transforms and Fourier integrals.

The mathematical model of shallow geothermal energy system can be represented as a set of differential equations, subjected to initial and boundary conditions. Initial boundary conditions specify the state of the system at \( t = 0 \). The initial value problems specify the constraint on all independent values, and the value is at one point in time or space. The boundary value problem specifies the boundary constraints of the independent variable, in space. For example, at \( x=0\text{m} \) (the central axis of the coaxial pipe), \( T \) at \( x=0 \) is assumed to be 294K, and at \( x=10\text{m} \) (far field of the pipe), \( T \) is 283K. Three models are studied by solving for exact solutions of governing equations—Analytical 1-D steady state analysis of a cylindrical model, 1-D steady state analysis by numerical finite difference method and 1-D transient analysis by finite difference method.

Since the numerical and analytical model has been simplified to a 1-D model, governing equation for 1-D steady state analysis of cylindrical model is given by,

\[
\frac{d}{dr} \left( r \frac{dT}{dr} \right) = 0
\]

The general solution for the above differential equation is given by,

\[
T(r) = A \ln r + B
\]
Applying Dirichlet Boundary conditions and solving for A and B,

\[ A = \frac{(T_2 - T_1)}{\ln \left( \frac{r_2}{r_1} \right)} \]

where \( T_2 \) is the temperature at far field and \( T_1 \) is temperature of brine.

\[ B = \frac{(T_1 \ln r_2 - T_2 \ln r_1)}{\ln r_2 - \ln r_1} \]

By substituting the values for A and B in the general solution, the temperature gradient profile is obtained as a function of distance from the center of the pipe, mathematically.

Similarly, the case of 1-D Transient analysis by finite difference model can be given by:

\[
\frac{dT}{dt} = \alpha \frac{d}{dr} \left( \frac{r \, dT}{dr} \right)
\]

Dirichlet boundary conditions (Assuming 283K everywhere in the system at \( t=0 \) and uniform material properties) are applied, without Neumann boundary conditions, where \( T \) is the temperature as a function of distance \( x \) and time \( t \). The time period is taken as 200,000s. [27]

Steady state analysis is computed by setting \( \frac{dT}{dt} = 0 \).

The following graph is obtained:
Figure 16: Comparative graph of three analytical models

It is observed that the steady state and transient models appear to converge to the same temperature points for a time period of 200,000s. It is inferred that the system reaches steady state values in almost 2 days, for the heating condition (summer months). This system is then compared with the numerical models designed on Abaqus and similar profiles are plotted to validate the analytical model.
4.5 NUMERICAL MODEL OF THE SYSTEM

Steady state and transient models of the geothermal system has been carried out by imposing suitable boundary conditions. The analysis consists of 2 dimensional and 3 dimensional models of different lengths of geothermal wells. Distribution of heat as it moves away from the center of the pipe is studied. The parameters defined to the system has been as close to the practical setting as possible. However, there are certain assumptions which works well for a practical setting:

1. Inlet and outlet temperatures of the brine has been calculated intuitively. Exact temperature data has not been determined. However, realistic assumptions for inlet and outlet temperatures for summer condition have been made.

2. The analysis has been carried out only for a unit length of pipe, at a particular instant. This assumption simplifies the model, and still provides vital information for parameter variation.

3. All transient analysis have an increment of 15s. Since transient simulations involve a lot of data for small increments, and because this research does not deal with temperature data at every instant, a large increment size has been chosen.

4. The contact conductance between each interface has not been defined in any literature. In that case, a contact conductance of 100 W/m²K.

5. Mesh sizes have been adjusted to capture maximum heat and temperature data near each interface and minimum data as the heat moves away from the piping and grout system.
Based on these assumptions and parameter values, multiple numerical simulations have been carried out.

The observations and conclusions of these numerical models have been explained in detail in Chapter 8. To test the numerical and analytical analysis, it is necessary to have an experimental setup to understand the practical application and working of a geothermal energy system. This calls for a laboratory scale experimental design to test the parameters discussed in this chapter.
CHAPTER 5

EXPERIMENTAL DESIGN FOR COAXIAL AND U-BEND GEOTHERMAL ENERGY SYSTEM

Experimental design is an excellent method to extract useful information like temperature and heat flux of a system using data collection and analysis methods. This method is also called as design of experiments. Based on the analytical and numerical solutions, we can set up an experiment to determine parameters which cannot be quantified easily in theory. Experimental study helps us to understand the real-time working of the system, with its association with external factors like temperature, pressure and humidity.

In this case, an extensive system design has been carried out to determine the temperature gradient of three systems - U-bend pipe, coaxial pipe with vortex generator and coaxial pipe without vortex generator at different points from the pipe surface. Temperature points at different points are difficult to determine using numerical simulations due to the impact of various factors. Hence, an experimental design has been proposed to determine the temperature field surrounding the pipe, under different soil conditions.

The experiment depends on 5 important factors which needs to be taken into account:

- Pumping the refrigerant: Refrigerant circulation is an important part of the experimental setup. The flow rate of the system has to be maintained at the inlet and outlet of the pipe, to capture the desired temperature difference. Alternatively, there is a water pipe to cool the refrigerant to capture the desired temperature difference. Hence, pump characteristics largely determine the effective heat
removal from the pipe system. Different types of submersible and jet pumps with a suitable power rating are ideal for this type of experimental setting.

- Measuring the flow rate of refrigerant: Flow rate has to be measured at the inlet and outlet of the pipes to measure the temperatures in the soil. As the change is flow rate induces a significant change in the borehole thermal resistance, and in turn the temperature distribution in the soil, it is necessary to measure the flow rate using equipment using high precision water meter and rotameters.

- Controlling the flow rate of the refrigerant: Apart from measuring the flow rate, controlling the flow rate is a challenge. The flow is in the turbulent region and it has to be maintained using control valves at inlet and outlet of the refrigerant. Calculations for the ideal flow rate has to be done for corresponding refrigeration space.

- Cooling and Heating the fluid at high flow rate: As the experimental setup involves a closed loop, the refrigerant and water loops have to be heated and cooled rapidly to be fed at inlet continuously. This is the biggest challenge of the experimental setup. High efficiency heat exchanger and chiller has to be used. A heating coil circuit controlled by Arduino can also be used for heating purposes.

- Measuring the temperature of the fluid: Temperature drop across the length of the pipe is of the order of 0.5-1 degree. This calls for a high precision temperature measuring devices with high sensitivity, which can be incorporated to the system at the inlet and outlet of the refrigerant.
5.1 DETERMINING TEMPERATURE GRADIENT

Instead of modeling the entire length of the pipe (80m or 100m), it is of prime importance that the rate of heat transfer in different materials is captured in the system. Hence, a 1m section of 80m long pipe is taken, and the temperature gradient of the brine with respect to depth is determined, using linear interpolation. With the gradient, temperatures at different depths can be used to set up the experiment, just by varying the inlet and outlet temperature of the brine. The summer condition of the U-bend pipe, where the heat is removed from the house and carried to the ground, can be given as follows:

Figure 17: The summer condition of a full-size geothermal pipe with the temperature of brine at different entry and exit points.
From the figure, it is assumed an inlet temperature of 25°C, and the temperature at a depth of 80m is a constant temp of 15°C and the outlet temperature of 12°C, the rate of temperature drop across the length of the pipe is determined.

