

ABANDONED OIL/GAS WELLS AS SUSTAINABLE SOURCES OF RENEWABLE ENERGY

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ABSTRACT

A petroleum well that is not in use because it has ceased to produce oil/gas economically and dry holes are referred to as abandoned wells. Once a well is abandoned it is plugged with cement and can take anywhere from two days up to a week to cure depending on the number of plugs in the well. Since plugging a well costs capital, most wells are abandoned at the lowest possible cost and with the minimum obligations set by regulation agencies. These wells can present an enduring liability to petroleum companies. However, the depth and abundance of abandoned petroleum wells makes them an economically attractive source of geothermal energy. Geothermal energy harvested from an oil/gas well is a renewable energy source as long as it is extracted in a sustainable manner. The energy can be used to generate electricity, used directly for heating, incorporated into a water desalination process, or used by a heat pump for heating/cooling applications. In this paper we examine the possibility of extracting geothermal energy from abandoned oil/gas wells by studying the heat transfer in underground geothermal heat exchangers installed in these wells. The design configurations for the geothermal heat exchangers embedded inside a petroleum borehole can be a u-tube design or a shell and tube design (i.e. double pipe). Using in-situ gathered information from some representative petroleum boreholes, the effects of key parameters such as geothermal gradient, ground temperature values, and the flow inside of the tubes are evaluated. In order to provide a constant power production the inlet temperature can be adjusted to keep the difference between outlet and inlet temperatures equivalent. Higher differences between inflow and outflow temperatures will result in a less sustainable load put on the in-situ geothermal energy. Adding insulation to certain sections of the designs can minimize the transfer of thermal energy from the fluid to the surroundings. Insulation can also limit the thermal loss between the inflow and outflow tubes in the shell and tube design. Minimizing the energy loss of these designs leads to an increase in the outlet temperature, meaning a higher grade of heat. The sustainability of long term geothermal heat extraction is a balance between the rate at which geothermal energy is extracted and the rate at which the ground formation can replace this heat. Higher outlet temperatures can lead to a larger amount of power generation, and a higher coefficient of performance for heat pump applications.

KEYWORDS

Geothermal energy, closed loop, shell and tube, abandoned wells, petroleum

INTRODUCTION

Geothermal energy is an increasingly popular alternative energy source that can be used to produce electricity, space heating/cooling, and many direct-use applications. The installed generating capacity from global geothermal energy has increased from 1300 MWe in 1975 to 10,715MWe in 2010 (Bu, Maa, & Li, 2011). The increase can be attributed to higher global energy demand/prices, new technologies, and the need to reduce the impact on the environment. The electric output from a geothermal power plant is calculated by multiplying its thermal energy output by the efficiency of the operation. Geothermal heat pumps can heat a home anywhere in the world by extracting energy from shallow ground. Deeper wells are needed for the higher temperatures demanded by power generation and industrial applications (e.g. agricultural drying, zinc and gold ore recovery, etc.). The depth of the borehole can be minimized by tapping into a hot spring, hot aquifer, or an area with an elevated geothermal gradient because of the higher natural heat flux.

Typically, a production well is drilled to extract hot water or steam from the ground, and an injection well is drilled in order to replenish the water that is extracted. Geothermal operations that extract heat by way of the groundwater are open loop systems, and require processes to deal with water management (e.g. injection well). Alternatively, geothermal systems can operate by removing heat from the rock surrounding a borehole by pumping a fluid through a system composed of a closed loop of pipes (i.e. closed loop system).

The advantages of geothermal energy lie in its low impact on the surrounding environment, continuous power output, low greenhouse gas emissions, and worldwide availability. The main disadvantages of geothermal energy are the high capital cost associated with drilling and pumps, and the accessibility to water for open loop systems. Drilling for geothermal wells can comprise up to 50% of the costs of the entire geothermal project (Bu,

Maa, & Li, 2011). The high capital cost incurred from drilling can be offset by using existing wells from petroleum exploration and production operations.

