Abandoned petroleum wells as sustainable/renewable sources of geothermal energy

Jeffrey Templeton

Master of Engineering

Department of Mining and Materials Engineering

McGill University

Montreal, Quebec, Canada

July 2013

A thesis submitted to McGill University in partial fulfillment of the requirements of the degree of Master of Engineering

Acknowledgments

I would like to begin by thanking Professor Ferri Hassani for his supervision, guidance and support through this process. Additionally, I would like to thank Ali Ghoreishi for being a patient co-supervisor and providing continued guidance and support. Finally, I would like to thank my grandmothers, parents, brothers, sister, Jenni, and friends for the continued encouragement to self-improve.

Publications

Templeton, J.D., Ghoreishi-Madiseh, S.A., Hassani, F., Al-Khawaja, M.J. (2013). Abandoned oil/gas wells as sustainable sources of renewable energy. *World Mining Congress 2013, Montreal*.

Templeton, J.D., Ghoreishi-Madiseh, S.A., Hassani, F., Al-Khawaja, M.J. (2013). Abandoned petroleum wells as sustainable sources of geothermal energy. To be submitted to the *Renewable Energy* journal.

Table of Contents

List of Tables

List of Figures

Abstract

Geothermal energy is an important emerging renewable technology that has the potential to provide power from a virtually unlimited reserve worldwide. The downside to exploiting geothermal energy is the capital intensive drilling of the borehole needed to access relatively hot resources located deep under the ground. However, abandoned petroleum wells present an interesting opportunity to circumvent the capital costs associated with drilling. This thesis proposes a sophisticated heat transfer model that is capable of realistically simulating the heat flow through a double pipe heat exchanger and the surrounding rock mass. The sophisticated model is compared with the analytical cylindrical source model, and two numerical models and reaches comparable results. The purpose of this model is to provide an accurate and realistic representation of heat flow and temperature distribution for a heat exchanger retrofitted to an abandoned well. The effects that inlet fluid temperature, insulation, thermal conductivity of the rock mass, mass flow rate of the working fluid, and vertical movement of groundwater have on the sustainability and performance of the double pipe heat exchanger are investigated. A constant power model is also proposed in order to assess the sustainable rate of heat extraction from a geothermal resource.

Abrégé

L’énergie géothermique est une technologie renouvelable émergente importante qui a le potentiel de fournir de l’énergie d’une source pratiquement illimitée. Le désavantage de l’énergie géothermique est l'ampleur du capital des forages qui sont requis pour accéder aux ressources plus chaudes. Utiliser les forages de pétrole abandonnés est une opportunité originale pour circonvenir ce désavantage. Cette thèse propose un modèle sophistiqué qui est capable de simuler le flux de chaleur à travers un échangeur de chaleur à tube double et le flux de chaleur à travers la masse rocheuse autour du forage. Le modèle sophistiqué est comparé avec le modèle analytique de source cylindrique, et deux autres modèles numériques et arrivent aux résultats comparables. Le but de cette modèle sophistiqué est de fournir une représentation précise et réaliste du flux de chaleur et la distribution de la température pour un échangeur de chaleur situé dans un forage de pétrole abandonné. Les effets de la température d’entrée de fluide, l’isolation, la conductivité thermique de la masse rocheuse, le taux de débit massique du fluide actif, et le mouvement vertical de l’eau souterraine sur la durabilité et performance de la conception sont enquêtés. Un modèle de puissance

constante est aussi proposé pour l'extraction de l'énergie géothermique encore plus durable.

Chapter 1 Introduction

1.1 Importance of Geothermal Energy

Geothermal energy is an increasingly attractive source for renewable energy that can be used for power generation, heating/cooling, and a multitude of other direct-use applications. Each application will require a distinctive fluid temperature, with power generating operations requiring the highest fluid temperatures. Globally, the installed geothermal energy capacity has burgeoned from 1,300 MWe in 1975 to 10,715 MWe in 2010 (Bu, Maa, & Li, 2011). The rise in geothermal energy is due to a higher global energy demand, rising energy prices, new innovative technologies, and the growing need to reduce the anthropogenic impact on the environment. Geothermal energy is important since it is accessible from anywhere in the world, provides a steady source of thermal power, is easily scaled up, and can be switched on/off to follow demand. The main disadvantage of extracting geothermal energy from deep resources is the high capital cost needed to drill the well(s), in order to access the higher temperature resources.

1.2 Classification of Geothermal Resources

The classification systems used to categorize geothermal reservoirs stem from the varying forms of energy that can be captured from a geothermal resource and the differing methods of quantifying that energy. Geothermal reservoirs can provide energy in the form of thermal energy, hydraulic energy, and chemical energy. An example of a geothermal reservoir with these characteristics would be a deep geopressured resource with dissolved hydrocarbons. The multiple methods used to define and categorize geothermal sources are based on temperature, intended use of the geothermal fluid, type of extraction, status of development, economic and realization potential, and the amount of heat in place (i.e. stored heat and power potential) (Falcone, 2012).

The temperature of the geothermal resource is often used because it is relatively simple to estimate/measure compared to other thermodynamic properties. The bottomhole temperature is a good indicator of the amount of energy available for a closed loop geothermal system because the thermal properties of the working fluid are known and remain constant throughout operation. Whereas, in the case of an open loop system the thermodynamic properties of the extracted fluid (e.g.

pressure, enthalpy, impurities, etc.) are transient and will introduce uncertainties.

Geothermal resources can be sorted into low, intermediate and high enthalpy sources according to the average reservoir temperature (c.f. Table 1). The classes of resources depicted in Table 1 are divided subjectively according to different authors. The authors cited do not reach a consensus on the appropriate temperature ranges to describe each class of geothermal resource. In the case of a closed loop geothermal system the corrected bottomhole temperature of the borehole is a good estimate of the reservoir temperature, as the geothermal reservoir is the surrounding rock mass in this case.

Table 1: Classification of geothermal resources by temperature (a): (Muffler & Cataldi, 1978), (b): (Hochstein, 1990), (c): (Benderitter & Cormy, 1990), (d): (Haenel, 1988), (Dickson, 1990)

Resource	(a)	(b)	(c)	(d)
Low enthalpy	<90˚C	<125˚C	<100˚C	≤150˚C
Intermediate enthalpy	90-150˚C	125-225˚C	100-200˚C	--
High enthalpy	>150˚C	>225˚C	>200˚C	>150˚C

The main reason that the bottomhole temperature of a borehole is not an exact indicator of the reservoir temperature for a closed loop system is because the working fluid will not be able to conduct 100% of the energy from the surrounding rock mass (i.e. the working fluid won't achieve the bottomhole temperature).

1.3 Usages of Geothermal Energy

The uses for geothermal energy vary depending on specific demands and also on the temperature of the outlet fluid from the heat exchanger. Hotter geothermal resources will have a wider variety of uses, compared to cooler geothermal resources.

1.3.1 Direct and Indirect Uses

Direct applications of geothermal energy utilize the heated fluid directly from the ground source heat exchanger (c.f. Figure 1). Open loop systems require a heat exchanger to transfer heat from the geothermal fluid and working fluid (c.f. Figure 1), in order to limit the deterioration the geothermal fluid may cause. Closed loop systems do not require a heat exchanger as there is no geothermal fluid that needs isolation. The steam produced from intermediate to high enthalpy resources is capable of being used directly to operate a turbine and create electricity. The majority of

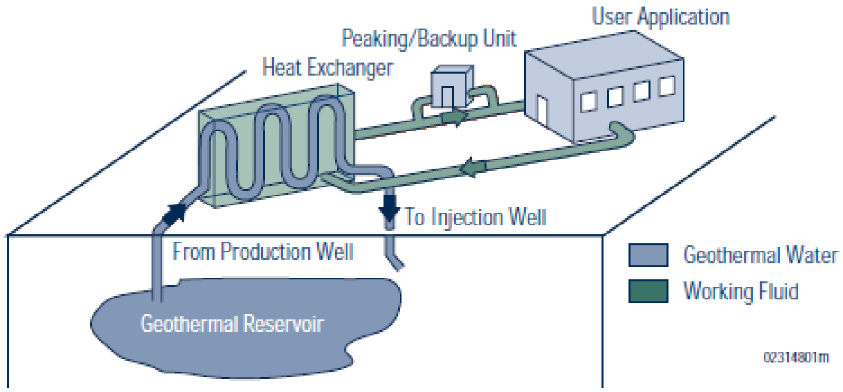

Figure 1: Example of an open loop direct use geothermal design (National Renewable Energy Laboratory, 1998)

direct applications pertain to geothermal sources that provide fluid that isn't hot enough to produce electricity.

Indirect applications generally comprise of an operation where the geothermal energy extracted from the ground is used in a heat pump or turned into electricity in a power plant. Heat pumps are used to further increase/decrease the temperature of a fluid for space heating/cooling, and can operate with geothermal fluids that are as low as 5˚C. Typically, electricity can be produced from a geothermal resource that is of intermediate to high enthalpy (i.e. 90˚C-225˚C), however binary power plants have been designed that produce electricity from a 74˚C geothermal fluid (Lund J. W., 2006).

1.3.2 Open Loop and Closed Loop Geothermal Cycles

Geothermal systems are designed as either an open loop or a closed loop circuit of pipes. Depending on the soil and rock types, available land, water sources, economic feasibility of drilling a well, and the presence of an existing well the decision can be made between a closed loop and an open loop system. Open loop systems are designed with at least one injection well, and at least one extraction well (c.f. Figure 1). In the open loop system, water is pumped through the injection well, the water then circulates through the reservoir gaining heat from the rock mass, and the water is then removed through the extraction well. Closed

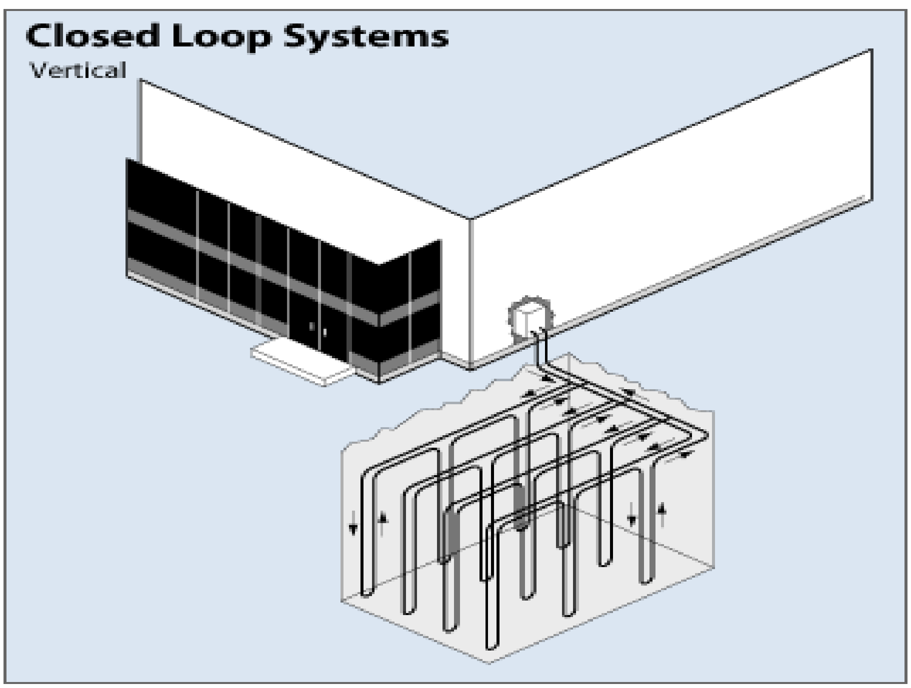

Figure 2: Example of a closed loop geothermal system utilizing u-tube heat exchangers in series and parallel (McCarthy)

loop designs are composed of a system of pipes that contains and isolates a working fluid from the geothermal resource (c.f. Figure 2).

Closed loop systems are advantageous over open loop designs because of the absence of scaling on the pump and pipes caused by minerals present in the groundwater, zero emissions from dissolved gas, lower pumping work (i.e. siphon effect), the option to use a non-aqueous working fluid with a lower boiling point than water, the elimination of the need for a water management system, and significantly lower capital costs associated with only requiring one borehole. Open loop designs have the advantage of much higher rates of geothermal heat extraction due to higher flow rates and a greater interaction between the working fluid and the ground.

1.3.3 Power Generation

Condensing systems (c.f. Figure 3) are the most popular type of power plant design used to harness geothermal energy, as they provide a long and reliable service and exhibit a good load following capability. Condensing systems are normally used to process geothermal resources that have a reservoir temperature in the range of 200˚C to 320˚C (Eliasson, Thorhallsson, & Steingrímsson, 2011). Condensing systems are advantageous over back pressure and binary cycle power plants as they operate at a reasonable thermal efficiency.