Temperature drop of incoming brine across the length of the pipe \((x)\) is given by:

\[
\frac{dT}{dx} = \frac{(15-25)}{80} = -0.125 \degree C/m \text{ (Temperature decreases)}
\]

Temperature drop of outgoing fluid across the length of the pipe \((x)\) is given by:

\[
\frac{dT}{dx} = \frac{(15-18)}{80} = 0.0375 \degree C/m \text{ (Temperature increases)}
\]

Based on this temperature gradient, the temperatures of the brine for a unit section of the pipe can be determined as follows:

Figure 18: The temperatures of the brine at different points in a unit pipe section.
The laboratory equipment is calibrated to these temperatures. As the temperature drop in the system is very small, it calls for high precision temperature measuring gauges and flow meters to control the temperature.

The above experiment setup can be repeated for a system operating in winter conditions, where the system is reversed and heat is received from the ground:

**Figure 19: The winter condition of a full-size geothermal pipe with the temperature of brine at different entry and exit points.**

Here, the inlet temperature of the brine is at 5°C and outlet temperature is at 12°C. Based on this concept, an experimental setup is designed to measure the heat transfer outside the pipes (into the grout and the soil).
5.2 EXPERIMENTAL SETUP

The experimental design is done based on calculations for temperature gradient. The equipment used for coaxial and U-Bend pipe experiments is shown below:

<table>
<thead>
<tr>
<th>PRODUCT</th>
<th>SPECIFICATION</th>
<th>QUANTITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Submersible Pump</td>
<td>0.5HP, 220V, 26GPM, Single Phase</td>
<td>1</td>
</tr>
<tr>
<td>Garden water pump</td>
<td>0.5HP, 1GPM</td>
<td></td>
</tr>
<tr>
<td>Purge Rotameter with Control valve</td>
<td>7 GPH to 20 GPM, 33F-125F, Brass/SS connections</td>
<td>2</td>
</tr>
<tr>
<td>5m radius Tank</td>
<td>Polycarbonate, Open at top</td>
<td>1</td>
</tr>
<tr>
<td>Hot Water Tank heater</td>
<td>2.5in Steel Flange 1.25KW, 110V, 11in immersion</td>
<td>1</td>
</tr>
<tr>
<td>Industrial Water Chiller</td>
<td>25A, 24000Btu/hr</td>
<td>1</td>
</tr>
<tr>
<td>High Density Cartridge Immersion Heater</td>
<td>1000W, 22W/cm2</td>
<td>1</td>
</tr>
<tr>
<td>Digital Temperature Controller</td>
<td>Accuracy 0.2C</td>
<td>1</td>
</tr>
<tr>
<td>J-type thermocouple</td>
<td>Accuracy 0.01C</td>
<td>4+4</td>
</tr>
<tr>
<td>Arduino UNO</td>
<td>5V</td>
<td>1</td>
</tr>
<tr>
<td>Solid State Relay</td>
<td>10A, 800V</td>
<td>1</td>
</tr>
<tr>
<td>Fuse</td>
<td>15A time-delay fuse</td>
<td>1</td>
</tr>
<tr>
<td>Surge Protection Diode (TVS diodes)</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Connecting Wires</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Bill of Materials for the experimental setup.

The experimental setup consists of 2 main components:

- Overall setup to measure the temperature gradient in different types of soil. This includes the piping system and thermocouple probes embedded in the
polycarbonate tank to measure temperature values at different points of running time.

- The automatic feedback electrical circuit to maintain the required brine temperature. This includes the Arduino and steady state relay to monitor and adjust the temperature of the brine automatically, based on reference user input temperature.

The experiment design is illustrated as follows:

![Diagram of experimental design](image)

**Figure 20: Small scale experimental design of a coaxial geothermal pipe system for summer condition.**

The aim of this experimental setup is to measure the temperature gradient in the soil by varying different key parameters. The key parameters include flow rate, length of the pipe,
soil texture, pipe diameter and can further extended to compare the heat transfer characteristics between U-Bend and coaxial pipes.

A submersible pump of specified horsepower is used to drive the brine from a reservoir into the piping circuit. The flow rate in the inlet pipe is measured and controlled using a purge rotameter and a control valve at the inlet. Thermocouple A is used to measure the temperature of the brine before its entry into the inlet pipe. The brine passes through the inlet pipe and enters the chiller to reduce the temperature. Thermocouple B reads the temperature at the exit of the inlet pipe. Chiller cools the brine to a specific temperature and feeds into the outlet pipe, at a temperature lower than that of inlet pipe. Thermocouple C measures the temperature of brine at the entry of outlet pipe. Thermocouple D measures the temperature at the exit of outlet pipe, before it is fed into the heating circuit. The heating circuit is an automatic feedback loop controlled using an Arduino connected to a heating coil.

5.3 AUTOMATIC FEEDBACK HEATING CIRCUIT

Heating the brine to the required temperature is automatically controlled using an Arduino feedback loop system, coupled with a heating coil. The block diagram for the heating circuit is as shown below. A high-sensitive J-type thermocouple is immersed into the brine for reading the temperature. The values are read on an Arduino Uno, which are compared with a user defined temperature for the brine. Once the temperature of the brine falls below the user defined temperature, the Arduino activates the solid state relay to supply power into the heating coil. Once the temperature reaches the user defined temperature, the circuit is switched off automatically.
Thermocouples 1, 2, 3 and 4 measure the temperature at 4 different points in the soil. The water pipes at the end of the polycarbonate tank is to maintain a constant temperature at the boundary.

The readings from the thermocouple are read on a computer.

The experiment is repeated by varying different parameters, for different piping systems. The schematic diagram is as follows:
Figure 22: Small scale experimental design of a U-Bend geothermal pipe system for summer condition.

By conducting an experiment comparing the heat transfer characteristics of a U-Bend, coaxial without vortex generator and with vortex generator pipes, a quantitative heat transfer analysis can be carried out to determine the better efficient system.
5.4 SPECULATIVE GRAPHS

Although the experimental was not carried out, the speculative trends which will be obtained are as follows:

![Expected Variation of Temperature with Radial distance for different Pipes](image)

**Figure 23: Variation of Temperature with radial distance for different pipes**
Speculative graphs give an intuitive idea of the trend which would be observed by carrying out the experiments. From figures 23 and 24, coaxial pipes with vortex generator will have better heat distribution properties compared to coaxial pipe without vortex generator and U-Bend pipe.

Figure 24: Variation of Temperature with time for different pipes
CHAPTER 6

INSTALLATION, COST ANALYSIS AND MARKETABILITY – CASE STUDY

The following case study is a real time working model of a coaxial system from GeoKoax GmbH, drilled in Pennsylvania.

6.1 GEOLOGICAL SETTING

The site geology was as follows:

- 80% siltstone/shale with a minor amount of sandstone of the Pennsylvania Aged Conemaugh Group.
- Average thermal conductivity is estimated at ~1.2 btu / hr. – ft. - °F (2.075 WmK)
- Water table is at ~40ft below ground surface.
- Topographical Elevation is 875Ft Above mean Sea Level.
- Average Earth Temp @23ft is 51 F.
6.2 SPECIFICATION INFORMATION

The information provided is via an ACCA Manual J analysis using “Wrightsoft” computer software completed by Espyville Heating. This information was used by coaxial geothermal energy for ground heat exchanger (probe) sizing.