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 in depth (EIA, 2012). Dry holes refer to drilled wells that contain an economically unfeasible amount and/or type of petroleum deposit. With over 2.5 million petroleum wells drilled since the 1950's and the highest rate of oil and gas drilling in the world (Baker Hughes, 2012), the US provides a satisfactory sample of worldwide 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 they 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 subsurface formations (i.e. abnormal underground pressure zones, underground shale, and sources of contamination) have 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 hanging the string on the preceding casing. 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 will be reduced by logging data during/following the circulation of drilling fluids, during production, and by logging at high speeds (Prensky, 1992). There exists many methods of extrapolating the measured bottom hole temperature to estimate the temperature under static conditions or formation temperature (Goutorbe, Lucazeau, & Bonneville, 2007). The precision of well temperature logging is generally $\pm 0.5^{\circ}\text{C}$ for petroleum and geothermal wells, however, more accurate temperature logging may be required for exceptionally hot resources, open loop operations, and heat flow analyses (Steingrímsson, 2013; Grasby, Majorowicz, & Ko, 2009). More precise well logging can be achieved by allowing the well to thermally recover from the circulation of drilling fluids, and reach a stable temperature closer to the formation temperature of the rock. 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:

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

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).

Petroleum extraction and geothermal extraction are two very different operations; however, they are similar in the fact that both activities require a borehole in order to extract resources from the earth. Abandoned petroleum

wells can be repurposed as geothermal wells given a high enough resource temperature and demand. Repurposing abandoned petroleum wells cuts out the cost of drilling geothermal wells, which can constitute from 42% to 95% of the total cost of the geothermal project (for open loop geothermal systems), depending on the quality of the geothermal gradient (Tester, Herzog, Chen, Potter, & Frank, 1994; Bu, Maa, & Li, 2011). An important aspect of using the abandoned petroleum wells is the large amount of data available for the existing wells. The data that exists on the abandoned wells can help to identify the most lucrative wells that are closest to the potential applications and also to define conditions and resources that can be used to retrofit a well for geothermal purposes. Existing petroleum wells can be redrilled to access better resources/conditions at a lower cost than drilling a new well (Combs, 2008).

The majority of the work that has been done on generating geothermal energy from abandoned oil wells has been on open loop designs that repurpose the depleted oil reservoir as a geothermal reservoir. Several countries have or are planning on using geothermal energy from open loop systems installed in abandoned petroleum wells, including: Poland (Barbacki, 2000), Croatia (Kurevija & Vulin, 2011), New Zealand (Reyes, 2007), China (Wei, Wang, & Ren, 2009), USA (Davis & Michaelides, 2009), Israel, and Albania (Lund, Freeston, & Boyd, 2005). Further work has been done by Sanyal & Butler (2010), Davis & Michaelides (2009), and Bu et al. (2011) on the factors influencing the power generated from an open loop system operating in an abandoned well.

Alternatively, abandoned wells can be retrofitted in order to become a closed loop heat exchanger by introducing a system of tubes into the production casing of the well. The most popular types of single well downhole heat exchangers are shell and tube, u-tube, and multiple u-tubes in different configurations. Making use of a closed loop design offers advantages such as the ability to use a non-aqueous fluid, a reduction in the amount of energy needed for pumping compared to open loop designs, and the elimination of the need to manage water resources. A technique is being developed by EPRI to maximize the amount of energy that can be removed from a single well closed loop heat exchanger by modelling variations in conduction, grout, and working fluid enhancements (i.e. non-aqueous solution) (Electric Power Research Institute, 2010). The model designed by the Electric Power Research Institute boasts a power output of 0.5 to 1 MWe per abandoned well. Similarly, a single u-tube heat exchanger model was developed by Ghoreishi-Madiseh et al. (2012) in order to determine the effects of the natural convection of water through the rock.

Shell and Tube Geothermal Heat Exchanger

An abandoned well can be retrofitted with an insulated pipe of a smaller diameter in order to create the shell and tube heat exchanger (c.f. Figure 1). There are two variations of exchanging heat with the shell and tube setup: one is to pump fluid down through the outer annulus and up through the insulated inner pipe, and the second is to inject the fluid through the insulated inner pipe and up the outer annulus. The fluid that flows through the outer shell will transfer heat with the rock surrounding the borehole. The inner tube is insulated in order to minimize the transfer of heat between the bidirectional flows, as the cooler injection flow would lower the outlet temperature of the hotter exiting flow. For exceptionally deep or hot wells, insulation can also be added to the outside of the casing.