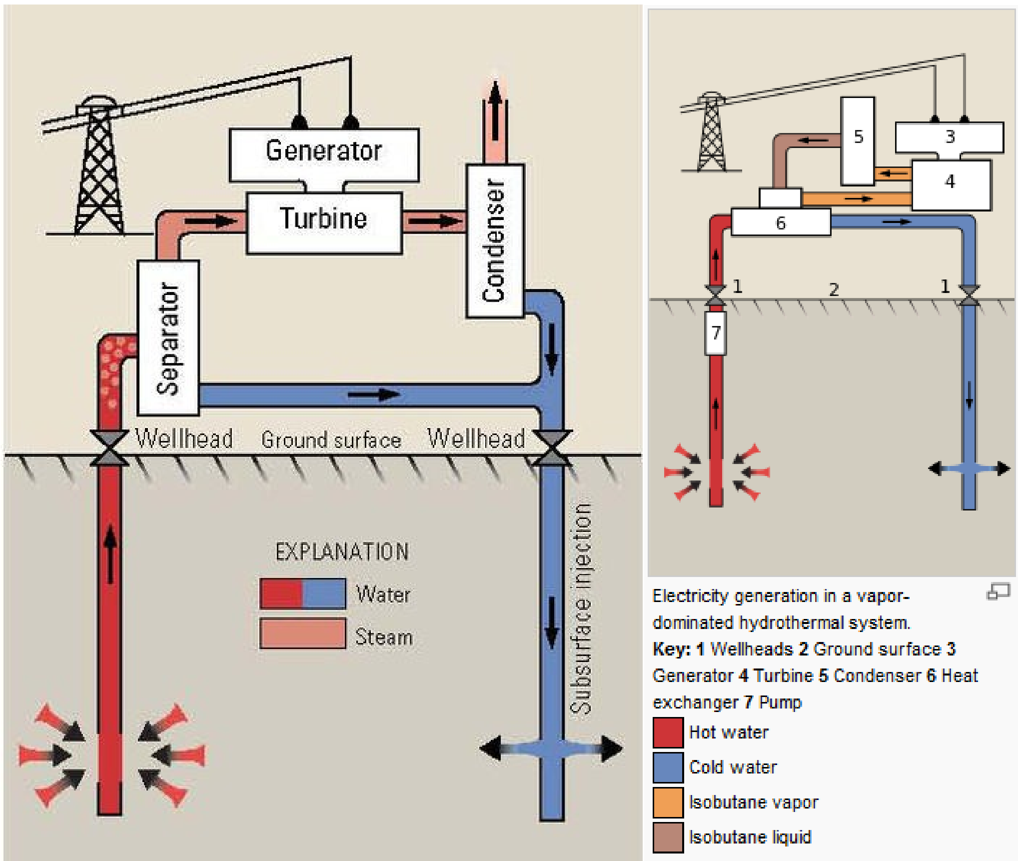

Figure 3: General design of a geothermal power plant utilizing a condensing system (left); General design of a geothermal power plant utilizing a binary cycle (right) (Duffield & Sass, 2004)

A back pressure system is slightly simpler than the condenser system, as there is no need for a condenser or a gas exhaust system. Back pressure systems are the simplest, least expensive, and have the lowest thermal efficiency of all the geothermal power plants mentioned.

Back pressure systems are generally used to process geothermal resources that exhibit temperatures in the range of 200˚C to 350˚C, and they are widely used in hybrid power plants, multiple use applications, the mining industry, and to temporarily provide power while resources are developed (Eliasson, Thorhallsson, & Steingrímsson, 2011).

Binary cycle geothermal power plants (c.f. Figure 3) are the most recent development in the domain of power plants, and are unmatched at extracting energy from low temperature resources. Binary systems exchange the geothermal heat extracted from the production wells to a secondary fluid that has a lower boiling point than water. The secondary fluid then provides the motive force to power the turbine in the binary system. The type of secondary fluid used in a binary system will depend on whether the Organic Rankine Cycle or the Kalina Cycle is being employed. The Organic Rankine Cycle makes use of a carbohydrate with a low boiling point (e.g. butane, propane, etc.), or a specially designed fluid with a low boiling point that complies with low ozone layer depletion regulations. The Kalina Cycle makes use of a water and ammonia solution as the secondary fluid. Generally, binary systems are able to convert geothermal resources with relatively low reservoir temperatures ranging from 120˚C to 190˚C into electricity (Eliasson, Thorhallsson, &

Steingrímsson, 2011). However, a binary system at Chena Hot Springs Resort in Alaska is able to produce electricity from a 74°C geothermal resource (Lund J. W., 2006). While the binary system is relatively complex, maintenance intensive, and achieves a low overall thermal efficiency, its secondary fluid system allows the deterioration caused by scaling, gas, and erosion to be confined to the initial stage of the heat exchanger.

1.3.4 Direct and Indirect Heating

Ground source geothermal heat pumps (GSHP) are one of the fastest growing areas of renewable energies, providing a source of heating, cooling, and hot water for private, governmental, and commercial buildings (Lund, Sanner, Rybach, Curtis, & Hellström, 2004). GSHPs make use of ground or groundwater temperatures from 5˚C and upwards depending on whether the GSHP is utilizing a closed loop (aka. ground coupled) or open loop (groundwater) system. The GSHP will transport heat energy in a direction that it wouldn't naturally flow (e.g. cold to hot), and is analogous to a refrigeration unit. Closed loop systems make use of horizontal or vertical loops of pipe to take advantage of the heat held in the earth, and open loops employ a setup composed of wells or lakes to take advantage of the heat preserved in underground water reservoirs.

A water and antifreeze solution is pumped through plastic piping in a closed loop GSHP setup, whereas groundwater or lake water is used directly and released through irrigation or injected back into the ground in an open loop GSHP setup. Both these methods are forms of indirect exchange, as they have a water loop to exchange heat with the separate refrigeration loop. Direct exchange systems are a type of closed loop system in which the water loop is removed and the refrigeration loop is extended into the earth. Copper piping is used to minimize refrigerant leakage, and because of the augmented heat exchange, direct exchange systems are more efficient than indirect exchange systems. However, direct exchange systems require a relatively large volume of refrigerant based on the size of the system.

Each GSHP is composed of a heat exchanger surrounded by earth or water, a compressor, an expansion valve, and a heat exchanger to the air distribution system and/or hot water system (c.f. Figure 4). The heat exchanger surrounded by earth or water (i.e. the open or closed loop) acts as an evaporator when the heat pump is used for heating or hot water

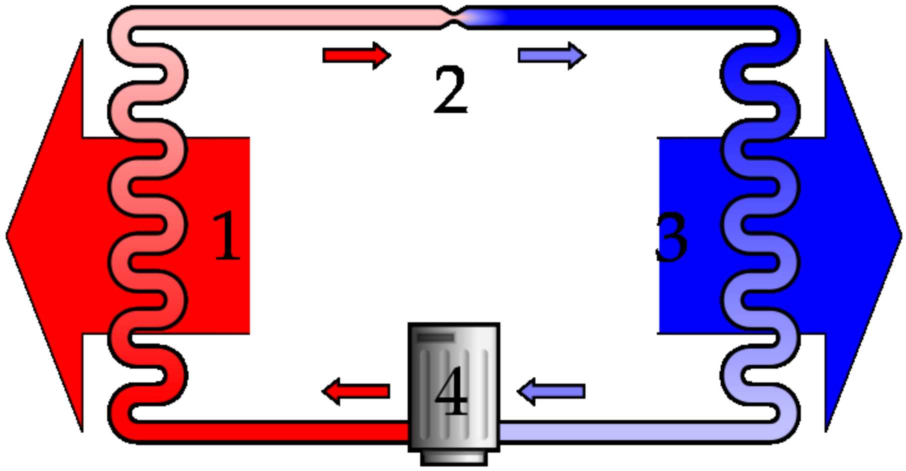

Figure 4: General design of a heat pump, where: 1) condenser, 2) expansion valve, 3) evaporator, 4) compressor (Karonen)

applications, and acts as a condenser when the heat pump is used for cooling applications. Alternatively, the heat exchanger used for air distribution and/or hot water heating will behave as a condenser when the heat pump is used for heating or hot water applications, and as an evaporator when the heat pump is used for cooling applications. If the heat pump is being used for heating and/or hot water applications the evaporator will provide a heated fluid to the compressor, the compressor will use electricity to compress the fluid to create a higher temperature and higher pressure vapor, the condenser will remove a specified amount of heat energy, an expansion valve will transform the high temperature and high pressure vapor to a lower temperature and lower pressure fluid, and the fluid will recirculate through the evaporator to begin the cycle again. This reverse vapor-compression refrigeration method can be used normally, as vapor-compression refrigeration, in order to operate cooling applications. The efficiency of GSHPs is known as the coefficient of performance for the heating cycle, and the energy efficiency ratio for the cooling cycle. In each case the efficiency is calculated as the ratio of the output energy to the input energy (i.e. electricity consumed by the compressor), and is generally in the range of two to six.

1.3.5 Miscellaneous Applications

Geothermal energy can be utilized for direct purposes such as space heating, greenhouse and soil heating, agricultural drying, aquaculture (fish and algae), water desalination, and balneology (Rafferty et al., 2005; Andritsos et al., 2011). Direct use applications of geothermal energy use various types of heat exchangers in lieu of heat pumps to reap the benefits of geothermal resources.

1.3.6 Advantages/Disadvantages

Geothermal power has the ability to decrease society's dependence on non-renewable energy sources such as coal, oil, natural gas, and nuclear energy. The production of electricity with geothermal energy is advantageous because of the reliability and flexibility it provides to the power grid. Geothermal energy's reliability makes it a good base load source because it is unaffected by weather and can remain available to operate 98% of the time (NGC, 2004). Alternatively, geothermal energy's good load following capabilities (i.e. ability to ramp up or down power production as needed) makes it useful in providing power during peak hours, or as a complement to intermittent solar and eolian energy. Deriving power from geothermal energy helps to stabilise the price of electricity, as the source of geothermal energy is secured before power generation, it is not subject to market fluctuations like fossil fuels. By diversifying the resources a state depends on for power there is a reduction on the reliance of foreign fuel markets and an increase in national security. Furthermore, geothermal extraction with a closed loop system releases no dissolved gas that may be in the groundwater or soil, whereas the very low emission of dissolved gas released from open loop systems is many times lower than the gas emissions of fossil fuel sources of energy.

The main disadvantage of harnessing geothermal energy is the capital cost associated with drilling the borehole(s), as these costs can comprise over 50% of the total project costs (Bu, Maa, & Li, 2011). Open loop designs are more susceptible to the high costs of drilling, due to a requirement of a greater number of wells, and also require a water management system to cope with the large volume of groundwater.

1.4 Abandoned Petroleum Wells as Economic and Environmental Liabilities

Petroleum wells are abandoned when the oil/gas reservoir becomes unfeasible for petroleum extraction, or when a dry hole is drilled. Dry holes refer to drilled wells that contain an economically unfeasible amount and/or type of petroleum deposit. Abandoned wells are plugged with cement and decommissioned, however they become an enduring financial and environmental liability. The cement involved with plugging the abandoned well can take up to a week to set depending on the number of plugs in the well. Because of the cost associated with abandoning a well, most wells are abandoned at the minimal cost and meet the minimal obligations set by regulating agencies. Furthermore, any type of failure in the containment and abandonment of the well will leave the company responsible for the subsequent environmental cleanup, restoration, and possible litigation.

1.5 Using Abandoned Petroleum Wells for Geothermal Energy Production

Retrofitting abandoned petroleum wells for the purpose of geothermal extraction is a novel idea due to the fact that petroleum wells are generally deep enough to access high temperature strata. The depth of exploratory and developmental wells for crude oil, natural gas, and subsequent dry holes drilled in the US from 1949 to 2008 range from 945 to 2560 metres feet in depth (EIA, 2012). The US has drilled over 2.5 million petroleum wells since the 1950's and has the highest rate of oil and gas drilling in the world (Baker Hughes, 2012), therefore the US provides a satisfactory illustration of the characteristics of petroleum wells worldwide.

Besides creating a useful purpose for an enduring liability, retrofitting an abandoned well has the potential to reduce the cost of a geothermal project by 50% (Bu, Maa, & Li, 2011). Additionally, the availability of thermophysical data that has been logged while sinking petroleum wells is extremely beneficial when analysing and designing a geothermal system. Likewise, the information can be used to define the geothermal resources. The information on existing wells can be used to identify which boreholes have the highest bottomhole temperature, the greatest heat flow, and which are closest to the demand for energy. Abandoned wells can also be retrofitted by redrilling the bottom of the well (i.e. extending borehole depth), in order to gain access to more advantageous conditions and superior resources, at a lower cost than drilling a new well (Combs, 2008).

Both open loop and closed loop geothermal systems can be retrofitted to existing petroleum wells. An open loop system will make use of the petroleum reservoir, as long as there are at least two wells drilled into the same resource. The groundwater can be stored in the abandoned reservoir in order to gain heat from the surrounding rock, before being extracted from an existing petroleum well. Closed loop geothermal systems adapted to a single well are generally designed to use either a u-tube heat exchanger or a double pipe heat exchanger.

1.6 Properties of Abandoned Petroleum Wells

Casings (linked metal tubes) are lowered into newly drilled wells, anchored firmly with cement and serve to provide strength to the well as well as to maintain a two way barrier to fluids and gases. Oil and gas wells are drilled with a series of casings arranged concentrically along their axis. Each subsequent well casing is installed within the previous casing (i.e. the diameter of the well decreases with depth) and are referred to as conductor casing, surface casing, intermediate casing, and production casing. A conductor casing has the largest diameter of the casings, and its main purpose is to prevent soil from collapsing back in on the well. Surface casing is the second tier of casing to be lowered into the petroleum well, and serves to prevent hydrocarbon contamination in underground freshwater and salt water. Intermediate casing is the third tier of casing and minimizes the effects of subsurface formations (i.e. abnormal underground pressure zones, underground shale, and sources of contamination) on the well. Production casing is the innermost and deepest of the casings, and provides a conduit from the surface to the desired petroleum deposit. An alternative to installing a casing string is to install a liner string. Liner strings resemble casing strings as they are composed of linked metal tubes, however liner strings do not reach to the surface. Liner strings are suspended at the bottom of a casing string by hangers instead of being cemented into place, creating a less permanent form of casing. Liners may be preferred over casings because of the lower cost due to no cement being needed for installation, and by reducing the amount of pipe needed by hanging the liner string on the preceding casing (i.e. instead of extending to surface). A liner string can be converted to a casing string at a later date by extending the existing string to the surface and cementing it into place.