The pertinent data is as follows:

<table>
<thead>
<tr>
<th>Building Parameters</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building size</td>
<td>1299sqft</td>
</tr>
<tr>
<td>Building volume</td>
<td>10,281 cubic feet</td>
</tr>
<tr>
<td>Heating load</td>
<td>44,155 btu / hr. (13.765 Kwh)</td>
</tr>
<tr>
<td>Cooling load</td>
<td>22,327 btu / hr. (6.421 Kwh)</td>
</tr>
<tr>
<td>Domestic hot water requirement</td>
<td>2807 btu / hr. (823 Kwh);</td>
</tr>
<tr>
<td>Run time in heating</td>
<td>1,750 hrs</td>
</tr>
<tr>
<td>Run time in cooling</td>
<td>800 hrs</td>
</tr>
<tr>
<td>Ground Source Heat Pump Manufacturer</td>
<td>Climate Master</td>
</tr>
</tbody>
</table>

**Table 2: Building specifications in Pennsylvania for installing coaxial probes.**

Model: Trilogy 45 Q-Mode with iGateTM Internet-Connected Communicating system. This model comes with variable speed compressor, variable speed ECM fan and variable speed ground loop circulation pumps and can affectively be controlled / limited via DIPS switches to operate between a 2 – ton – 24,000 btu / hr. (7.03Kwh) and up to a 5 – ton – 60,000 btu / hr. (17.6 Kwh).


6.3 PROBE SIZING

Geokoax GmbH determined that to support the energy loads as described in Section above, a 2.5 ton – 27,300 Btu / hr. (8Kwh) ground source heat pump would be required. The total length of Coaxial probe length needed to supply a 2.5 ton – 27,300 Btu / hr. (8 Kwh) ground source heat pump is 262 feet (80 m) However, as the ground source heat pump unit has the capability to supply up to 5 – ton – 60,000 Btu / hr. (17.6 Kwh), Coaxial recommends that a total of 492 feet (150 m) be installed.

6.4 PROBE INSTALLATION

Drilling Service by Adam Locke provided the following drilling services and materials:

- Drilling of 2 boreholes to a depth of 80 m (262 feet) and minimally spaced at 6.1 m (20 feet) center – to -center;
- Borehole diameter to 8 inch (200 mm) to completed target depth – drilling contractor to ensure that borehole is sufficient in diameter to accommodate the 140 mm.
- (5.5 inch) coaxial probe to full installed depth;
- Grout material: Carbon / graphite based;
- Grout thermal conductivity: 1.2 Btu / hr. ft. - °F; Probes will be fully grouted from bottom to top of boreholes and top – up if settling occurs; Temporary steel casing as required; Total borehole length: 150 m (492 feet);
- The supply of butt fusion equipment capable of accommodating up to 203mm (6 inch) HDPE piping.
6.5 LATERAL PIPE INSTALLATION

Adam Locke provided the following lateral piping installation services and materials: Excavation / trenching services to depth below the local frost line from the installed Coaxial probes to the building penetrations; All HDPE lateral piping – 1.25” - (including fusion services) connected to the coaxial probes from the borefield location into the building; Backfilling of trenches to grade as required.

6.6 FLUSHING AND PURGING

Adam Locke flushed debris from each coaxial probe and all field lateral piping and purge each coaxial probe and all field lateral piping of air. Recommended flushing rate: velocity of 1.22 m / sec. (4ft / sec. +). Recommended purging rate: a minimum of 0.61 m/sec. (2ft / sec).

6.7 PRESSURE TESTING

Recommended pressure testing of each coaxial probe and all lateral field piping following the purging procedure: Hydrostatic pressure test for duration of 12 hours at 690 KPa (100 psig).

6.8 ANTI-FREEZE

Adam Locke will provide and install a methanol – based anti-freeze agent, with appropriate chemical inhibitors, to a level of 20% of total system volume.

6.9 PROBE SUPPLY AND EXPERTISE

Geokoax GmbH supplied the following materials and expertise:
• A total of 150 m (492 feet) of 140 mm (5.5 inch) patented coaxial ground heat exchanger probes shipped from Germany to the project site; coaxial probe heads will be modified to accept 1.25” HDPE lateral piping;

• Expert guidance and supervision personnel - from Germany and South Carolina, U.S.A respectively.

6.10 COST ANALYSIS

The materials costs incurred are given by:

<table>
<thead>
<tr>
<th>ITEM</th>
<th>PRICE IN USD</th>
</tr>
</thead>
<tbody>
<tr>
<td>150m Coaxial Probe</td>
<td>$3,302.64</td>
</tr>
<tr>
<td>Specialty Tools</td>
<td>$545.40</td>
</tr>
<tr>
<td>Shipping and Transportation</td>
<td>$1,650.00</td>
</tr>
<tr>
<td>Technician</td>
<td>$2,684.81</td>
</tr>
<tr>
<td>Specialty Consultant</td>
<td>$1503.50</td>
</tr>
<tr>
<td>TOTAL</td>
<td>$9,686.35</td>
</tr>
</tbody>
</table>

Table 3: Material and manpower costs from Geokoax GmbH

These costs are for the customer to the geothermal piping company (here Geokoax GmbH).
Drilling and Installation costs are as follows:

<table>
<thead>
<tr>
<th>ITEM</th>
<th>PRICE IN USD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drilling 8in – 150m</td>
<td>$6,875.00</td>
</tr>
<tr>
<td>Graphite grout</td>
<td>$2,000.00</td>
</tr>
<tr>
<td>• Trenching &amp; backfill for lateral piping;</td>
<td>$2,750.00</td>
</tr>
<tr>
<td>• Supply and Install 1.25 inch lateral piping from Probe location into building</td>
<td></td>
</tr>
<tr>
<td>Supply and Install:</td>
<td></td>
</tr>
<tr>
<td>• Methanol anti – freeze agent to 20% of system volume;</td>
<td></td>
</tr>
<tr>
<td>• Flushing &amp; Purging of probes and lateral piping;</td>
<td></td>
</tr>
<tr>
<td>• Building pipe penetrations and sealing</td>
<td></td>
</tr>
<tr>
<td>Rental of “2 – 6” Butt Fusion welding equipment</td>
<td>$550.00</td>
</tr>
<tr>
<td>TOTAL</td>
<td>$12,175.00</td>
</tr>
</tbody>
</table>

Table 4: Installation costs for the coaxial probes in Pennsylvania
### COST CALCULATIONS

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>COST ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total cost of Installation</td>
<td>21861.35</td>
</tr>
<tr>
<td>Costs borne due to Tax rebates (30% of installation costs)</td>
<td>6558.41</td>
</tr>
<tr>
<td>Difference to be borne by the customer</td>
<td>15302.94</td>
</tr>
<tr>
<td>Average Monthly Summer Bill (1300sqft)</td>
<td>150</td>
</tr>
<tr>
<td>Average Monthly Winter Bill (1300sqft)</td>
<td>230</td>
</tr>
<tr>
<td>Yearly Electricity Bill (6months + 6 Months)</td>
<td>$2,280</td>
</tr>
<tr>
<td>Yearly Savings increase going into next year</td>
<td>4%</td>
</tr>
<tr>
<td>Average Repairs and Maintenance for Conventional systems</td>
<td>500</td>
</tr>
</tbody>
</table>

Table 5: Average estimated costs of power consumption for a 1300sqft house.