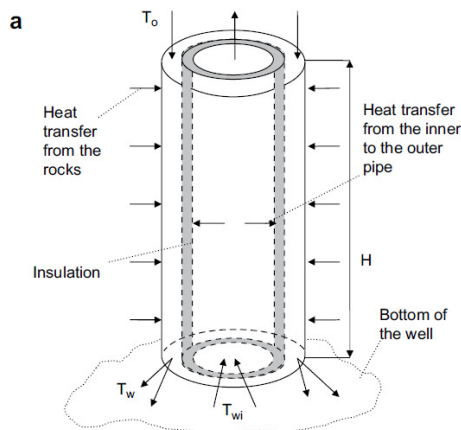


Figure 1-Shell and tube heat exchanger that can be retrofitted to a petroleum well (Davis & Michaelides, 2009)

near the top of the borehole in order to limit loss of heat to the comparatively cool ground. The added insulation on the outer casing is applicable to both variations of the shell and tube heat exchanger; however the depth that the insulation reaches will vary.

To make the system more efficient, the bottom of the well can be sealed and a secondary non-aqueous fluid is used in the shell and tube setup (Davis & Michaelides, 2009). Isobutene, freon, and ammonia are popular secondary fluids because they vaporize at a lower temperature than water. Sealing the well bottom and using a secondary fluid poses challenges such as preventing leaks between the two pipes, preventing leaks to the surrounding earth (especially with environmentally unfriendly fluids), developing sufficient insulation between the two pipes, and needing a large volume of secondary fluid (depending on diameter of pipe and depth of the well).

The power that can be extracted from a double pipe heat exchanger set up depends mainly on the fluid flow rate and the geothermal gradient (Bu, Maa, & Li, 2011). Other factors that influence the power capacity include ambient temperature, temperature of the produced water, geothermal gradient, underground water convection (Ghoreishi-Madiseh, Hassani, & Al-Khawaja, 2012), efficiency of the geothermal plant, etc. Fluid flowing too fast will not heat sufficiently, while fluid flowing too slowly will not achieve optimal power. The study done by Bu et al. (2011) demonstrated that there is a zone of influence around a well where the heat is being taken from, and the overlap of these zones will result in diminished power potential because of the shared thermal resource.

MODEL DESCRIPTION

The purpose of this model is to evaluate the factors affecting the extraction of geothermal energy from abandoned petroleum wells, and to evaluate the feasibility of using abandoned petroleum wells as geothermal resources for a closed loop geothermal system. The closed loop system modeled is a shell and tube style heat exchanger, which operates by injecting water through the outer annulus and extracting the heated water through the insulated inner pipe. Fourier's 3-dimensional heat equation (c.f. Equation 2) can be used to describe the heat conduction through the rock surrounding the abandoned well and the water inside of the well.

$$\vec{q} = -k\vec{\nabla}T \quad (2)$$

Where q is the heat flux, k is the thermal conductivity, and T is the temperature at any given point. In order to model the water flowing through the shell and tube exchanger, Equation 2 must be modified. The flow of water causes the model to be transient (i.e. $q \neq 0$); therefore a term must be added in order to take into account the unsteady state of the model. Also, a term must be added to account for the advective and conductive properties of the moving fluid in the outer annulus and inner pipe of the heat exchanger. Finally, in order to take full advantage of the symmetry about the vertical axis of the heat exchanger, Fourier's heat equation and the two additional terms can be converted to cylindrical coordinates (c.f. Equation 3).

$$\frac{1}{r}dr(krdr(T)) + dz(kdz(T)) = \rho C_p dt(T) + \rho_{fluid} C_{p,fluid} U_z dz(T) \quad (3)$$