The logging of temperature in a petroleum well is an important factor in determining the level of maturation of a hydrocarbon deposit. The temperatures that are logged from petroleum wells are usually taken under dynamic conditions, therefore not accurately representing the static condition of the subsurface temperature. The natural rock temperatures are disturbed by the circulation of the drilling fluid, and the accuracy of the temperature logging can be reduced by logging data during/following the circulation of drilling fluids, during production, and by logging at high speeds (Prensky, 1992). There are many methods of extrapolating the measured bottomhole temperature to estimate the temperature under static conditions, or formation temperature (Goutorbe, Lucazeau, & Bonneville, 2007). The precision of the temperature logging is suited to the needs of the petroleum industry, however further precision is needed in order to make accurate predictions concerning heat flow. Heat flow refers to the transfer of terrestrial heat from deep within the earth, through layers of rock and soil, and to the surface. The relationship can be described as:

$$Q_z = \frac{\Delta T}{\lambda \Delta D} \qquad (1)$$

Where Q_z is heat flow, $\Delta T/\Delta D$ is the geothermal gradient, and λ is the thermal conductivity. The geothermal gradient can be determined by calculating the difference between the mean surface temperature and the corrected value of the bottomhole temperature, and then dividing by the depth of the well. The thermal conductivity is of little use to the petroleum industry because although oil has a different thermal conductivity than other fluids and rock, it is not significant enough to substantially change the thermal conductivity of the reservoir rocks (Prensky, 1992). The direct measurement of thermal conductivity is a time consuming and expensive process that is usually deemed to not be economically feasible by petroleum well developers (Goss, Combs, & Timur, 1975). Typically, the thermal conductivity can be estimated by analyzing nearby well logs and also by inferring a value based on similar geological settings (Forrest, Marcucci, & Scott, 2005).

Chapter 2 Literature Review

2.1 Background of Geothermal Energy in Petroleum Wells

The bulk of the research that has been carried out on capturing geothermal energy from abandoned petroleum wells has focused on open loop designs. The open loop designs for existing petroleum wells seek to repurpose the oil/gas reservoir as a groundwater geothermal reservoir. Many countries have supported research and work into retrofitting an abandoned petroleum resource with an open loop geothermal design, including: Albania (Lund, Freeston, & Boyd, 2005), China (Wei, Wang, & Ren, 2009), Croatia (Kurevija & Vulin, 2011), Hungary (Kujbus, 2007), Israel (Lund, Freeston, & Boyd, 2005), New Zealand (Reyes, 2007), Poland (Barbacki, 2000), and the United States (Limpasurat, 2010). Sanyal & Butler (2010) have advanced the research on open loop designs retrofitted to abandoned wells by demonstrating the effects of different design parameters on the extraction of geothermal energy.

The overwhelming majority of the research that has been done concerning closed loop designs retrofitted to abandoned wells has been with u-tube and double pipe heat exchangers. There is only one available paper concerning the modeling of a u-tube heat exchanger in an abandoned well, and it focuses on the need to model the convective heat flow in the porous medium surrounding the borehole (Ghoreishi-Madiseh, Hassani, & Al-Khawaja, 2012). There are only a few published papers concerned with the retrofitting of double pipe heat exchangers to existing petroleum wells, namely: Kujawa et al. (2005), Davis & Michaelides (2009), and Bu et al. (2011). Moreover, there exists a plethora of research concentrating on the design of u-tube and double pipe heat exchangers for a newly drilled geothermal borehole (e.g. Al-Khoury & Bonnier, 2006; Garbai & Méhes, 2011; Wang, McClure, & Horne, 2010; Zhongjian & Zheng, 2009).

2.2 U-tube Heat Exchangers

Abandoned petroleum wells can be retrofitted with single or multiple u-tube (more than one u-tube in a bore) heat exchangers by lowering the u-tube into the abandoned well and filling the void with grout. U-tube heat exchangers are recognised as having a “U” shaped bend at the bottom of two parallel tube strings, so a fluid pumped through one tube string will come out of the other. It is by this action of flowing through the well that the fluid in the u-tube can gain heat energy from the surrounding rock and groundwater to satisfy the energy demand. Variations in the u-tube design include how far the tubes are spaced apart in the borehole, diameter and type of tubing used, insulation, and the presence of a secondary u-tube installed perpendicular or parallel to the primary u-tube. Insulation can be added in order to limit the transfer of heat from one tube to another and also to limit the loss of heat to the surrounding earth near the tops of higher temperature wells.

A non-aqueous secondary fluid with a lower boiling point than water, like isobutene or ammonia, can be circulated through the u-tube instead of water. The benefit of using a non-aqueous fluid that has a lower boiling point than water is that it can be used to directly turn a turbine in order to produce power. The primary advantage of the u-tube heat exchanger over the double pipe heat exchanger is that the well casing doesn’t have to be leak proof in order to circulate a secondary fluid (i.e. fluid is contained in the u-tube).

2.3 Double Pipe Heat Exchangers

In order to retrofit an abandoned petroleum well with a double pipe heat exchanger, an insulated pipe with an inferior diameter is installed into the borehole (c.f. Figure 5) and the bottom of the borehole is sealed. The double pipe can be operated in one of two different manners: the first method is to pump fluid down through the outer annulus and up through the inner insulated pipe (i.e. Figure 5); the second method is to pump the fluid down through the insulated inner pipe and up through the outer

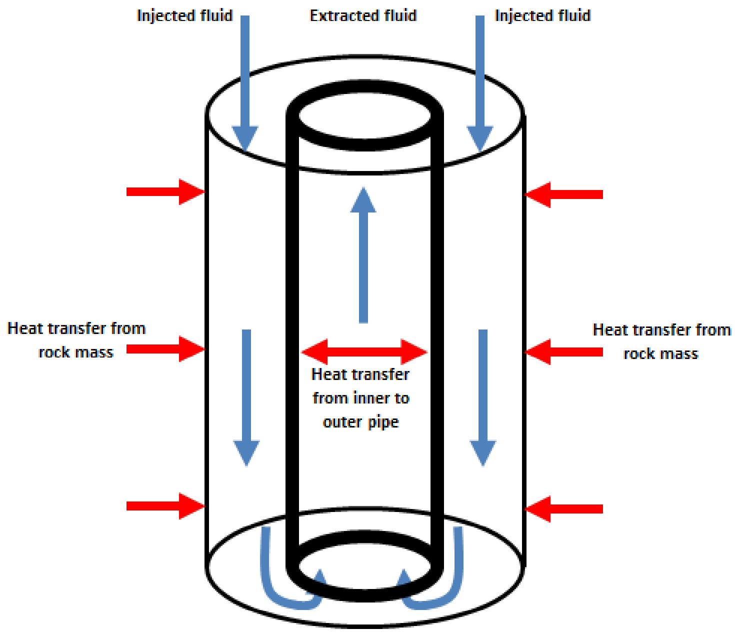

Figure 5: Schematic of a double pipe heat exchanger that can be retrofitted to a petroleum well

annulus (i.e. reverse flow of Figure 5). Most double pipe heat exchangers use the method demonstrated in Figure 5, as it enables a more efficient heat transfer from the ground to the working fluid (i.e. working fluid increases in temperature along with the geothermal gradient). The fluid flowing through the outer annulus is responsible for the heat flow from the rock mass to the heat exchanger. The inner pipe is insulated to minimize the heat transfer between countercurrent flows, as the cooler inflow will lower the temperature of the hotter outflow and result in a lower outlet temperature. Extremely deep, high temperature, or high heat flow boreholes may require additional insulation on an upper portion of the well casing in order to limit the loss of heat from the working fluid to the comparatively low temperature ground. The application of insulation to the borehole's casing applies to both variations of the double pipe heat exchanger; however the depth to which they extend will be different.

The efficiency of the system can be improved by using a non-aqueous fluid in lieu of an aqueous working fluid in the double pipe design (Davis & Michaelides, 2009). Isobutane, freon, and ammonia are ideal working fluids since they have a lower boiling point than water and will therefore vaporize to steam at a lower temperature. Using a non-aqueous solution as a working fluid poses challenges such as preventing leaks between the injection and extraction pipes, averting potential leaks of the working fluid to the surrounding medium (especially crucial for environmentally damaging fluids), designing sufficient insulation on the inner pipe, and requiring a large volume of non-aqueous fluid to fill the heat exchanger (dependent on the depth and diameter of the borehole).

The thermal power that can be harnessed from a double pipe heat exchanger depends primarily on the fluid flow rate through the double pipes and the geothermal gradient (Bu, Maa, & Li, 2011). Additional factors that have an influence on the extraction of geothermal energy include ambient temperature, underground water convection (Ghoreishi-Madiseh, Hassani, & Al-Khawaja, 2012), diameter and depth of the borehole, properties of the working fluid, geology, etc.. Fluid flowing at too high of a velocity will not transfer heat sufficiently, and fluid moving at too slow of a velocity will transfer too much heat to the countercurrent flow and the rock mass. Furthermore, the research done by Bu et al. (2011) indicates that there is a zone of influence around a borehole where the heat is harnessed from, and that the overlap of these zones will result in sub-optimal power generation due to the sharing of a thermal resource.

2.4 Purpose of the Model

The purpose of this research is to develop a sophisticated model that is able to accurately simulate the heat transfer through the rock mass surrounding the borehole to the double pipes, as well as the heat transfer taking place inside the heat exchanger. Furthermore, this model will be used to demonstrate the feasibility of an abandoned petroleum well to be retrofitted with a double pipe heat exchanger in order to harness geothermal energy.

2.4.1 Heat Transfer Inside the Pipes

The purpose of modelling the heat transfer within the double pipe heat exchanger is to impose a sophisticated heat flow and verify the temperature of the outlet fluid temperature. Also, it is important to get a transient solution of the heat flow through the pipes and from the surrounding rock mass to the heat exchanger.

2.4.1.1 Fluid Temperature as it Moves Through the Pipes

In order to present a model that accurately simulates a scenario that is close to reality, the fluid temperature transition is followed as it moves through the pipes. It is important to model the fluid temperature transition as it will lead to a more accurate simulation of the heat transfer between the countercurrent fluids in the heat exchanger, and also between the injected fluid and the surrounding rock mass. Not only does modelling the temperature transition lead to a more realistic and accurate model, but it also serves as a check to see that the simulation is running properly. In the proposed sophisticated model an advection term is added to the heat equation in order to accurately simulate the heat transfer through the fluid.

2.4.1.2 Constant Heat Flux Models

The heat transfer occurring between the heat exchanger and the rock mass can be simplified by assuming a constant heat flux along the wall of the heat exchanger. The cylindrical source model makes use of this assumption, however it is a very basic way to represent the situation. A constant flux along the well is unrealistic due to the geothermal gradient of the ground and the changing temperature difference between the fluid and ground. A constant flux will simplify the model down to having an equal amount of energy flowing through the heat exchanger irrespective of depth.

2.4.1.3 Empirical Convection Models for Flow Inside the Tubes

The convection heat transfer inside the annulus and inner tube of the heat exchanger can be approximated by the application of the Dittus-Boelter relation. The Dittus-Boelter relation was designed to determine the Nusselt number for smooth tubes. This relation becomes less accurate when it is applied to rough pipes (i.e. majority of commercial settings), non-circular pipes, and when there is a large temperature across the fluid. The Davis & Michaelides (2009) and Bu et al. (2011) papers both assume the Dittus-Boelter relation for the inner pipe and outer annulus, which leads to an oversimplification of the problem since it is applied to an annulus, applied to pipes that are not smooth, and applied to fluid that has a significant temperature difference across it’s diameter.

2.4.2 Heat Transfer in the Ground

Correctly modelling the heat transfer through the surrounding rock mass is important in order to avoid over/under estimating the effect it has on the performance of the heat exchanger. It is imperative that the heat transfer through the rock mass is as realistic as possible, so as to accurately predict the performance and feasibility of this design.

2.4.2.1 Steady Ground Conduction Models

Simplifying the heat transfer by conduction through the ground to a steady conduction, will result in an overestimation of the geothermal resources available and an over exaggeration of the performance of the heat exchanger. This assumption is employed by Davis & Michaelides (2009), and results in an overstatement of the available geothermal energy. In reality the temperature of the ground will decrease as geothermal energy is removed by the heat exchanger, and over time the heat exchanger will be able to remove less energy than it did initially.

Assuming a constant temperature along the wall is far from reality and portrays the ground temperature as unaffected by the extraction of energy.

2.4.2.2 Empirical Unsteady Assumptions for Conduction Through the Ground

The heat conduction through the ground can also be represented by an empirical unsteady conduction relationship. The relationship utilizes a time dependent radius of interaction in order to define a linear thermal resistance for the ground. Kujawa et al. (2005) make use of this simplification and as time progresses in their time dependent model, the radius of interaction grows ever larger. This simplification is inaccurate due to the radius being only a function of time and the thermal diffusion of the rock mass. The calculations used to determine the radius of interaction don't take into consideration the amount of heat extracted by the heat exchanger (i.e. same radius regardless of whether amount of heat extracted is 1W, 1kW, or 1MW).

2.4.2.3 Possibility of Underground Water Movement and its Convective Effect

The role of underground water movement has been proven to play an important role in the extraction of geothermal energy, as demonstrated by Ghoreishi et al. (2012). The convective effect of groundwater displacement can have positive or negative effects on closed loop and open loop designs; however it is usually a positive effect. As the groundwater permeates the soil and moves laterally it will transfer heat from the hotter undisturbed ground to the heat exchanger, while also moving the cooler groundwater away from the borehole. Groundwater solely flowing vertically down through the rock mass will have a negative effect as it will effectively be cooling the hotter ground with the relatively cool water.