### SAVINGS TABLE

<table>
<thead>
<tr>
<th>SAVINGS PER YEAR</th>
<th>COST ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Savings at End of Year 1</td>
<td>2780.00</td>
</tr>
<tr>
<td>Savings at End of Year 2</td>
<td>6171.20</td>
</tr>
<tr>
<td>Savings at End of Year 3</td>
<td>9698.05</td>
</tr>
<tr>
<td>Savings at End of Year 4</td>
<td>13365.97</td>
</tr>
<tr>
<td>Savings at End of Year 5</td>
<td>17180.61</td>
</tr>
</tbody>
</table>

Table 6: Cumulative estimated savings calculation at the end of 5 years.
DETAILED CALCULATIONS

Savings at of year 1, = 2250 + 500 = $2780

According to the reports from DOE, a geothermal system saves 4% more going into each year.

End of year 2, cumulative savings = 2780 + (2780+ 4% of 2780 + 500) = $6171.20

End of year 3, cumulative savings = 6171.20 + (2780+ 4% of 6171.20 + 500) = $9698.05

Total Savings at the end of 5 years = 17180.61

Time taken to get back the invested money ($15302.94) = 4.58 years

Geothermal energy systems have a very long lifetime. The average lifetime of a geothermal system before the first maintenance is 15-20 years.

Savings after clearing the invested costs, at the end of 15 years = $49508.59
Table 7: Return on Investment table at the end of 15 years.

Table shows the worst case and best case scenarios of monthly electricity bills. SHigh and SLow indicates the average highest and lowest electricity bills in summer, while WHigh and WLow indicates the average highest and lowest electricity bills in winter. It is observed that the average time taken to clear the initial invested cost is about 4.5 years.

Geokoax claims that the time taken to get back the costs is between 3-5 years, which is justified. Also, the savings at the end of 15 years is of the order of $50,000, which is highly significant in terms of monetary and environmental gains. This makes coaxial geothermal energy systems an affordable and environmentally friendly product for resident and commercial use. Two drawbacks of this cost analysis is that off-days (days of extreme
temperatures) are not taken into consideration, and the cost of using natural gas on these
days have not been included, which is for future development of this work. [12]

CHAPTER 7: OBSERVATIONS AND CONCLUSIONS:

(All thermal property data have been obtained from www.engineeringtoolbox.com.)

7.1 ANALYSIS OF PVC PROPERTIES

Based on the transient analysis of numerical model, keeping the other parameters of
concrete and soil constant (values mentioned in chapter 5), the following observations for
PVC were made:

<table>
<thead>
<tr>
<th>PVC</th>
<th>Thermal Conductivity (W/mK)</th>
<th>HFL @ Int 1</th>
<th>HFL @ Int 2</th>
<th>HFL @ Int 3</th>
<th>HFL @ FF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexible</td>
<td>0.14</td>
<td>64.5037</td>
<td>58.6368</td>
<td>53.0046</td>
<td>7.30E-13</td>
</tr>
<tr>
<td>Flexible</td>
<td>0.2</td>
<td>68.1831</td>
<td>62.0544</td>
<td>56.5602</td>
<td>7.30E-13</td>
</tr>
<tr>
<td>Rigid</td>
<td>0.28</td>
<td>70.7001</td>
<td>64.402</td>
<td>59.0651</td>
<td>7.30E-13</td>
</tr>
</tbody>
</table>

Table 8: Numerical Analysis of Heat Flux by varying PVC parameters.

Int 1 refers to Brine-PVC interface, Int 2 refers to PVC-Grout Interface and Int-3 refers to
the Grout-Soil Interface. FF refers to the heat flux at the distance of 10m from the central
axis of the pipe. R Int 1 , R Int 2 and R Int 3 refer to the radii of the three interfaces. A Int
1, A Int 2 and A Int 3 refers to the area of unit section that the respective interfaces. Q Int
1, Q Int 2 and Q Int 3 represents the Total heat passing through the respective interface.
The percentage change in HFL vs parameter change is shown below:

<table>
<thead>
<tr>
<th>Percentage Change in Parameter</th>
<th>Percentage Change in HFL</th>
<th>Ratio of Change of Parameter and HFL</th>
<th>1/R</th>
<th>Percentage change in HFL vs Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>66.67</td>
<td>9.17</td>
<td>7.3</td>
<td>0.14</td>
<td>13.75</td>
</tr>
</tbody>
</table>

**Table 9: Variation of Thermal conductivity of PVC vs Heat flux in the system.**

It implies that for a 66.67% change in thermal conductivity, there is a corresponding change of 9.17% in the HFL of the system. This means that there is a 13.75% change in heat flux for every unit change in thermal conductivity.

To calculate the Q passing through each interface, the calculations are as follows:

<table>
<thead>
<tr>
<th>R Int 1</th>
<th>R Int 2</th>
<th>R Int 3</th>
<th>A Int 1</th>
<th>A Int 2</th>
<th>A Int 3</th>
<th>Q Int 1</th>
<th>Q Int 2</th>
<th>Q Int 3</th>
<th>Net% Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.064</td>
<td>0.070</td>
<td>0.073</td>
<td>0.401</td>
<td>0.439</td>
<td>0.460</td>
<td>25.857</td>
<td>25.716</td>
<td>24.378</td>
<td>5.751</td>
</tr>
<tr>
<td>0.064</td>
<td>0.070</td>
<td>0.073</td>
<td>0.401</td>
<td>0.439</td>
<td>0.460</td>
<td>27.332</td>
<td>27.215</td>
<td>26.014</td>
<td>4.845</td>
</tr>
<tr>
<td>0.064</td>
<td>0.070</td>
<td>0.073</td>
<td>0.401</td>
<td>0.439</td>
<td>0.460</td>
<td>28.341</td>
<td>28.245</td>
<td>27.166</td>
<td>4.162</td>
</tr>
</tbody>
</table>

**Table 10: Net Amount of Heat passing through each interface in the system.**

It can be concluded that increase in thermal conductivity of PVC increases heat flux through each interface. It is observed that the net amount of Q through the system decreases as the thermal conductivity increases. However there is about 5% decrease as the heat...
passes through each interface. This can be due to improper contact or build-up heat during ramp up period.