Where r is the radial coordinate, C_p is the specific heat, and U_z is the velocity of the water in the heat exchanger. The left hand side of Equation 3 is the cylindrical coordinate equivalent of Equation 2, with the Θ (i.e. angular) component becoming a zero term due to symmetry about the z -axis. The two terms on the right hand side refer to the unsteady state component and the convective component of the fluid circulating in the heat exchanger, respectively. Further modifications were made to Equation 3 in order to mathematically scale down the geometry in the z axis, thereby reducing the number of nodes required to model the scenario. As can be seen in Equation 4, the z -axis is scaled by a factor "Zscale", with a factor less than 1 mathematically shrinking the z -axis.

$$\frac{1}{r}dr\left(\frac{krdr(T)}{Zscale}\right) + dz(kdz(T)Zscale) = \frac{\rho C_p dt(T)}{Zscale} + \rho_{fluid} C_{p,fluid} U_z dz(T) \quad (4)$$

Equation 4 coupled with the properties of the heat exchanger and surrounding rock mass can be modeled with the help of the finite element modeling software FlexPDE. FlexPDE makes use of the Galerkin finite element method which computes the integral of Equation 4 in order to form a discretized equation at the mesh nodes (PDE Solutions Inc., 2011). FlexPDE calculates the spatial and temporal relative differences as it runs, and it will generate a model that complies with a user established limit on the relative difference. Too high of a relative

difference in the spatial portion will result in a mesh refinement and too large of a relative difference in the temporal portion will cause a reduction in the timestep. After testing for mesh independency an acceptable limit of 10^{-4} was placed on the relative differences, meaning any differences lower than this would not significantly affect the simulation. Conversely, an ideal domain size was arrived at after testing for domain independency (i.e. zone of influence), meaning that increasing the domain size would not have an effect on the accuracy of the simulation.

The shell and tube heat exchanger used for the simulations was designed to retrofit an abandoned well with a typical casing having an outside diameter of 19.6 centimetres (7 5/8 inches) and an inside diameter of 15 centimetres. The inner tube that is to be lowered into the well was designed to have an inside diameter of 2 centimetres and 2 centimetres of insulation. Only half the heat exchanger was modeled due to symmetry about the z axis, and after conducting a domain independence study the heat exchanger was bounded by 40 metres of rock. The properties assumed for the fluid and insulation in heat exchanger as well as the surrounding rock are highlighted in Table 2.

Table 1- Material properties used in the simulation of a shell and tube heat exchanger

Material	Density (kg/m ³)	Thermal Conductivity(W/m·K)	Specific Heat (J/kg·K)
Rock	2200	2	1000
Fluid	1000	0.608	4200
Insulation	1.225	0.025	1010

The properties for the rock are assumed to be homogeneous and are based on empirical values for sedimentary rocks (Manger, 1963; Clauser & Huenges, 1995; Schön, 2011), as petroleum occurs mainly in sedimentary basins. The values used for the properties of the circulating fluid are based on empirical values of water. Finally, the properties of the insulation were assumed to mimic the characteristics of an efficient insulating material.

RESULTS AND DISCUSSION

A sensitivity analysis was done in order to analyze the effects of thermal properties and conditions on the steady state outlet temperature and power produced. The properties that were varied were the inlet temperature, mass flow rate, and thermal conductivity of the rock mass. The simulations were carried out on a model based on the geothermal gradient and depth of an onshore petroleum well in the Persian Gulf, so as to make the simulations as realistic as possible. The abandoned well is 3400 m in depth with a geothermal gradient of 30°C per kilometer (i.e. bottomhole temperature of 114°C). All simulations were modelled over a period of 15 years in order to verify the sustainability and long term consequences of extracting the geothermal energy. Insulation (2 centimetres thick) was added to the outer casing in order to conserve the heat of the fluid, so that a hotter inlet temperature could be used. The insulation extended to a depth where the temperature of the rock was equal to that of the inlet fluid, so that the maximum amount of heat energy could be extracted from the rock mass. The effects of the insulation are exhibited in Figure 2, where the presence of insulation on the casing increased the steady state outlet temperature by 4.4°C. The power available at the steady state increased by over 40% with the introduction of insulation to the casing, so all subsequent simulations had a partially insulated casing. The amount of power available is directly proportional with the difference between the outlet and inlet temperatures. The two simulations in Figure 2 are based on the most realistic case properties.