2.4.3 Variable Loading

Designing the heat exchanger in the abandoned well with variable loading means that only the required amount of energy is extracted and there is minimal waste. This is useful in designing a model with sustainable heat extraction, and it will also lead to a more accurate model as it is a more realistic representation.

2.4.3.1 Variable Flow

One option of controlling the extraction of geothermal energy is through regulating the flow of the working fluid through the heat exchanger. Higher working fluid flow rates result in a higher thermal power output with a relatively lower outlet temperature, and a smaller temperature difference between the inlet and outlet fluid temperatures. Conversely, lower working fluid flow rates produce a comparatively lower thermal power, with a higher outlet temperature, and a greater difference between inlet and outlet fluid temperatures. A variable flow model would be especially practical for use with direct applications and heat pumps.

2.4.3.2 Variable Inlet Temperature

A variable inlet temperature allows the model to simulate a thermal load, as its demands will vary over the span of a year (e.g. heating/cooling). For example, during the summer months the heat exchanger can be used to dump heat to the ground, effectively providing a cooling effect with the cooler outlet fluid. The variable inlet temperature is also important in modeling the extraction of geothermal energy to provide a constant power source. The double pipe heat exchanger can be manipulated to extract a constant amount of energy by adjusting the inlet fluid temperature so that the difference between the inlet and outlet fluid temperatures remains constant (i.e. constant ΔT).

2.4.4 Effect of Insulation

Insulation performs two important roles in the double pipe heat exchanger retrofitted to a petroleum well. Firstly, insulation is used to restrict heat flow between the countercurrent inlet and outlet fluid flows, as the heat exchanger will not function properly without. This insulation is added to the inner pipe, and is subject to a large temperature difference from both sides (e.g. cool inflow and hot outflow).

Secondly, for very deep, hot, or high heat flow wells where the inlet temperature is generally much hotter than the surface temperature, insulation applied to an upper portion of the casing on the borehole will prevent the loss of heat to the comparatively cooler rock mass. The insulation applied to the casing will generally extend to a depth where the temperature of the rock mass is equivalent to the mean temperature of the inlet fluid.

2.4.5 Sustainable Rate of Heat Extraction

As the double pipe heat exchanger begins extracting geothermal energy from the surrounding rock mass, it is drawing down the stored thermal energy. Over time, the heat exchanger will remove the stored thermal energy and the system will reach a steady state, where the heat extraction is limited by the ability of the rock mass to conduct heat. Extracting geothermal energy at a higher rate than the rock mass can conduct heat to replace it will result in an inefficient operation. If the geothermal resource is overexploited then the resource will not last very long, however a sustainably exploited resource will provide geothermal energy for a very long time.

Chapter 3 Model Description

3.1 Heat Equation Formulation

The closed loop geothermal heat exchanger modelled for this research is a double pipe heat exchanger (a.k.a. shell and tube heat exchanger), which injects water down through the annulus and extracts the fluid through the insulated inner pipe. The double pipe design was preferred over the u-tube design due to the higher cross sectional area dedicated to fluid flow, leading to a more efficient use of the volume within the abandoned petroleum well.

A fixed control volume (c.f. Figure 6) can be visualised to be surrounding the model, which posits that the energy entering the model equals the energy leaving the model. This relationship can be described as:

$$q_{in} - q_{out} + q_g = q_{St} \tag{2}$$

Or equivalently as:

$$q(x) - q(x + \Delta x) + q(y) - q(y + \Delta y) + q(z) - q(z + \Delta z) + q_g = q_{St} \tag{3}$$

Where q_g is the energy generated by an energy source, and q_{St} is the energy of the control volume at a steady state. Making use of the following relationship:

$$q(x) = q''(x) \times A_x = q''(x)\Delta y \Delta z \tag{4}$$

Where $q''(x)$ is the flux in the x direction per unit of area, and Δx, Δy, and Δz are the respective lengths of the control volume (c.f. Figure 6).

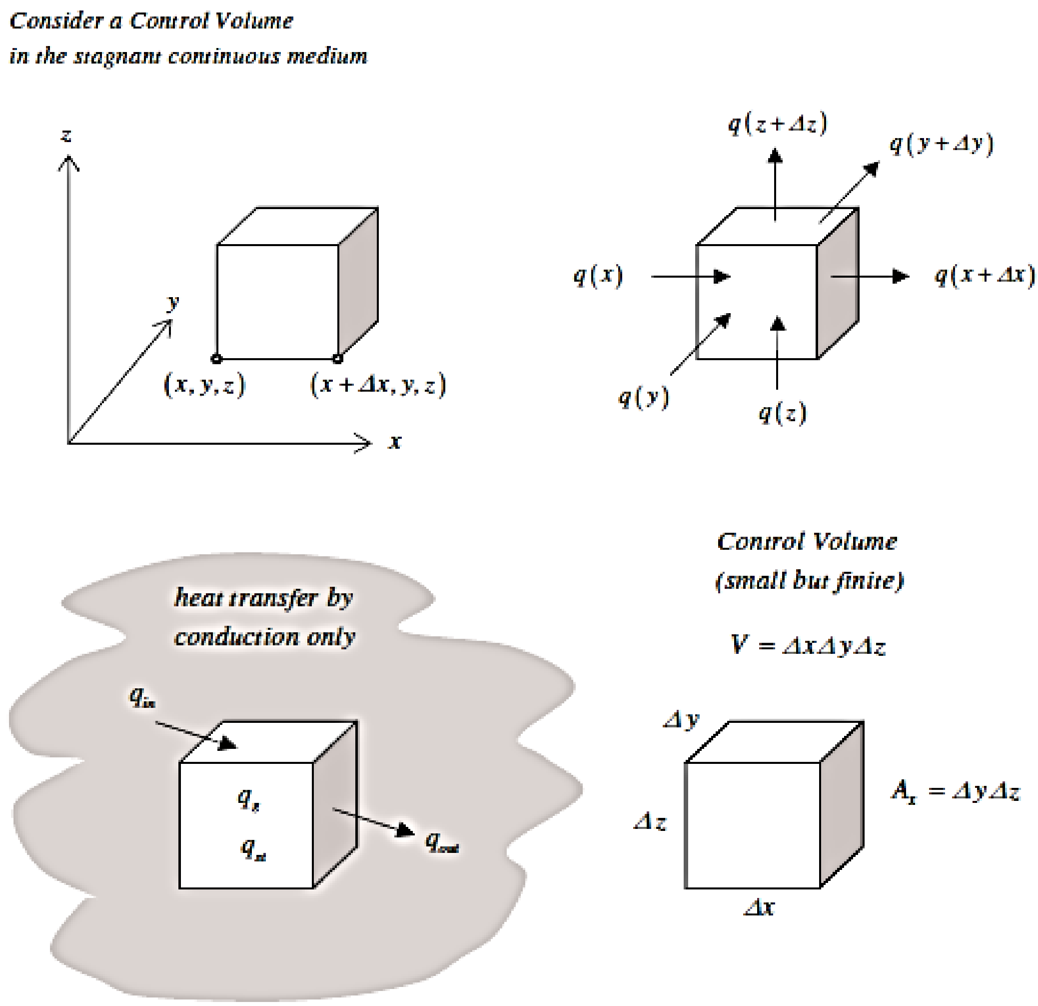

Figure 6: Definition of the control volume (Soloviev)

The relationship exhibited in Equation 4 is equally applicable to the y and z ordinates and the subsequent relationships. Equation 3 can be modified into Equation 5 with the substitution of Equation 4 and the subsequent relationships in y and z.

$$[q''(x) - q''(x + \Delta x)]\Delta y \Delta z + [q''(y) - q''(y + \Delta y)]\Delta x \Delta z + [q''(z) - q''(z + \Delta z)]\Delta x \Delta y + \dot{q}\Delta x \Delta y \Delta z = \rho C_p \frac{\partial T}{\partial t}\Delta x \Delta y \Delta z \quad (5)$$

Dividing Equation 5 by ΔxΔyΔz yields:

$$-\frac{q''(x+\Delta x) - q''(x)}{\Delta x} - \frac{q''(y+\Delta y) - q''(y)}{\Delta y} - \frac{q''(z+\Delta z) - q''(z)}{\Delta z} + \dot{q} = \rho C_p \frac{\partial T}{\partial t} \quad (6)$$

And taking the limit of Equation 6 as Δx→0, Δy→0, Δz→0:

$$-\frac{q''(x)}{\partial x} - \frac{q''(y)}{\partial y} - \frac{q''(z)}{\partial z} + \dot{q} = \rho C_p \frac{\partial T}{\partial t} \quad (7)$$

Fourier's three dimensional law (c.f. Equation 8) will describe the heat flow moving through heat exchanger and the surrounding rock mass.

$$\vec{\dot{q}} = -k\vec{\nabla}T \quad (8)$$

Where *q* is the heat flux, *k* is the thermal conductivity of the specific material, and *T* is the temperature at any point within the model. Applying Fourier's law (c.f. Equation 8) to Equation 7 and assuming a homogeneous thermal conductivity leads to the three dimensional heat equation in Cartesian coordinates:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + \dot{q} = \rho C_p \frac{\partial T}{\partial t} \quad (9)$$

Since, there is no heat source in the sophisticated model $\dot{q}$ is assumed to be null. A modification has to be made to Equation 9 in order to model the water flowing through the inner pipe and annulus of the heat exchanger. The flowing water in the double pipe system creates unsteady state conditions (i.e. q ≠ 0), thus the term on the right side of Equation 9 will take into account the unsteady nature of the model. Furthermore, due to the advective and conductive properties of the flowing water, a term must be added to Equation 9 to account for these properties. Finally, Equation 9 and the two new terms are converted into cylindrical coordinates (c.f. Equation 10) with the purpose of taking full advantage of the symmetry about the vertical axis (i.e. Z-axis).

$$\frac{1}{r}dr\big(krdr(T)\big) + dz\big(kdz(T)\big) = \rho C_p dt(T) + \rho_{fluid} C_{p,fluid} U_z dz(T) \qquad (10)$$

Where r is the radial ordinate, C_p is the specific heat of the particular material, and U_z is the velocity of the water in the outer annulus and inner pipe of the heat exchanger. The terms on the left hand side of Equation 10 are the cylindrical equivalent of the terms from the right hand side of Equation 9. It should be noted that the angular component (i.e. Θ) in Equation 10 is null, due to the symmetry about the vertical axis. The first term on the right hand side of Equation 10 serves to describe the transient nature of the heat flow through the ground and heat exchanger. The second term on the right hand side of Equation 10 represents the effects of advection and conduction caused by the fluid flowing through the heat exchanger. Equation 10 was further modified by factoring in a term, “Zscale”, which will mathematically scale the geometry in the vertical sense. Since this model is relatively slender (i.e. depth >> radius), a Zscale factor inferior to one was used to mathematically shrink the vertical geometry, effectively decreasing the number of nodes needed to model the simulation.

$$\frac{1}{r}dr\left(\frac{krdr(T)}{Zscale}\right) + dz(kdz(T)Zscale) = \frac{\rho C_p dt(T)}{Zscale} + \rho_{fluid}C_{p,fluid}U_z dz(T) \quad (11)$$

Equation 11, complemented by the boundary conditions and properties of the heat exchanger and surrounding rock mass, can be simulated by utilizing the commercial finite element modeller FlexPDE.

3.1.1 Heat Transfer in the Soil

The heat transfer within the rock mass was assumed to be purely conductive, and can therefore be completely described by the left hand side of Equation 11. However, the thermal energy already stored in the rock mass also has to be taken into account in order to create an accurate depiction of heat flow. The stored energy can be modelled by the transient term present in the right hand side of Equation 11, which describes how the rock mass changes temperature over time.

Groundwater flow is common underground and has been shown to be an important factor in the operation of heat exchangers (Ghoreishi-Madiseh, Hassani, & Al-Khawaja, 2012). Due to the axisymmetric simplification of the model, it is unable to realistically simulate the lateral flow of groundwater. However, it is possible to model the vertical flow of groundwater and gain basic insight into its effects on heat exchange. The factor U_z is used to describe the groundwater flow along the Z-axis, and has a zero value for conduction-only conditions.

3.1.2 Heat Transfer in the Heat Exchanger

The heat transfer occurring within the heat exchanger is a combination of conduction and advection. The conduction through the heat exchanger is modelled along the same equation and terms as conduction through the rock mass. The transient portion of Equation 11 also applies to all the components of the double pipe heat exchanger. In order to simulate a realistic model, the advection within the heat exchanger caused by the flowing fluid has to be considered. The advection term (i.e. second term on the right hand side of Equation 11) is needed to accurately model the heat transfer through the fluid contained in the double pipe heat exchanger.

3.2 FlexPDE

FlexPDE is used to simulate the double pipe heat exchanger retrofitted to an abandoned petroleum well, and makes use of the Galerkin finite element method. Utilizing the Galerkin method, FlexPDE goes on to determine the integral of Equation 11 to create a discretized equation at each of the mesh nodes (PDE Solutions Inc., 2011). The model is discretized by FlexPDE into an unstructured mesh, which will result in a much finer mesh at the heat exchanger due to the relatively small radius of the borehole compared with the rock mass. As FlexPDE runs the simulation, it calculates the temporal and spatial relative differences and creates a model that respects a user defined limit for the relative differences. If the temporal relative difference grows larger than the user defined limit, then the time step will be reduced. Similarly, if the spatial relative difference becomes too large during the simulation, then the mesh will undergo refinement. Mesh and domain independency studies were analyzed in order to find a realistic mesh and domain size that would provide accurate results.

3.3 Model Properties

The properties of the abandoned petroleum well, double pipe heat exchanger, and rock mass were chosen to accurately represent real conditions. The geothermal gradient of the rock mass was taken to be 30˚ C/km, measured from a petroleum well in the Persian Gulf. The depth of the borehole, 3.4 kilometres, was also taken from the aforementioned borehole to keep the simulations as realistic as possible. This results in a bottomhole temperature of 114˚C, when the surface temperature is assumed to be 12˚C.