### 7.2 ANALYSIS OF CONCRETE PROPERTIES

Based on the transient analysis of numerical model, keeping the other parameters of concrete and soil constant (values mentioned in chapter 5), the following observations for PVC were made:

<table>
<thead>
<tr>
<th>Concrete</th>
<th>Thermal Conductivity</th>
<th>Density</th>
<th>Specific Heat</th>
<th>Thermal Diffusivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>0.2</td>
<td>1600</td>
<td>720</td>
<td>1.74E-07</td>
</tr>
<tr>
<td>Medium</td>
<td>0.55</td>
<td>1680</td>
<td>860</td>
<td>3.81E-07</td>
</tr>
<tr>
<td>Dense</td>
<td>1.4</td>
<td>1950</td>
<td>920</td>
<td>7.80E-07</td>
</tr>
<tr>
<td>Concrete Stone</td>
<td>1.7</td>
<td>2400</td>
<td>960</td>
<td>7.38E-07</td>
</tr>
</tbody>
</table>

Table 11: Thermal Properties of different concrete types.
The heat flux measured at each interface for different types of concrete is as shown below:

<table>
<thead>
<tr>
<th>Concrete</th>
<th>Thermal Conductivity</th>
<th>HFL @ Int 1</th>
<th>HFL @ Int 2</th>
<th>HFL @ Int 3</th>
<th>HFL @ FF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lightweight</td>
<td>0.2</td>
<td>63.98</td>
<td>58.2635</td>
<td>52.956</td>
<td>7.30E-13</td>
</tr>
<tr>
<td>Medium</td>
<td>0.55</td>
<td>67.113</td>
<td>61.0899</td>
<td>55.6401</td>
<td>7.30E-13</td>
</tr>
<tr>
<td>Dense</td>
<td>1.4</td>
<td>68.253</td>
<td>62.1174</td>
<td>56.6204</td>
<td>7.30E-13</td>
</tr>
<tr>
<td>Concrete Stone</td>
<td>1.7</td>
<td>68.385</td>
<td>62.2363</td>
<td>56.734</td>
<td>7.30E-13</td>
</tr>
</tbody>
</table>

Table 12: Numerical Analysis of Heat Flux by varying PVC parameters.

The percentage change in HFL vs parameter change is shown below:

<table>
<thead>
<tr>
<th>Percentage Change in Parameter</th>
<th>Percentage Change in HFL</th>
<th>Ratio of Change of Parameter and HFL</th>
<th>1/R</th>
<th>Percentage change in HFL vs Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>150.00</td>
<td>6.46</td>
<td>23.2</td>
<td>0.043</td>
<td>4.31</td>
</tr>
<tr>
<td>102.22</td>
<td>1.88</td>
<td>54.4</td>
<td>0.018</td>
<td>1.84</td>
</tr>
</tbody>
</table>

Table 13: The relative change in Heat Flux to the Thermal conductivity of Concrete.
It implies that for a 150% change in thermal conductivity between Light and Medium concrete, there is a corresponding increase of 6.46% in the HFL of the system. This means that there is a 4.31% change in heat flux for every unit change in thermal conductivity. However, for a change of 102.22% in thermal conductivity yields only 1.88% increase in HFL. This shows a non-linear relationship between the thermal conductivity and heat flux.

The Net change in $Q$ for the system is given by:

<table>
<thead>
<tr>
<th>$R_{\text{Int}}$ 1</th>
<th>$R_{\text{Int}}$ 2</th>
<th>$R_{\text{Int}}$ 3</th>
<th>$A_{\text{Int}}$ 1</th>
<th>$A_{\text{Int}}$ 2</th>
<th>$A_{\text{Int}}$ 3</th>
<th>$Q_{\text{Int}}$ 1</th>
<th>$Q_{\text{Int}}$ 2</th>
<th>$Q_{\text{Int}}$ 3</th>
<th>Net % Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.064</td>
<td>0.070</td>
<td>0.073</td>
<td>0.401</td>
<td>0.439</td>
<td>0.460</td>
<td>25.647</td>
<td>25.552</td>
<td>24.356</td>
<td>5.054</td>
</tr>
<tr>
<td>0.064</td>
<td>0.070</td>
<td>0.073</td>
<td>0.401</td>
<td>0.439</td>
<td>0.460</td>
<td>26.903</td>
<td>26.792</td>
<td>25.590</td>
<td>5.054</td>
</tr>
<tr>
<td>0.064</td>
<td>0.070</td>
<td>0.073</td>
<td>0.401</td>
<td>0.439</td>
<td>0.460</td>
<td>27.360</td>
<td>27.243</td>
<td>26.041</td>
<td>4.900</td>
</tr>
<tr>
<td>0.064</td>
<td>0.070</td>
<td>0.073</td>
<td>0.401</td>
<td>0.439</td>
<td>0.460</td>
<td>27.413</td>
<td>27.295</td>
<td>26.094</td>
<td>4.842</td>
</tr>
</tbody>
</table>

**Table 14: The net change in Heat passing through each interface of the system.**

Generally, it can be concluded that increase in thermal conductivity of concrete increases heat flux through each interface. However there is about 5% decrease as the heat passes through each interface. This can be due to improper contact or build-up heat during ramp up period. It is also observed that the net change in $Q$ decreases as the thermal conductivity of concrete increases. Hence, lightweight and medium concrete is preferred over dense concrete as an ideal grouting material for geothermal systems.
7.3 ANALYSIS OF SOIL PROPERTIES

Based on the transient analysis of numerical model, keeping the other parameters of concrete and PVC constant (values mentioned in chapter 5), the following observations for different soil types were made:

<table>
<thead>
<tr>
<th>SOIL TYPES</th>
<th>k</th>
<th>rho</th>
<th>Cp</th>
<th>Alpha</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil with org matter</td>
<td>0.175</td>
<td>1235</td>
<td>1000</td>
<td>1.4E-07</td>
</tr>
<tr>
<td>Gravel</td>
<td>0.7</td>
<td>1800</td>
<td>1200</td>
<td>3.2E-07</td>
</tr>
<tr>
<td>Moist Sand</td>
<td>1</td>
<td>1905</td>
<td>1400</td>
<td>3.7E-07</td>
</tr>
<tr>
<td>Dry Sand</td>
<td>0.5</td>
<td>1555</td>
<td>800</td>
<td>4.0E-07</td>
</tr>
<tr>
<td>Clayey</td>
<td>1.1</td>
<td>1680</td>
<td>1381</td>
<td>4.7E-07</td>
</tr>
<tr>
<td>Very moist sand</td>
<td>1.4</td>
<td>1905</td>
<td>1480</td>
<td>5.0E-07</td>
</tr>
<tr>
<td>Saturated sand</td>
<td>3</td>
<td>1840</td>
<td>2512</td>
<td>6.5E-07</td>
</tr>
</tbody>
</table>

Table 15: Thermal Properties of different soil types.

The heat flux measured at each interface for different types of soil is as shown below:

<table>
<thead>
<tr>
<th>SOIL TYPES</th>
<th>HFL @ Int 1</th>
<th>HFL @ Int 2</th>
<th>HFL @ Int 3</th>
<th>HFL @ FF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil with org matter</td>
<td>64.58</td>
<td>58.67</td>
<td>53.39</td>
<td>2.56E-13</td>
</tr>
<tr>
<td>Gravel</td>
<td>113.62</td>
<td>103.61</td>
<td>96.15</td>
<td>1.02E-12</td>
</tr>
<tr>
<td>Moist Sand</td>
<td>126.66</td>
<td>115.59</td>
<td>107.75</td>
<td>1.46E-12</td>
</tr>
<tr>
<td>Dry Sand</td>
<td>93.25</td>
<td>84.93</td>
<td>78.31</td>
<td>7.30E-13</td>
</tr>
</tbody>
</table>
Table 16: Numerical Analysis of Heat Flux by varying Soil parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Percentage Change</th>
<th>Ratio of Change</th>
<th>1/R</th>
<th>Percentage Change in HFL vs Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clayey</td>
<td>126.57</td>
<td>115.51</td>
<td>107.73</td>
<td>1.61E-12</td>
</tr>
<tr>
<td>Very moist sand</td>
<td>135.47</td>
<td>123.70</td>
<td>115.68</td>
<td>2.04E-12</td>
</tr>
<tr>
<td>Saturated sand</td>
<td>156.33</td>
<td>142.90</td>
<td>134.49</td>
<td>4.38E-12</td>
</tr>
</tbody>
</table>