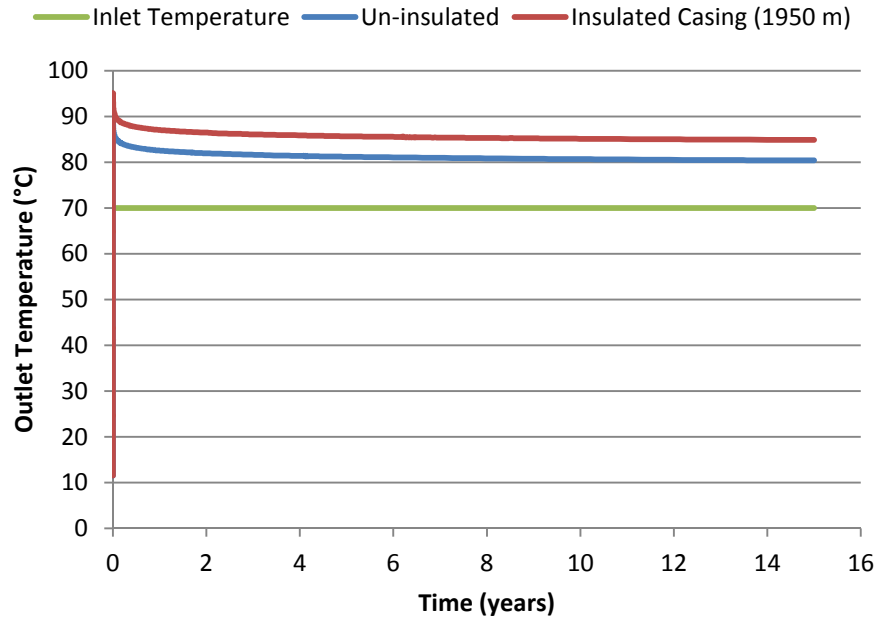


Figure 2- Effect of adding insulation to the outer casing

The effect of the inlet temperature with a partially insulated casing was tested next, so as to find an inlet temperature that will result in an optimal balance between the outlet temperature and the available power. The trade-off between outlet temperature and power can clearly be seen in Figure 3 (mass flow rate of 4.4 kg/s). The outlet temperature increases with increasing inlet temperatures, but hotter inlet temperatures reduce the steady state power. An inlet temperature of 70°C was determined to be the best temperature for our simulations, as ultimately we are trying to arrive at a setup capable of power generation.

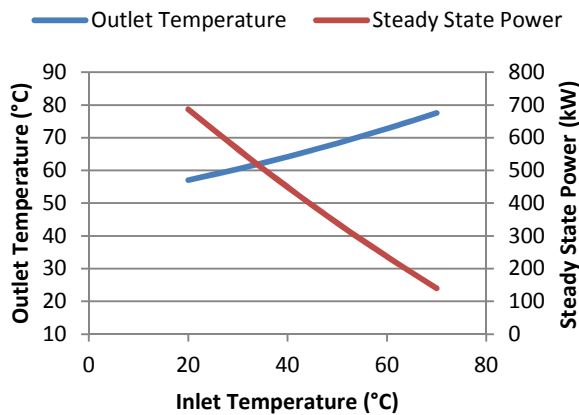


Figure 3- The effect of inlet temperature on outlet temperature and steady state power