The double pipe heat exchanger was designed to retrofit an abandoned well with a typical outer casing diameter of 19.6 centimetres (7 $^{5}/_{8}$ inches) and an inside diameter of about 15 centimetres. The relatively hot bottomhole temperature means that insulation is required on the top portion of the casing, so that a hotter inlet temperature can be used. The 2 centimetre thick insulation is extended to a depth where the virgin rock temperature is equal to the inlet fluid temperature. Insulating the casing according to this method, allows the maximum amount of heat flow from the rock mass to the heat exchanger. The inner pipe of the heat exchanger is designed to have an inner radius of 2 centimetres, with an additional 2 centimetres of insulation to cover the pipe. To take advantage of the symmetry around the vertical axis, only half of the model is simulated. This model, using the above properties, is considered as the base case model. All of the simulations (except verification simulations) were modelled over a period of 15 years, so as to verify the sustainability and long term consequences of extracting geothermal energy from the borehole.

The properties of the rock mass are assumed to be homogeneous and are based on empirical values for sedimentary rocks (c.f. Table 2) (Manger, 1963; Clauser & Huenges, 1995; Schön, 2011). The rock mass was assumed to be sedimentary due to the predominant occurrences of petroleum in sedimentary basins. The working fluid was designed to be water and its properties assumed to be homogenous and follow empirical values of water. The properties of insulation were assumed to imitate those of an efficient insulating material.

Table 2: Material properties used in the simulation of a double pipe heat exchanger retrofitted to an abandoned well

Material	Density (kg/m^3)	Thermal Conductivity(W/m·K)	Specific Heat (J/kg·K)
Rock	2200	2.0	1000
Fluid	1000	0.608	4200
Insulation	1.225	0.025	1010

3.4 Boundary Conditions

As the model is axisymmetric, only half of the heat exchanger is modelled along with the full domain of the rock mass. The boundary running along the length of the middle of the heat exchanger is a no flux boundary, as this allows the model to be axisymmetric. The surface boundary is a constant temperature boundary, and is kept at a constant 12 ˚C. As a constant surface temperature isn't realistic, 12˚C is chosen as a conservative average annual temperature. The far rock mass boundary remains at a constant temperature based on the geothermal gradient. This boundary is where the heat extracted from the abandoned well originates from after a steady state has been attained. The deep boundary of the rock mass is also kept at a constant temperature, based on geothermal gradient, but isn't a major source of heat. The deep boundary is at a depth 50 metres deeper than the bottom of the well, in order to respect the zone of influence of the heat exchanger. The boundary conditions on the bottom of the double pipe heat exchanger take the fluid temperature of the outer annulus and transfer it to the fluid ascending the inner pipe. It should also be noted that the model begins at an equilibrium state where the temperature of the heat exchanger (fluid, pipes, and insulation) is equivalent to the virgin rock temperature.

3.5 Domain Independency and Mesh Independency of the Results

Testing the model for mesh independency is a crucial step in designing an accurate model, and is a comparison of the mesh density versus the resulting accuracy. The mesh independency is directly related to the spatial temporal difference in FlexPDE, and a relative difference of 10^{-4} was determined to provide an acceptable level of accuracy. Limiting the relative difference at 10^{-4} implies that any differences that are lower will not significantly affect the outcome of the simulations.

Domain independency is another crucial step to designing an accurate model, as it denotes the distance at which the heat exchanger has no significant influence. After running several simulations, the zone of influence of the double pipe heat exchanger was found to be 40 metres. This represents 40 metres of rock mass with half of a double pipe heat exchanger installed at one end.

3.6 Outputs and Post Processing of the Results

FlexPDE allows for real time monitoring of the simulation as it is running, permitting the user to check the temperature and flux anywhere within the model. The monitors in place can be used as a check to ensure that the model is obeying the equations and boundary conditions placed on it (c.f. Figure 7). Figure 7 demonstrates the temperature contour of the entire model, and from this it can be concluded that there is minimal heat

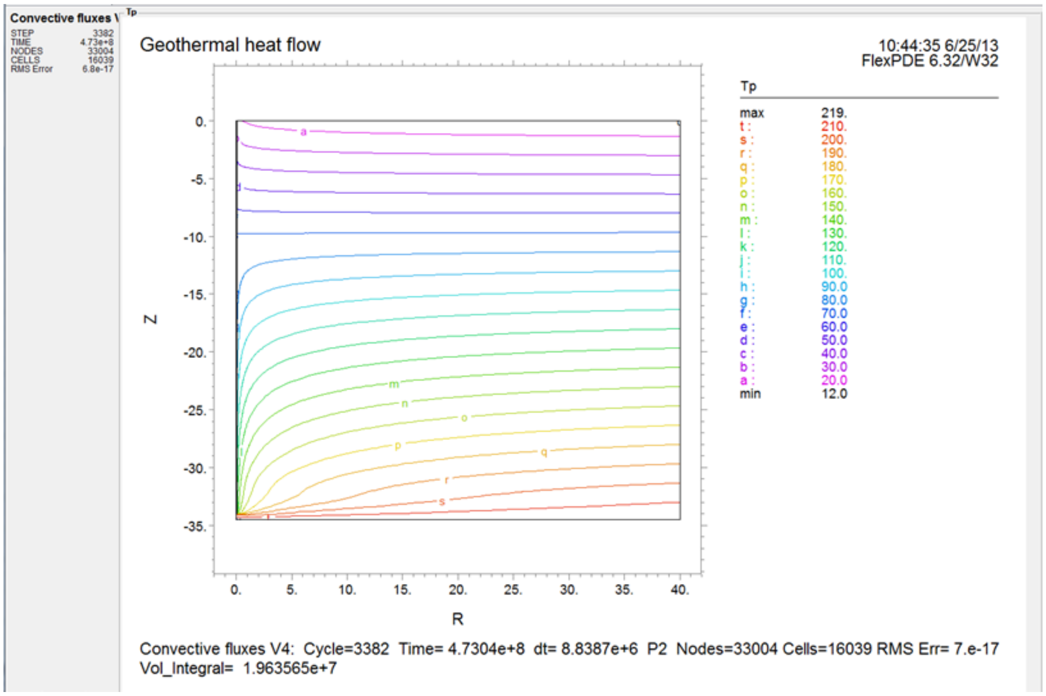

Figure 7: An example of an output from FlexPDE showing the temperature contours of the entire model

loss on the insulated portion of the casing (upper left side of Figure 7), and much heat gain on the uninsulated portion of the casing (bottom left side of Figure 7). Another verification that is employed, is to compare the flux through the soil with the flux extracted through the heat exchanger (i.e. energy in equals energy out).

For the purpose of this research, the inlet and outlet temperatures at each time step are exported to be analysed. The data can then be used to plot graphs, calculate extracted power, compare with other models, and get a temperature profile of the inlet/outlet fluid.

Chapter 4 Results and Discussion

4.1 Model Validation

In order for this sophisticated model to generate useful results, the model must be validated with previously authenticated works. This serves as a basis for the proposed sophisticated model to build from models that make more generalized assumptions, all the while gaining a realistic and accurate portrayal of how the double pipe heat exchanger will function in an abandoned well.

4.1.1 Cylindrical Source Model Verification

The cylindrical source model is a very basic analytical representation of a heat exchanger situated in a borehole, where the cylindrical source is surrounded by an infinite medium. The line source model is a simplification of the cylindrical source model, and both simplified models are used to model interactions with heat exchangers due to the speed at which they can be solved. The cylindrical source simplifies the heat exchanger situated in the borehole as a constant energy sink. Mathematica was used to simulate the one dimensional cylindrical source model, with the same characteristics as used in the sophisticated model. The following equation is used to describe the cylindrical source:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{k}g(r,t) = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{5}$$

Where *g(r,t)* is the rate of heat extraction through the cylinder, *k* is the thermal conductivity, *r* is the radius from 0 to b, and *α* is the thermal diffusivity. For the purpose of our calculations the heat extraction function, *g(r,t)*, is only valid from 0 to the outer radius of the borehole (i.e. behaving like a heat exchanger). Equation 5 is converted to the associated Green's function, and solved to yield the following solution:

$$\Delta T = \frac{2\propto}{kb^2}\int_0^t \int_0^{0.5\times D_{in}} x g(r,t) \sum_{m=1}^{Num} e^{-\propto \beta_m^2 (t-\tau)} \frac{J_0(B_m r)}{J_1^2(B_m b)} J_0(B_m x)\, dx d\tau \tag{6}$$

Where J_i are Bessel functions, D_{in} is the diameter of the borehole, and *x* is the Sturm-Liouville weight function. Equation 6 calculates the change in temperature over time at a certain radius (i.e. one dimensional).

The cylindrical source model can be compared with the developed model by using the constant power version of the sophisticated model. The constant power version of the model maintains a constant temperature difference between inlet and outlet temperatures, effectively acting as a constant energy sink. Figure 8 demonstrates the change in temperature at specific points through the two models, where: *r* is the radius beginning from the middle of the heat exchanger; D_{in} is the diameter of the borehole; *Domain* is the rock mass with the necessary zone of influence (i.e. 40 metres). The cylindrical source model can be solved much more rapidly than the sophisticated model, due to its simplistic approach. As can be seen in Figure 8, the cylindrical source model underestimates the temperature change at the borehole, while it

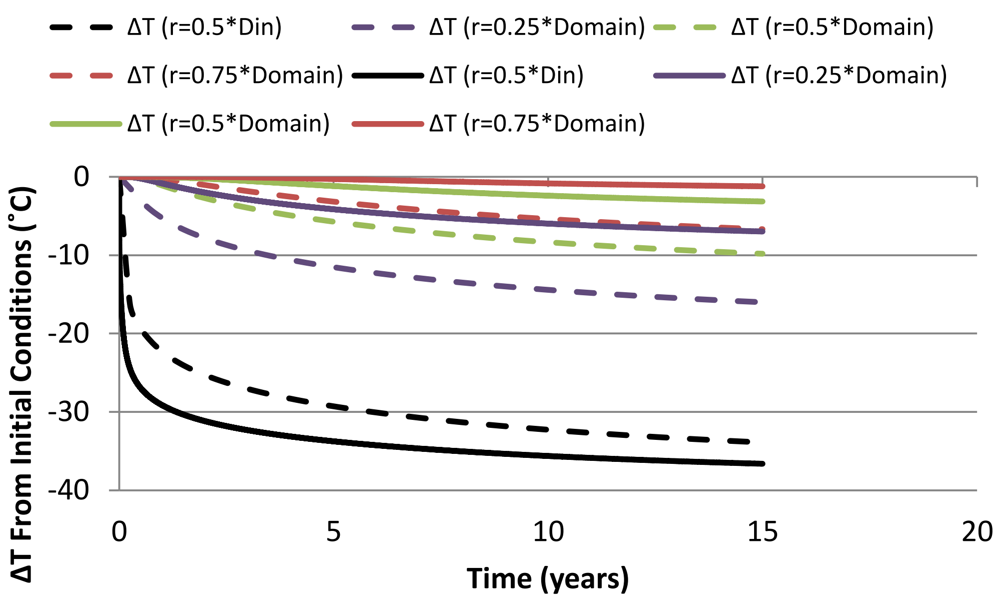

Figure 8: Verification of the sophisticated model (solid lines) with the cylindrical source model (dashed lines)

overestimates the change in temperature within the rock mass or geothermal reservoir. As can be seen in Figure 8, the results from the cylindrical source model are within the same order as the results of the sophisticated model, and the discrepancy can be attributed to the simplifications inherent in the one dimensional cylindrical source model.

4.1.2 Verification with Other Numerical Models

The model developed by Kujawa et al. (2005) was the first to tackle the idea of retrofitting a double pipe heat exchanger to an abandoned petroleum well. The simplifications used in the model proposed by Kujawa et al. (2005) are outlined above. The results they achieved with the air gap insulation between the inner pipe and outer annulus were compared against the results from the sophisticated model. The physical properties of the heat exchanger, as well as the thermophysical properties of the

Table 3: Comparison of the sophisticated model against the results from the model developed by Kujawa et al. (2005)

Properties	Model Results	Kujawa et al.
T_{out} (°C)	52.85	64.42
Power (kW)	99.98	124.68
Nusselt #	45-474	9

materials involved were translated to the sophisticated model and simulated over the course of one year. The particular case study used for comparison was for the volumetric flow of 2m^3/hour, and constant inlet temperature of 10˚C (c.f. Table 3).

As perceived in Table 3, the results from the model developed by Kujawa et al. (2005) are an overestimate of the results obtained by the more sophisticated model. This can be attributed to the simplification used to develop their model, namely the empirical unsteady assumption of heat transfer through the rock mass. The overestimate can also be attributed to the formulation of the Nusselt number employed in Kujawa et al. (2005) model (c.f. Table 3), as it is significantly less than the Nusselt numbers calculated in the sophisticated model.

Bu et al. (2011) provide the latest proposed model for a double pipe heat exchanger adapted to an abandoned petroleum well. The assumptions made by Bu et al. (2011) to construct their model are outlined above. The sophisticated model made use of the inputs instituted by Bu et al. (2011) such as the properties of insulation, rock mass, flow rate, and physical dimensions of the borehole and double pipe heat exchanger. The particular case that was used for comparison had the characteristics comprising of a geothermal gradient of 45˚C/km, fluid velocity of 0.03 m/s, and an inlet temperature of 30˚C over a period of ten years (c.f. Table 4).