The percentage change in HFL vs parameter change is shown below:

<table>
<thead>
<tr>
<th>Parameter Change in</th>
<th>Percentage Change in HFL</th>
<th>Ratio of Change of Parameter and HFL</th>
<th>1/R</th>
<th>Percentage Change in HFL vs Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>128.70</td>
<td>75.95</td>
<td>1.7</td>
<td>0.590</td>
<td>59.01</td>
</tr>
<tr>
<td>164.61</td>
<td>96.14</td>
<td>1.7</td>
<td>0.584</td>
<td>58.41</td>
</tr>
<tr>
<td>183.65</td>
<td>44.40</td>
<td>4.1</td>
<td>0.242</td>
<td>24.18</td>
</tr>
<tr>
<td>234.59</td>
<td>96.00</td>
<td>2.4</td>
<td>0.409</td>
<td>40.92</td>
</tr>
<tr>
<td>250.43</td>
<td>109.79</td>
<td>2.3</td>
<td>0.438</td>
<td>43.84</td>
</tr>
<tr>
<td>358.05</td>
<td>142.08</td>
<td>2.5</td>
<td>0.397</td>
<td>39.68</td>
</tr>
</tbody>
</table>

Table 17: The relative change in Heat Flux to the Thermal conductivity of Soil

It implies that for a 128.70% change in thermal conductivity between soil with organic matter and gravel, there is a corresponding change of 75.95% in the HFL of the system. This means that there is a 59.01% change in heat flux for every unit change in thermal conductivity.
conductivity. It is evident that soil characteristics have a major influence on the HFL in the system.

The Net change in Q for the system is given by:

<table>
<thead>
<tr>
<th>R Int 1</th>
<th>R Int 2</th>
<th>R Int 3</th>
<th>A Int 1</th>
<th>A Int 2</th>
<th>A Int 3</th>
<th>Q Int 1</th>
<th>Q Int 2</th>
<th>Q Int 3</th>
<th>%Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.064</td>
<td>0.070</td>
<td>0.073</td>
<td>0.401</td>
<td>0.439</td>
<td>0.460</td>
<td>25.887</td>
<td>25.731</td>
<td>24.554</td>
<td>5.180</td>
</tr>
<tr>
<td>0.064</td>
<td>0.070</td>
<td>0.073</td>
<td>0.401</td>
<td>0.439</td>
<td>0.460</td>
<td>45.547</td>
<td>45.438</td>
<td>44.223</td>
<td>2.914</td>
</tr>
<tr>
<td>0.064</td>
<td>0.070</td>
<td>0.073</td>
<td>0.401</td>
<td>0.439</td>
<td>0.460</td>
<td>50.775</td>
<td>50.693</td>
<td>49.559</td>
<td>2.398</td>
</tr>
<tr>
<td>0.064</td>
<td>0.070</td>
<td>0.073</td>
<td>0.401</td>
<td>0.439</td>
<td>0.460</td>
<td>37.381</td>
<td>37.248</td>
<td>36.017</td>
<td>3.662</td>
</tr>
<tr>
<td>0.064</td>
<td>0.070</td>
<td>0.073</td>
<td>0.401</td>
<td>0.439</td>
<td>0.460</td>
<td>50.738</td>
<td>50.659</td>
<td>49.546</td>
<td>2.353</td>
</tr>
<tr>
<td>0.064</td>
<td>0.070</td>
<td>0.073</td>
<td>0.401</td>
<td>0.439</td>
<td>0.460</td>
<td>54.307</td>
<td>54.249</td>
<td>53.205</td>
<td>2.031</td>
</tr>
<tr>
<td>0.064</td>
<td>0.070</td>
<td>0.073</td>
<td>0.401</td>
<td>0.439</td>
<td>0.460</td>
<td>62.667</td>
<td>62.670</td>
<td>61.858</td>
<td>1.292</td>
</tr>
</tbody>
</table>

Table 18: The net change in Heat passing through each interface of the system.

Generally, nothing can be concluded by increasing thermal conductivity of soil and heat flux through each interface. However there is a gradual decrease as the heat passes through each interface. This can be due to improper contact or voids in soil composition. It is also observed that the net change in Q decreases as the thermal conductivity of soil increases, although the Q through each interface increases with increasing conductivity. Hence, it is critical that soil parameters have to be studied before drilling and installation.
7.4 THERMAL CONTACT CONDUCTANCE

Initially, steady state analysis to determine the effect of thermal contact conductance at interface 1 was carried out. The following graph was obtained:

![Graph showing variation of temperature with contact conductance C1, at different locations in the soil.](image)

**Figure 25: Variation of temperature with contact conductance C1, at different locations in the soil.**
<table>
<thead>
<tr>
<th>Contact Conductance</th>
<th>HFL @ Int 1 (W/m²)</th>
<th>HFL @ Int 2 (W/m²)</th>
<th>HFL @ Int 3 (W/m²)</th>
<th>HFL @ FF (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>68.18</td>
<td>62.05</td>
<td>56.56</td>
<td>7.30E-13</td>
</tr>
<tr>
<td>120</td>
<td>69.70</td>
<td>63.46</td>
<td>57.96</td>
<td>7.30E-13</td>
</tr>
</tbody>
</table>

**Table 19: Numerical Analysis of Heat Flux by varying contact conductance.**

<table>
<thead>
<tr>
<th>Percentage Change in Parameter</th>
<th>Percentage Change in HFL</th>
<th>Ratio of Change of Parameter and HFL</th>
<th>1/R</th>
<th>Percentage change in HFL vs Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.18</td>
<td>2.21</td>
<td>8.2</td>
<td>0.121</td>
<td>12.14</td>
</tr>
</tbody>
</table>

**Table 20: The relative change in Heat Flux to the contact conductance.**

For steady state analysis graph in Figure 25, contact conductance does not change significantly after 60W/m²K. However in transient analysis, there is a change of 12% in HFL when contact conductance is varied. This discrepancy calls for the need for transient analysis to determine the impact of contact conductance on the working of geothermal systems.
7.5 CONCLUSIONS

The comparative study of different properties with respect to the best case scenario is as follows:

<table>
<thead>
<tr>
<th>Type of PVC</th>
<th>Q (W)</th>
<th>Best Case % Change in Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexible PVC (K=0.14)</td>
<td>25.86</td>
<td>8.76</td>
</tr>
<tr>
<td>Flexible PVC (K=0.20)</td>
<td>27.33</td>
<td>3.56</td>
</tr>
<tr>
<td>Rigid PVC (K=0.28)</td>
<td>28.34</td>
<td></td>
</tr>
</tbody>
</table>

Table 21: Best case percentage change in energy for different types of PVC.

<table>
<thead>
<tr>
<th>Type of Concrete</th>
<th>Q (W)</th>
<th>Best Case % Change in Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lightweight Concrete Grout</td>
<td>25.552</td>
<td>6.38</td>
</tr>
<tr>
<td>Medium Concrete Grout</td>
<td>26.792</td>
<td>1.84</td>
</tr>
<tr>
<td>Dense Concrete Grout</td>
<td>27.243</td>
<td>0.19</td>
</tr>
<tr>
<td>Concrete Stone Grout</td>
<td>27.295</td>
<td></td>
</tr>
</tbody>
</table>

Table 22: Best case percentage change in energy for different types of Concrete.
<table>
<thead>
<tr>
<th>Type of Soil</th>
<th>Q (W)</th>
<th>Best case % Change in Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil with org matter</td>
<td>24.55</td>
<td>60.31</td>
</tr>
<tr>
<td>Dry Sand</td>
<td>36.02</td>
<td>41.77</td>
</tr>
<tr>
<td>Gravel</td>
<td>44.22</td>
<td>28.51</td>
</tr>
<tr>
<td>Clayey</td>
<td>49.55</td>
<td>19.90</td>
</tr>
<tr>
<td>Moist Sand</td>
<td>49.56</td>
<td>19.88</td>
</tr>
<tr>
<td>Very moist sand</td>
<td>53.21</td>
<td>13.99</td>
</tr>
<tr>
<td>Saturated sand</td>
<td>61.86</td>
<td></td>
</tr>
</tbody>
</table>

*Table 23: Best case percentage change in energy for different soil types.*

<table>
<thead>
<tr>
<th>Contact Conductance (W/m²K)</th>
<th>Q (W)</th>
<th>Best Case % Change in Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Conductance 100</td>
<td>27.332</td>
<td>2.41</td>
</tr>
<tr>
<td>Contact Conductance 120</td>
<td>27.942</td>
<td></td>
</tr>
</tbody>
</table>

*Table 24: Best case percentage change in energy for different contact conductance.*
Best case scenarios are computed to determine the best possible system for maximum performance efficiency. Based on the observations shown above, it is clear that soil properties are crucial for best operating efficiency. For example, a geothermal system in saturated soil conditions is observed to be 60.31% more efficient than a system surrounded by soil with organic matter. This difference in conditions directly impacts the initial and operating costs of the system, as improved system design should be considered to meet the requirements. The flow chart of impact of independent variables on the overall costs is as follows:

![Flow chart](image)

**Figure 26: Impact of independent variables on the initial and operating costs.**
The key observations based on this research are as follows:

1. It can be clearly observed that by varying the thermal parameters for different materials, soil characteristics play an important role in removing heat from the system. There is a highest change of 60% in heat flux passing through the soil for a unit change in thermal conductivity, compared to highest change of 13% in PVC and 4% in concrete. This is very influential in drilling and installation sites because it is a crucial factor to remove heat from the system as quickly as possible.

2. Soil properties with high thermal conductivities tend to distribute more heat compared to soils with lower thermal conductivities. Saturated sand has excellent properties for drilling and installation, and this further validates the statement that presence of aquifers and water table can increase the heat transfer properties of the system. Similarly, light and medium weight concrete have better thermos-physical properties for geothermal grouts. In terms of PVC, Flexible PVC holds better properties than rigid PVC. These factors contribute to the operating costs of the system.

3. Heat passing through each interface decreases as we move from the center of the pipe to the far field. Ideally, the exact heat should pass through the system without being lost. However, due to improper contact, numerical simulation accuracies and ramp up periods for transient analysis, the amount of heat decreases.

4. This research quantifies the impact of heat transfer coefficient on overall operating costs of the transient system. Contact conductance plays an important role in the transient heat transfer (12.14%), which is not seen in steady state analysis.
CHAPTER 8

GEOTHERMAL ENERGY SYSTEMS – CODES, REGULATIONS AND INCENTIVES

Public policies play a significant role in energy development and production and have shaped utility and energy systems for decades. Geothermal energy production and use are governed by numerous federal, state, and local laws ranging from environmental protection statutes to zoning regulations. Policies and incentives that are essential to new geothermal development include: state renewable portfolio standards; federal and state tax incentives; geothermal leasing and permitting; research and technology support; and pollution and climate change laws.

The following information has been obtained from United States Federal Energy Laws and Incentives. At the federal level, tax incentives are considered one of the most important incentives for driving growth in renewable energy. There are loan and grant programs, research support, and other federal measures that encourage geothermal and other renewable technologies.

- The Energy Policy Act of 2005 qualified geothermal power projects for a choice between the federal Investment Tax Credit and the Production Tax Credit, though the status of the credit is pending at the time of this printing.

- The Geothermal Research Development and Demonstration Act, passed by Congress in 1974, establishes a wide range of policies from loan guarantees to
educational support, but while the statute remains on the books it is largely not in effect.

- In 2007, Congress passed the Advanced Geothermal Energy Research and Development Act, which provides the authorization for much of the current DOE effort.

- Federal geothermal leasing is governed by the John Rishel Geothermal Leasing Amendments passed as part of the 2005 energy bill. These provisions are also codified in Title 30, Chapter 23, and sections 1001-10028 of the U.S. Code. Geothermal leasing and permitting on federal land is managed by the U.S. Bureau of Land Management (BLM).

- The primary sources for geothermal research and technology support are the U.S. DOE's Geothermal Technologies Program and the California Energy Commission, and in particular its Geothermal Resource Exploration and Development Program. For climate change, the U.S. EPA provides a range of information on its Web site.

- In additional to geothermal leasing and permitting on federal lands, states also issue leases for geothermal on state lands and have both regulatory and permitting requirements for geothermal development. At the state level, the most important laws are the renewable portfolio standards (RPS) that require utility companies to have a growing percentage of renewable power generation in their mix. In addition
to this, states offer a wide range of additional rules, policies and incentives for renewable generation. [7] [8]

A Renewable Portfolio Standard (RPS) is a mandate intended to increase the amount of renewable energy production. In 2014, the South Carolina Legislature unanimously passed SB 1189, which set a goal of having 2 percent of the state's generation capacity come from renewable sources by 2020. To achieve this goal, the state created a voluntary program that allows utilities to create net metering programs. Net metering is a billing system where customers who generate their own electricity from renewable sources are able to sell their excess electricity back to the grid. In order to be part of the program, electricity must be generated from "solar photo-voltaic, solar thermal, wind, hydroelectric, geothermal, tidal, wave, recycling, biomass, and combined heat and power and hydrogen fuel derived from renewable sources." Investor-owned utilities that are providing electricity to residential consumers can install systems that generate 20 kilowatts or less of electricity. Nonresidential consumers can install systems that generate 1 megawatt or less.

Clemson College of Engineering and Science Energy Program is preparing their college students to assist employees new to renewable energy and help them integrate new forms of energy into the grid system. They do this through educational programs, which cover wind and solar energy, and power systems, and renewable energy certificates. Through these programs the organization hopes to assist in significantly increasing the use of renewable energy sources [9]

Section 2 of H.3874: South Carolina Residential Geothermal State Income Tax Credit.
Sponsors of the geothermal tax credit amendment in the Senate- Senators Coleman, Cromer, Campbell, Cleary, J. Matthews, Nicholson, Hayes, Setzler, and Scott.

- Credit covers 25% of the cost of residential geothermal equipment and its installation.
- Residential customers can only take $3,500 annually on their tax form until the 25% cap is reached.
- Equipment must meet federal Energy Star energy efficiency requirements at time of installation.
- Credit is good for 3 years—Begins on January 1, 2016 and expires on January 1, 2019.
- Credit cannot exceed 50% of a person’s taxable liability in a single year.
- Credit can be carried forward for 10 years.
- Credit will accompany a 30% federal tax credit (geothermal equipment/installation).