As Table 4 demonstrates, the model proposed by Bu et al. (2011) generates significantly higher outlet fluid temperatures, and an overestimation from 60% up to 78% of the extracted thermal power. The overestimation is carried forward from year one to year ten, as can be

Table 4: Verification of the results obtained by Bu et al. (2011) with the results from the sophisticated model

Properties	T_{out} (°C)		Power (kW)		Power
Year	Model Results	Bu et al.	Model Results	Bu et al.	Overestimate
1	97.16	129.88	502.44	802.14	59.65%
2	94.46	129.28	482.22	796.94	65.26%
3	93.01	128.93	471.37	793.93	68.43%
4	91.99	128.69	463.78	791.81	70.73%
5	91.25	128.50	458.26	790.18	72.43%
6	90.62	128.35	453.49	788.85	73.95%
7	90.12	128.22	449.76	787.73	75.15%
8	89.72	128.11	446.76	786.77	76.10%
9	89.30	128.01	443.68	785.92	77.14%
10	88.97	127.92	441.19	785.17	77.96%

witnessed through the ever increasing overestimation percentage. The discrepancy between the two models is due to the empirical convection model employed by Bu et al (2011) to depict the heat flow within the tubes of the heat exchanger. As mentioned earlier, the Dittus-Boelter relation loses accuracy for the flow through an annulus or commercial tubes.

4.2 Constant Inlet Temperature Model

The sophisticated model can simulate the use of a constant inlet temperature, which is a similar method to those used by Kujawa et al. (2005), Davis & Michaelides (2009), and Bu et al. (2011). This model was used to test the effects of adding insulation to the well's casing, various mass flow rates, various inlet fluid temperatures, various geothermal gradients, various thermal conductivities of the rock mass, and the presence of vertical groundwater flow.

4.2.1 Effect of Insulation

In order to generate a high temperature outlet fluid sustainably, a relatively high temperature inlet fluid is needed. In these cases, the temperature of the inlet fluid is higher than the virgin rock temperature of the rock mass surrounding the borehole close to surface. In order to prevent the heat transfer from the hotter inlet fluid to the cooler ground (i.e. heat loss), insulation can be added the borehole's casing down to a depth where the virgin rock temperature is equivalent to the inlet temperature. This method of applying insulation to the borehole's casing insures that there is minimal heat loss and maximum heat gain from the rock mass.

The base case model was run twice with a constant inlet fluid temperature of 70˚C. The first run had no insulation on the casing of the borehole, and the second run had insulation installed on the casing from the surface to a depth of 1,950 metres. A depth of 1,950 metres was used for the extent of the insulation so that the inlet fluid of 70˚C wouldn't lose heat to the surrounding rock mass. The effects of fitting insulation to the casing compared to no insulation are demonstrated in Figure 9. The initial

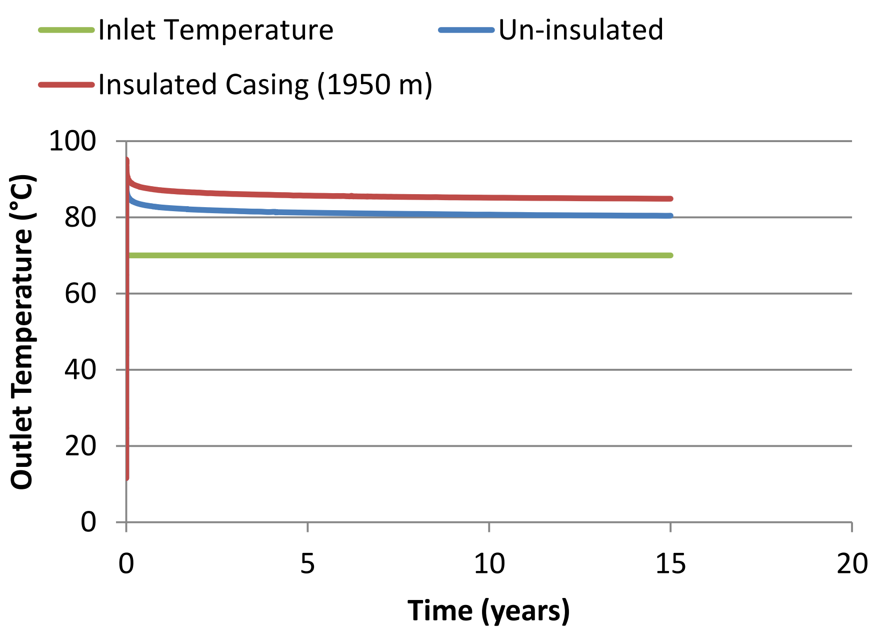

Figure 9: Effect of adding insulation the casing of the abandoned petroleum well

rise in outlet temperature, seen at the left of Figure 9, can be attributed to the initial conditions where the fluid within the heat exchanger was at equilibrium with the virgin rock temperature of the rock mass. The blue curve in Figure 9 exhibits the outlet fluid temperature profile of the uninsulated casing, over a 15 year period. Similarly, the red curve from Figure 9 reveals the temperature profile of the outlet fluid from the insulated casing over a 15 year period. From Figure 9 it is obvious that a steady state is reached after a period of about eight years, as the outlet fluid temperatures for both cases remain constant. The presence of insulation on the casing of the borehole is shown to increase the steady state fluid outlet temperature by 4.4˚C (c.f. Figure 9). The amount of thermal power available at the surface is proportional to the difference between the double pipe heat exchanger's inlet and outlet fluid temperatures. Therefore, with the introduction of insulation to the casing, the thermal power of the design increased by over 40%. Due to the appreciable boost in performance, each subsequent simulation has the necessary insulation included on the borehole casing.

4.2.2 Effect of Inlet Temperature

The effect that various inlet temperatures have on the base model is considered next, so that a favourable balance between the available thermal power and outlet fluid temperature can be reached. The effects of increasing inlet fluid temperature can be clearly seen in Figure 10, where the simulations were carried out on the base case with a mass flow rate of 1.26 kilograms per second. Figure 10 demonstrates hotter inlet fluid temperatures resulting in the trend of increasing outlet fluid temperature, along with reducing steady state power. It is simple to perceive from these trends that there is a trade-off between outlet fluid temperature and steady state power.

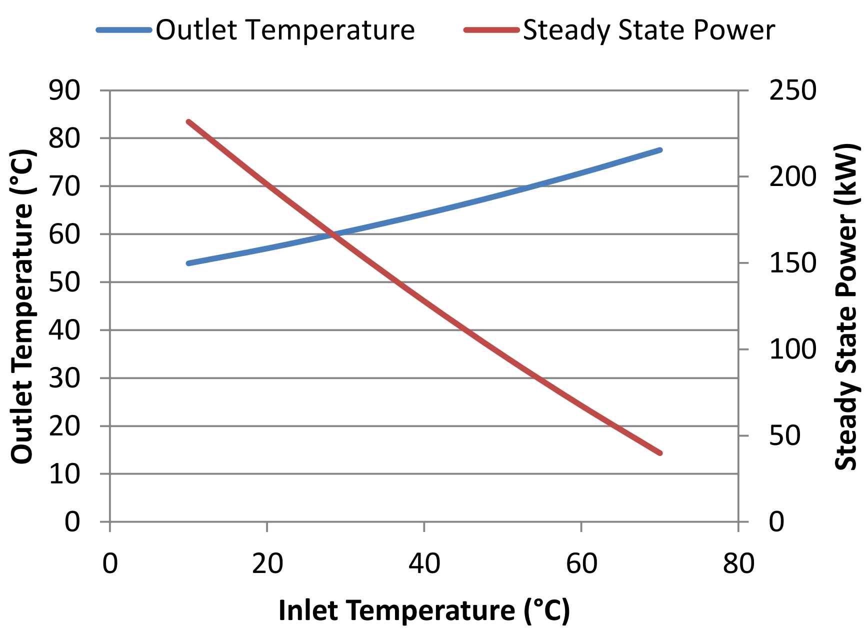

Figure 10: Effect of various fluid inlet temperatures on the steady state power and fluid outlet temperature

Making use of a binary geothermal power plant (i.e. Organic Rankine or Kalina cycle) would enable this modelled abandoned well to produce electricity, however, a single well would generate a small amount of electric power. The small amount of electric power from this well is due to the low energy conversion efficiency of binary power plants. Therefore, a more useful application of this well could be towards direct heating, diverse direct applications, or as a pre heating source for a hybrid power plant (i.e. combined with other energy sources). Using the abandoned well to supply geothermal energy for heating is feasible with lower temperature inlet fluid, which leads to a higher steady state temperature and a reduced need for insulation on the borehole's casing. For example, heating can be achieved with an inlet fluid temperature of 10˚C and steady state power of 232 kilowatts, compared to the 70˚C inlet fluid temperature required for power production and the associated steady state power of 40 kilowatts. For the case of the inlet fluid temperature of 10˚C, the well casing was left uninsulated as the ground is always at a higher temperature than the fluid. Nevertheless, for heating and direct applications to be viable uses for the geothermal energy extracted from an abandoned well, the well must be in a location relatively close to the thermal load/demand.

Assuming a conservative estimate of $0.06 per kilowatt hour of electricity, the potential savings from heating with geothermal energy will be in the range of $58 to $334 per day (c.f. Figure 10). Assuming that a typical cold season lasts for six months, the equivalent of $10,556 to $60,788 of electrical heating can be offset by the geothermal energy provided by the double pipe heat exchanger retrofitted to this abandoned petroleum well. Thus, designing a system with a lower inlet fluid temperature will bring about a higher amount of equivalent electrical heating.

4.2.3 Effect of Mass Flow Rate

The mass flow rate of the working fluid within the double pipe heat exchanger has a very important effect on the outlet fluid temperature, steady state power, and the sustainability of the system. The model used to simulate the results in Figure 11 was running a constant fluid inlet temperature of 70˚C with 1,950 metres of insulation on the casing. As can be seen in Figure 11, the outlet fluid temperature peaks at a mass flow rate of 0.4 kilograms per second, and the steady state power gradually approaches an upper plateau as the mass flow rate increases. The left

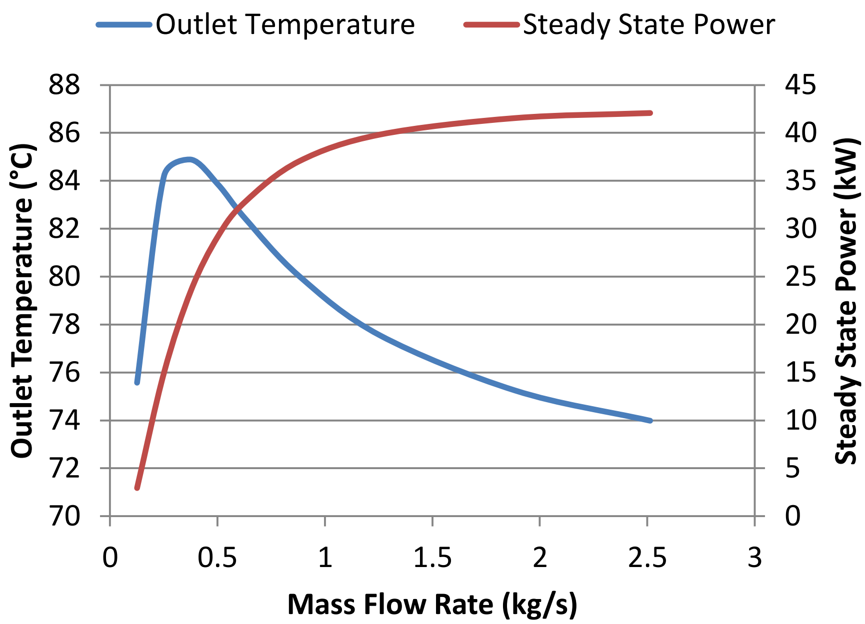

Figure 11: Effect of various mass flow rates on the steady state power and fluid outlet temperature

hand side of the outlet temperature peak decreases due to the fluids slow movement through the heat exchanger. The slow flow affects the heat transfer at the insulated portion of the casing, as there is more time for the fluid to lose heat to the rock mass. Furthermore, the slow flow through the inner pipe leaves more time for the hotter exiting fluid to lose heat to the cooler entering fluid. The steady state power is a function of the mass flow rate and the outlet fluid temperature, so even though the outlet fluid temperature decreases with increasing mass flow rate, the increase in mass flow rate is enough to compensate.

4.2.4 Effect of Geothermal Gradient

The geothermal gradient is one of the many factors influencing the performance of a geothermal heat exchanger. A higher geothermal gradient will undoubtedly result in a higher outlet fluid temperature and higher steady state power due to the higher resource temperature (c.f. Figure 12). The negative steady state power for the 0.02˚C per meter geothermal gradient (c.f. Figure 12), is due to the lack of heat flow to the

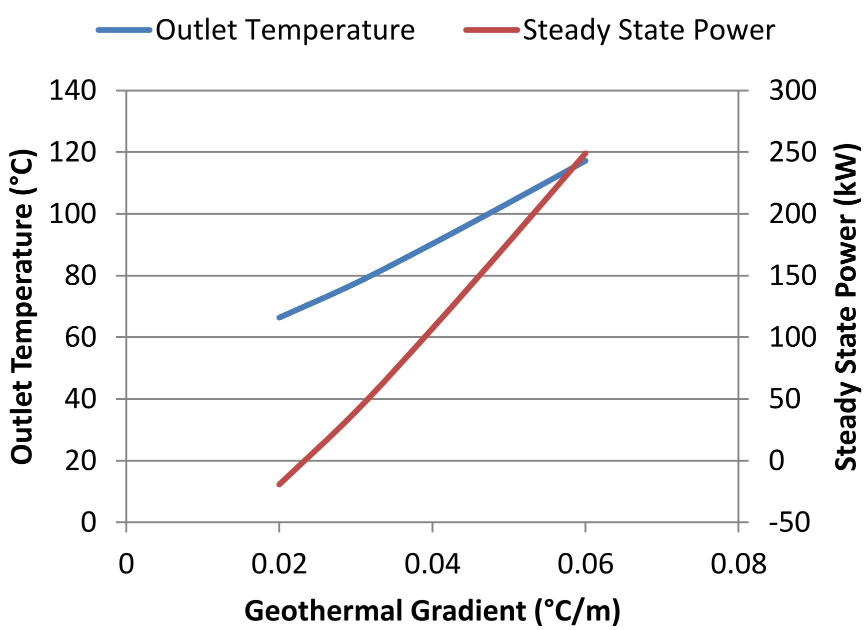

Figure 12: Effect of the geothermal gradient of the rock mass on outlet fluid temperature and steady state power

working fluid. The lack of heat flow results in an outlet temperature that is lower than the inlet temperature of 70˚C (c.f. Figure 12). The geothermal gradient is one of the properties that may already be determined from the temperature logging of petroleum wells, thus, it may be a useful property to identify the most lucrative resources.