The average cost of a geothermal installation is $21,000. The state tax credit would equal $5,250. The federal tax credit would reduce the cost by an additional $6,300 making the total average cost of the system $9,450 which is comparable with an equally energy efficient traditional HVAC system. [10]
8.1 POTENTIAL BENEFITS

Residential customers: Geothermal customers can expect to save 50 – 70% on their monthly heating and cooling costs. Equipment replacement would be extended to every 20 years compared to 8 to 10 years for traditional HVAC systems. Geothermal loops can last up to 200 years.

Geothermal industry: In 2015 approximately 337 geothermal units were installed statewide. The industry expects a state tax credit would help installations increase substantially in 2016. Geothermal installations can create up to 8 jobs per installation: plumbers, borers, well drillers, and geothermal installers. Traditional HVAC installations require only one to two installers.

SC Economy: In 2015 it’s estimated the geothermal industry added $10 million to SC’s economy. Making geothermal systems more affordable and thereby creating more jobs through increased installations, a state tax credit would help generate additional state income tax, unemployment tax, sales tax, and corporate income tax to our state’s economy.

Section 1 of H.3874: Business State Income Tax Credit for Superfund Sites

Primary sponsors of the bill: Reps. Mitchell, Cobb Hunter, Merrill, Loftis, Dillard and Govan.

- Credit covers 25% of the cost of installation, construction, purchase, or lease of solar energy property located on EPA’s National Priority List, National Priority
List Equivalent Sites, or on a list of related removal actions, as certified by the DHEC, located in SC and placed in service in SC.

- Projects must be nonresidential with a nameplate capacity of at least that (2,000 kw AC) that use solar radiation as a substitute for traditional energy for water heating, active space heating and cooling, passive heating, daylighting, generating electricity, distillation, desalination, detoxification, or the production of industrial or commercial process heat. Related devices necessary for collecting, storing, exchanging, conditioning, or converting solar energy to other useful forms of energy are included in the credit.

- Credit begins the year the solar energy property is placed in service.

- Credit must be taken in 5 equal annual installments beginning in the year in which the solar energy property is placed in service.

- Unused credits can be carried forward for 5 taxable years.

- Credit for each solar energy project is capped at $2.5 million.

- Total amount of credits for all projects/taxpayers is capped at $2.5 million annually.

- Credit begins January 1, 2016 and is available through December 21, 2017. However, unearned credits can be claimed for the projects that begin after 2015 and before January 1, 2018, until credits have been fully claimed.

- Credit is allowed on a first come first serve basis.
• No other solar tax credit can be used in conjunction with this credit.

• Only one taxpayer can take the credit. Someone leasing the property cannot take the credit if the owner is taking the credit.

• A lessor must give a taxpayer who leases solar energy property from him a statement that describes the solar energy property and states the cost of the property upon request.

• Credits are not allowed to the extent the cost of the solar energy property is provided by public funds which do not include federal grants or tax credits.

• Credit is halted if the solar energy property is disposed of, taken out of service, or moved out of the State in a year in which the installment of a credit accrues. The credit expires, and the taxpayer may not take any remaining installments of the credit.

• DOR is authorized to promulgate regulations necessary to implement this new section in law. [10]
CHAPTER 9

ENVIRONMENTAL IMPACT

The present world has reached a point where the consumption of fossil fuels for energy production has exceeded the rate of availability of those sources. Further, the amount of toxic gases being released into the atmosphere has only increased over the years. This calls for an immediate change to develop alternative and renewable sources of energy.

Renewable energy has entered into every policy-making country across the world, with topics ranging from immediate measures to long-term energy security of the country. The most common environmental change talked about is the climate change and global warming caused by increased level of greenhouse gases in the atmosphere. Hence, this directly emphasizes the need to create alternative and sustainable modes of energy. In this energy race, solar, wind, hydroelectric and geothermal energy has emerged as efficient front runners to cater the needs of present and future generations.

Geothermal energy provides clean and uninterrupted power supply, irrespective of the location and terrain. Geothermal energy has often been associated with energy tapped using steam emerging from cracks deep into the earth. However, it can be tapped even at shallow depths, based on the energy requirements. Although the initial cost of setting up the system is higher compared to solar and wind energy, it is highly efficient in terms of operational and maintenance. This is subjected to change with drastic developments in this field. The utilization of geothermal energy does not add significantly to greenhouse gas emissions - only the electricity required to run the pump, which can be supplied using solar or wind
energy sources. No hazardous nitrogen or carbon oxides are produced in the operation, which is significant considering the amount produced by burning fossil fuels. With the small fraction of energy used to run the pump, high orders of operating efficiencies can be achieved. Most geothermal energy systems work on COPs of 4, which means that a geothermal system can move up to 4 units of heat for every unit of electricity needed to power the system.

Overall, the working and efficiency of the system largely depends on how well the energy supplied can be obtained from renewable sources. If the power is supplied using solar or wind energy, geothermal can be a significant player in Zero energy buildings, complementing with other sources of energy. Also, the heating and cooling loads have to be balanced with seasonal fluctuations. When extreme temperatures are reached which are beyond the working capacities of the system (which constitutes less than 1% of the days of the year), alternative energy sources like natural gas can be used to power the system for an effective HVAC.
REFERENCES


17. Al, H. e. (2015). Uplift around the geothermal power plant of Landau (Germany) as observed by InSAR monitoring. Geothermal Energy, 2:3.


The results observed in Chapter 8 were obtained by modeling on Abaqus. The simulations are as shown below:

Figure A1: Transient 2D axisymmetric analysis of horizontal cross-section of geothermal well for a small angle of 10 degrees and time period of 3000s.
Figure A2: Transient 2D axisymmetric model of horizontal cross-section of geothermal well for a small angle of 10 degrees, for a time period of 3000s.
Figure A3: Transient 2D axisymmetric model of horizontal cross-section of geothermal well (360 degree view) with brine at the center.

Figure A4: Close up view of Transient 2D axisymmetric model of horizontal cross-section of geothermal well (360 degree view) with brine at the center.
Figure A5: Variation of Temperature with respect to distance from center of the pipe.
Figure A6: Transient 2D axisymmetric model of horizontal cross-section of geothermal well (360 degree view) without brine.

Figure A7: Close up view of Transient 2D axisymmetric model of horizontal cross-section of geothermal well (360 degree view) without brine.
Figure A8: Transient 2D axisymmetric model of vertical cross-section of geothermal well without brine.

Figure A9: Close up view of transient 2D axisymmetric model of vertical cross-section of geothermal well without brine.
Figure A10: Transient 2D vertical cross-section of geothermal well with axisymmetric with non-uniform in-depth temperature.

Figure A11: Variation of Temperature with distance from the well, along the x-axis.
Figure A12: Variation of Temperature with distance, along the Y-axis.
Figure A13: Isometric view of vertical cross section of the geothermal pipe with temperature gradient.

Figure A14: Vertical cross section of the geothermal pipe with temperature gradient.
Figure A15: Top view of a geothermal field and their thermal interactions in the X-direction.

Figure A16: Front view of a geothermal field and their thermal interactions in the Y-direction.