4.2.5 Effect of Thermal Conductivity

The thermal conductivity of sedimentary rocks has a range of values, and a conservative value of 2 watts per meter Kelvin was employed in the base case scenario. The effect that the thermal conductivity of the rock mass has on outlet fluid temperature and steady state power is revealed through Figure 13. The simulations carried out for

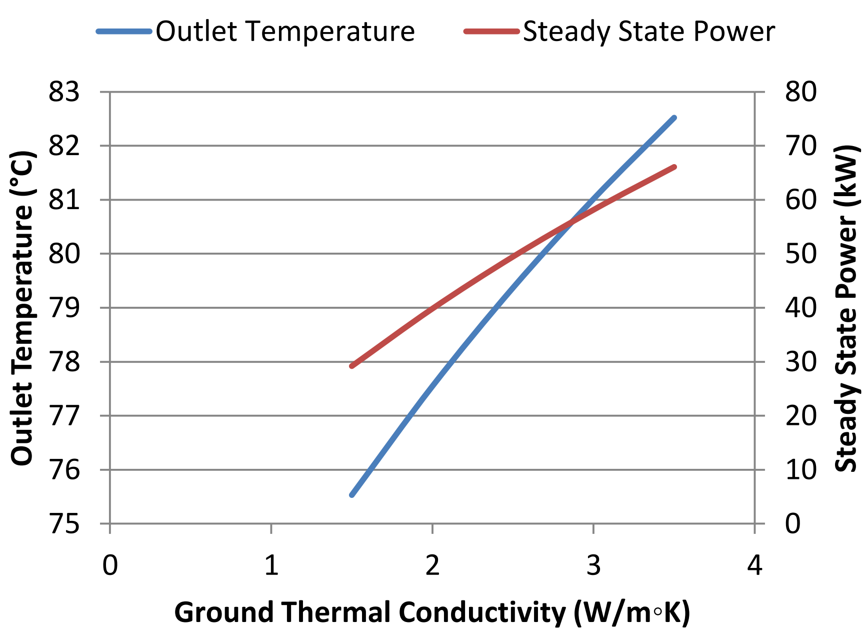

Figure 13: Effect of various rock mass thermal conductivities on the steady state power and fluid outlet temperature

Figure 13 had an inlet fluid temperature of 70˚C, and were carried out over a period of 15 years. Abandoned wells drilled into a rock mass with an elevated thermal conductivity will cause greater heat flow through the resource, resulting in an abandoned well that is more worthwhile to retrofit. Figure 13 demonstrates that the rock mass' thermal conductivity has a straightforward effect on the outlet fluid temperature and the steady state power. The effect is that abandoned wells that are situated in rock masses with higher thermal conductivities will have superior heat flow compared to resources with lower thermal conductivities.

4.2.6 Effect of Vertical Groundwater Flow

The effect of groundwater flow is an important factor in the heat exchange at significantly deep depths as demonstrated by Ghoreishi et al. (2012). Due to the axisymmetric approach to the model, it is only feasible to simulate the vertical movement of groundwater. Furthermore, due to the effects of gravity it is assumed that the general direction taken by the groundwater is downwards. The results shown in Figure 14 are for the base case with a 70˚C inlet fluid temperature over a period of 15 years. As can be seen in Figure 14, the effects of downward flowing water are adverse concerning the outlet fluid temperature and steady state power.

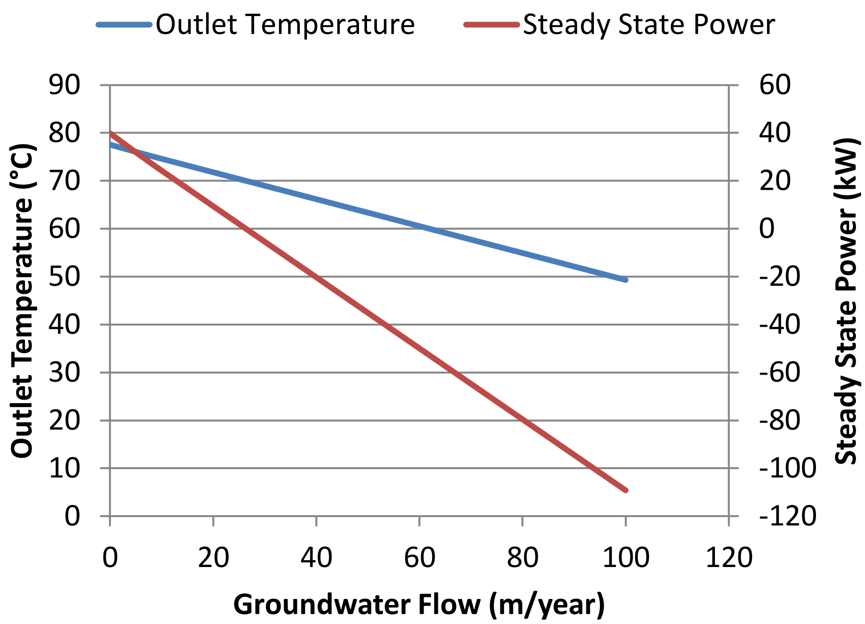

Figure 14: Effect of downward groundwater flow through the rock mass

The significance of the groundwater flow's negative effects escalate at displacements of 20 metres per year and higher. Groundwater flow is another property that is usually quantified while logging petroleum wells, and it would be wise to consider abandoned wells with less downward groundwater flow to retrofit.

4.3 Constant Power Model

In order to design the sophisticated model to be as realistic as possible, it was modified in order to extract a constant power from the rock mass. The extraction of a constant amount of power represents a more realistic case for the purpose of heating and direct applications, as they require a steady source of energy. A constant power can be extracted from the abandoned well by regulating the difference between the inlet

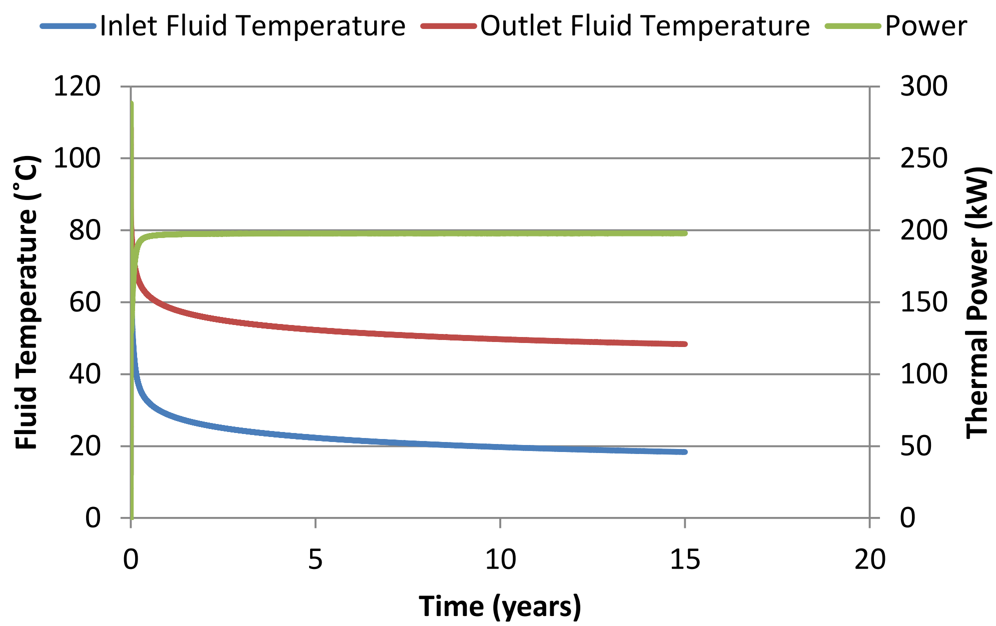

Figure 15: Example of the constant power model exhibiting control over the difference between inlet and outlet fluid temperatures

and outlet fluid temperatures and keeping the difference constant (c.f. Figure 15). The advantage of extracting a constant power is that only the demanded amount of energy is extracted, and it increases the sustainability of the geothermal resource. The effect of the mass flow rate of the fluid within the double pipe heat exchanger on the outlet temperature and power is demonstrated through Figure 16. As would be expected, lower mass flow rates result in a higher outlet fluid temperature and lower power. The available power in the constant power design is dependent on the set difference in fluid temperatures and the mass flow

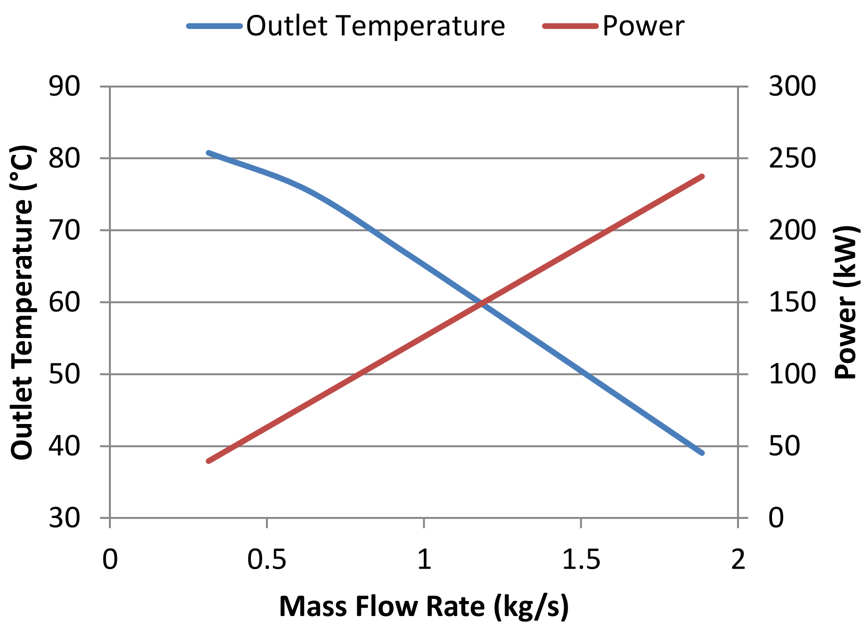

Figure 16: Effect of mass flow rate on the constant power heat exchanger design

rate (i.e. linear relation shown in Figure 16). For these simulations the inlet and outlet fluid temperatures were set apart at a constant difference of 30˚ C, and the well casing had 1,600 metres of insulation. There is room to improve on the optimization of insulation applied to the casing as the inlet fluid temperature changes over time. These simulations demonstrate the applicability of this design to suit the needs of heat pumps and various other direct applications.

Chapter 5 Conclusion

The feasibility and performance of a closed loop double pipe heat exchanger retrofitted to an abandoned well has been demonstrated through this sophisticated model. The model was validated with the cylindrical source model, the model developed by Kujawa et al. (2005), and the model proposed by Bu et al. (2011). The sophisticated model was shown to reach solutions with the same orders as each of the aforementioned models. The discrepancies can be explained by the simplifications made by these three models, compared with the more accurate sophisticated model. This model has also shown that an abandoned well can be adapted in order to produce outlet fluid temperatures hot enough to generate electricity. The higher outlet fluid temperatures required for power generation necessitate insulation on the well casing in order to prevent heat loss from the hot inlet fluid temperature to the relatively cool rock mass.

However, electricity generation isn’t the only purpose of this design; it may also be utilized for heating/cooling, and a multitude of other direct use applications. The ability for an abandoned well to be used for any purpose other than power generation is conditional upon the circumstance that it is in proximity to thermal demand/load. Extracting energy from the well at a lower inlet fluid temperature would allow more energy to be extracted from the resource compared to the higher inlet fluid temperatures needed for power generation. Making use of the constant power model is particularly suited to heat pump and direct use applications, as only the amount of energy that is needed is extracted. This results in a more sustainable extraction of energy from the geothermal resource.

The mass flow rate has a significant effect on the steady state power and outlet fluid temperature. Higher mass flow rates through the heat exchanger will result in a lower outlet temperature and higher steady state power, compared to the higher outlet temperatures and lower power of lesser mass flow rates. However, too small of a mass flow rate will result in a negative effect on the outlet fluid temperature, as the slow moving fluid will lose too much heat. The geothermal gradient and thermal conductivity both have a positive effect on the overall performance, and abandoned wells situated in areas with elevated values of either of these properties is positively influenced. The vertical groundwater flow through the rock mass has a negative effect on the performance of the heat exchanger, and tests should be carried out to determine the extent of groundwater flow. Too high of a vertical groundwater flow will decrease the performance of a design so far as to render it unfeasible.

List of References

Al-Khoury, R., & Bonnier, P. G. (2006). Efficient finite element formulation for geothermal heating systems. Part II: Transient. *International Journal for Numerical Methods in Engineering*, 725-745.

Andritsos, N., Dalabakis, P., Karydakis, G., Kolios, N., & Fytikas, M. (2011). Characteristics of low-enthalpy geothermal applications in Greece. *Renewable Energy 36*, 1298-1305.

Baker Hughes. (2012). *Baker Hughes Investor Relations*. Retrieved January 2013, from http://investor.shareholder.com/bhi/rig_counts/rc_index.cfm?showpage=int

Barbacki, A. P. (2000). The Use Of Abandoned Oil And Gas Wells In Poland For Recovering Geothermal Heat. *Proceedings World Geothermal Congress 2000.* Kyushu - Tohoku, Japan: Polish Academy of Science, Mineral and Energy Economy Research Institute.

Benderitter, Y., & Cormy, G. (1990). *Possible approach to geothermal research and relative cost estimate.* Rome, Italy: In: Dickson MH and Fanelli M (eds) Small Geothermal Resources. UNITAR/UNDP Centre for Small Energy Resources.

Bu, X., Maa, W., & Li, H. (2011). Geothermal energy production utilizing abandoned oil and gas wells. *Renewable Energy xxx*, pp. 1-6.

Clauser, C., & Huenges, E. (1995). *Rock Physics and Phase Relations- A Handbook of Physical Constants.* Hannover, Germany: American Geophysical Union.

Combs, S. (2008). *Chapter 21- Geothermal*. Retrieved January 2013, from Window on State Government: http://www.window.state.tx.us/specialrpt/energy/renewable/geo.php

Davis, A. P., & Michaelides, E. E. (2009). Geothermal power production from abandoned oil wells. *Energy 34*, pp. 866–872.

Dickson, M. a. (1990). *Small Geothermal Resources.* Rome, Italy: UNITAR/UNDP Centre for Small Energy Resources.

Duffield, W. A., & Sass, J. H. (2004). Geothermal Energy- Clean Power from the Earth's Heat. Denver, Colorado, United States: U.S. Geological Survey. Retrieved from http://pubs.usgs.gov/circ/2004/c1249/

EIA. (2012, October). *Petroleum and Other Liquids*. Retrieved January 2013, from US Energy Information Administration: http://www.eia.gov/dnav/pet/pet_crd_welldep_s1_a.htm

Eliasson, E. T., Thorhallsson, S., & Steingrímsson, B. (2011). *Geothermal Power Plants.* Santa Tecla, El Salvador: UNU-GTP and LaGeo.

Falcone, P. D. (2012). *Worldwide Classification & Reporting Requirements for Geothermal Resources.* Institute of Petroleum Engineering, Department of Geothermal Engineering.

Forrest, J., Marcucci, E., & Scott, P. (2005). Geothermal Gradients and Subsurface Temperatures in the Northern Gulf of Mexico. *GCAGS Transactions* (pp. v. 55, p.233-248). New Orleans, Louisiana: GCAGS.

Garbai, L., & Méhes, S. (2011). Energy analysis of geothermal heat pumps with U-tube installations. *3rd IEEE International Symposium on Exploitation of Renewable Energy Sources* (pp. 107-112). Subotica, Serbia: IEEE.

Ghoreishi-Madiseh, S. A., Hassani, F. P., & Al-Khawaja, M. J. (2012, May 13-17). *A novel technique for extraction of geothermal energy from abandoned oil wells.* Retrieved January 2013, from World Renewable Energy Forum: https://ases.conference-services.net/programme.asp?conferenceID=2859&action=prog_titles

Goss, R., Combs, J., & Timur, A. (1975). *Prediction Of Thermal Conductivity In Rocks From Other Physical Parameters And From Standard Geophysical Well Logs.* New Orleans, Louisiana: SPWLA Sixteenth Annual Logging Symposium.

Goutorbe, B., Lucazeau, F., & Bonneville, A. (2007). *Comparison of several BHT correction methods: a case study on an Australian data set.* Paris, France: Institut de Physique du Globe de Paris.

Haenel, R. R. (1988). *Handbook of Terrestrial Heat-Flow Density Determination.* Dordrecht, Netherlands: Kluwer Academic.

Hochstein, M. (1990). *Classification and assessment of geothermal resources.* Rome, Italy: In: Dickson MH and Fanelli M (eds) Small Geothermal Resources. UNITAR/UNDP Centre for Small Energy Resources.

Karonen, I. (n.d.). Retrieved from https://upload.wikimedia.org/wikipedia/commons/7/7d/Heatpump.svg

Kujawa, T., Nowak, W., & Stachel, A. A. (2005). Analysis of the Exploitation of Existing Deep Production Wells for Aquiring Geothermal Energy. *Journal of Engineering Physics and Thermophysics*, Vol. 78, No. 1, pg 127-135.

Kujbus, A. (2007). New Approach in the Hungarian Geothermal Exploration. *Transactions - Geothermal Resources Council*, 605-607.

Kurevija, T., & Vulin, D. (2011). High Enthalpy Geothermal Potential of the Deep Gas Fields in Central Drava Basin, Croatia. *Water Resour Manage*, 25:3041–3052.

Limpasurat, A. (2010). *Artificial Geothermal Energy Potential of Steam-flooded Heavy Oil Reservoirs.* Texas A&M University.

Lund, J. W. (2006, September). Chena Hot Springs. *Geo-Heat Center Quarterly Bulletin*, pp. Vol. 27, No. 3, pp. 2-4.

Lund, J. W., Freeston, D. H., & Boyd, T. L. (2005). World-Wide Direct Uses of Geothermal Energy 2005. *Proceedings World Geothermal Congress 2005.* Antalya, Turkey: Geo-Heat Center, Oregon Institute of Technology.

Lund, J., Sanner, B., Rybach, L., Curtis, R., & Hellström, G. (2004). *Geothermal (Ground-Source) Heat Pumps A World Overview.* Klamath Falls, Oregon, USA: Geo-Heat Center.

Manger, G. E. (1963). *Porosity and Bulk Density of Sedimentary Rocks.* Washington, USA: United States Government Printing Office.

McCarthy, K. (n.d.). *Closed Loop Systems*. Retrieved from Geothermal Energy: http://ffden-2.phys.uaf.edu/212_spring2011.web.dir/Kevin_McCarthy/closedloop.html

Muffler, P., & Cataldi, R. (1978). *Methods for regional assessment of geothermal resources.* Geothermics.

National Renewable Energy Laboratory. (1998, March). *Energy Efficiency and Renewable Energy*. Retrieved from U.S. Department of Energy: www1.eere.energy.gov/geothermal/pdfs/directuse.pdf

NGC. (2004, July). Retrieved January 2013, from National Geothermal Collaborative: http://www.geocollaborative.org/publications/

PDE Solutions Inc. (2011). *FlexPDE 6.* PDE Solutions Inc.

Prensky, S. (1992). Temperature Measurements in Boreholes: An Overview of Engineering and Scientific Applications. *The Log Analyst*, pp. v. 33, no. 3, p.313-333.

Rafferty, K., Culver, G., Boyd, T., & Lund, J. (2005). *Geothermal Direct-Use Case Studies.* Klamath Falls, Oregon, USA: Geo-Heat Center.

Reyes, A. (2007). *Abandoned oil and gas wells -a reconnaissance study of an unconventional geothermal resource.* Avalon: GNS Science Report.

Schön, J. (2011). *Handbook of Petroleum Exploration and Production Volume 8- Physical Properties of Rocks.* Kidlington, Oxford: Elsevier.

Soloviev, V. (n.d.). *Heat Transfer- ME340.* Retrieved from Brigham Young University: https://www.et.byu.edu/~vps/

Wang, Z., McClure, M. W., & Horne, R. N. (2010). Modeling Study of Single-Well EGS Configurations. *Proceedings World Geothermal Congress*, (pp. 1-12). Bali, Indonesia.

Wei, Y., Wang, F., & Ren, B. (2009). *Drainage and production by using geothermal in Huabei oil region.* Renqiu: Huabei Oilfield Production Technology Research Institute.

Zhongjian, L., & Zheng, M. (2009). Development of a numerical model for the simulation of vertical U-tube ground heat exchangers. *Applied Thermal Engineering 29*, 920-924.

Appendix FlexPDE Code

```
TITLE 'Geothermal heat flow'

SELECT
Errlim=0.0001        {relative difference limit}

COORDINATES
YCYLINDER        {cylindrical coordinates with the Z ordinate on the Y axis}

VARIABLES
Tp          { the temperature }

DEFINITIONS
k               {Thermal Conductivities}
Ksoil = 2
Kfluid = 0.608
KInsulation=0.025
KSteel=54

Rho             {densities}
rhosoil=    2200
rhofluid = 1000
rhoinsulation = 1.225
RhoSteel=7850

CP              {Specific heats}
CpSoil=1000
Cpfluid = 4200
Cpinsulation = 1010
CpSteel=490
```

Inner = 0.02 *{Inner radius of inner pipe}*

Outer = 0.075 *{Inner radius of well casing}*

Thickness_Insulation=0.02 *{thickness of the insulation on the inner pipe and well casing}*

Domain = 40 *{zone of influence of the heat exchanger}*

Depth = 3400 *{depth of the abandoned well}*

OuterInsulatedDepth=1950 *{Depth to which the well's casing is insulated}*

Buffer=50 *{Extra slice of rock mass underneath the heat exchanger, note that it's greater than Domain}*

InletControl=70 *{Constant inlet fluid temperature}*

Tmax = 15*365*24*3600 *{Length of time the simulation runs for}*

Inlet_outflow = 2*line_integral(Tp*r, "InletBottom")/((outer-thickness_insulation)^2-(inner+thickness_insulation)^2) *{fluid temperature at the bottom of the annulus}*

Zscale=1/100 *{factor used to scale the geometry in the Z-axis}*

Geo_Gradient =0.03 *{geothermal gradient in degrees Celsius per meter}*

Tsurface=12-z/Zscale*Geo_Gradient *{virgin rock temperature of the rock mass}*

Uz *{Vertical velocity}*

Vi=1 *{fluid velocity through the inner pipe}*

Vo=Vi*(Inner^2)/((Outer-thickness_insulation)^2-(Inner+thickness_insulation)^2) *{fluid velocity through the outer annulus}*

Groundwater=-0/86400/365 *{vertical velocity of groundwater, "-" for downward flow, 0 for conduction only model}*

INITIAL VALUES

Tp = Tsurface *{Initially having the heat exchanger in temperature equilibrium*

```
                    with virgin rock temperature}

EQUATIONS
Tp : 1/r*dr(k*r*dr(Tp)/Zscale) + dz(k*Zscale*dz(Tp)) = (rho*Cp)*dt(Tp)/Zscale +
Rhofluid*Cpfluid*Uz*dz(Tp)      {Modified heat equation}

BOUNDARIES
Region "Domain"      {define outer domain, rock mass}
K=ksoil Rho=rhosoil Cp=Cpsoil Uz=Groundwater      {Properties of the rock
                                                   mass}
    Start (0, 0)
      line to (domain,0)         value(Tp)=Tsurface      {surface boundary at
                                                          surface temperature}
      line to (domain,-(depth+buffer)*Zscale) value(Tp) =Tsurface     {far away
                                                   boundary with virgin rock
                                                   temperature}
      line to (0,-(depth+buffer)*Zscale) natural (Tp) = 0      {No flux boundary at
                                                               the axis of symmetry}
     line to close

Region "TopOuterInsulation"    {Insulated region at the top part of the well casing}
k=kinsulation Rho=rhoinsulation Cp=cpinsulation Uz=0      {Properties of
                                                            insulation}
    Start (outer-thickness_insulation,0)
      line to (outer, 0)
      line to (outer, -OuterInsulatedDepth*Zscale)
      line to (outer-thickness_insulation, -OuterInsulatedDepth*Zscale)
    line to close

Region "BottomOuterInsulation"      {Uninsulated region on the well casing,
```

```
                                             assumed to have properties of steel}
k=kSteel Rho=rhoSteel Cp=cpsteel Uz=0        {Properties of steel pipe}
    Start (outer-thickness_insulation,-OuterInsulatedDepth*Zscale)
      line to (outer,-OuterInsulatedDepth*Zscale)
      line to (outer, -depth*Zscale)
      line to (outer-thickness_insulation, -depth*Zscale)
    line to close

Region "Outertube"       {overlay a region for the outer annulus}
k=kfluid Rho=rhofluid Cp=cpfluid Uz=-Vo     {Properties of the fluid in the
                                             annulus, fluid velocity is in the down
                                             direction}
    Start  (outer-thickness_insulation, 0)
      line to (outer-thickness_insulation, -depth*Zscale)
      line to (inner+thickness_insulation, -depth*Zscale)
      line to    (inner+thickness_insulation, 0)   Value(Tp)= Inletcontrol  {Set top
                                             of the annulus to the inlet temperature}
    line to close

Region "Insulation"    {overlay a region for the insulation around the inner pipe}
k=kinsulation Rho=rhoinsulation Cp=cpinsulation Uz=0    {Properties of
                                                         insulation}
    Start (inner+thickness_insulation,0)
      line to (inner+thickness_insulation, -depth*Zscale)
      line to (inner, -depth*Zscale)
      line to (inner, 0)     natural (Tp) = 0       {no flux through the top of the
                                                    insulation}
    line to close

Region "Innertube"    {overlay a region for the inner tube}
```

```
k=kfluid Rho=rhofluid Cp=cpfluid Uz=Vi    {Properties of the fluid inside the inner
                                           pipe, fluid velocity is in the up direction}
      Start (0,0) natural (Tp) = 0        {no flux through the top of the inner tube}
         line to (inner, 0)
         line to (inner, -depth*Zscale) value(Tp) = Inlet_outflow   {energy continuity
                                                   from the bottom of outer annulus}
         line to (0, -depth*Zscale) natural (Tp) = 0        {no flux through the axis of
                                                             symmetry}
      line to close
```