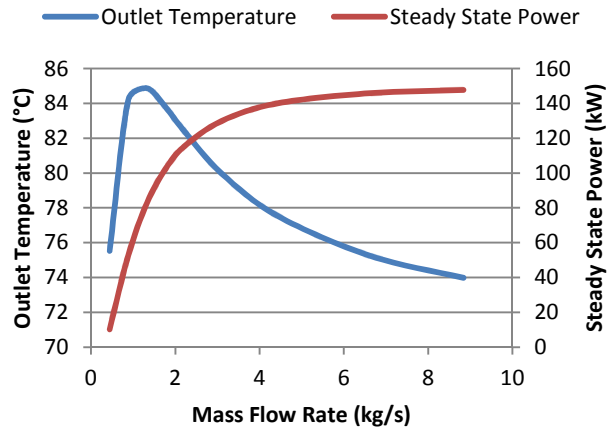


Figure 4- Effect of mass flow rate on outlet temperature and steady state power

A binary geothermal plant (i.e. Organic Rankine or Kalina cycle) can produce power from the modelled well, however, this single well would not produce much electricity. A better use of this well could be for direct heating, direct applications, and as a pre-heating component in a hybrid power plant (e.g. combined with solar, fossil fuel power plants, etc.). The lower outlet temperature demanded by heating applications would result in a significant increase of thermal power in the fluid. For example, heating could be accomplished with an inlet temperature of 20°C and a thermal power of 690 kW, compared to an inlet temperature of 70°C, needed for power

generation, with 130kW of thermal power (c.f. Figure 3). However, for direct heating to be feasible the resource well must be situated in proximity to the thermal demand/load.

The effect that the mass flow rate had on the system has to be taken into account in order to optimize the system. Figure 4 shows that the outlet temperature reaches a peak at 1.3 kg/s, and the steady state power gradually reaches an upper limit as the mass flow rate increases. The model used to generate Figure 4 did not have insulation present on the well casing because it was used as a proof of concept; however, the inner tube was insulated. Setting the inlet flow of an insulated shell and tube heat exchanger to 70°C and moving at 1.3 kg/s optimizes this scenario, by offering an outflow temperature high enough to produce power and by keeping a significant amount of power stored in the fluid. Further work can be done in order to constantly adjust the inlet temperature with regard to the amount of power needed, by fixing the temperature difference between the inlet and outlet temperatures. A steady output of power would be useful in providing baseline power to the power grid, and it would also serve to exploit the geothermal resource more efficiently by being more selective about how much power is extracted.

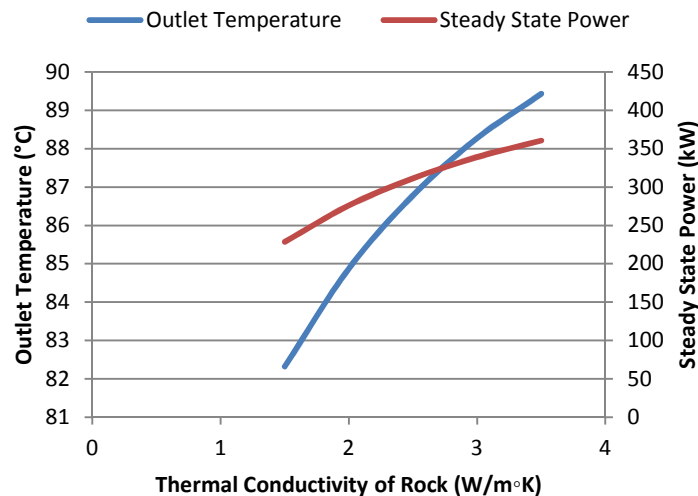


Figure 5- Effect of thermal conductivity of rock on the outlet temperature and steady state power

The thermal conductivity of sedimentary rocks varies, so a conservative value was used for the baseline scenario. Figure 5 shows how a resource occurring in rock with a higher thermal conductivity affects the outlet temperature and steady state power. The greater value of thermal conductivity for the rock mass will result in more heat flow for that specific resource, making resources with higher thermal conductivities more lucrative. Using a conservative estimate of \$0.06 per kilowatt hour for the price of electricity, the savings that can be accomplished by heating with geothermal energy will be in the range of \$329 up to \$519 per day (c.f. Figure 5). Over a six month period (i.e. typical cold season), an equivalent of \$94,458 of electric heating can be directly used from a geothermal system retrofitted to an abandoned well (inlet temperature of 70 °C). A lower inlet temperature will increase the amount of thermal power available to use for heating purposes, and therefore will provide more equivalent electric heating.

CONCLUSIONS

A heat transfer model for insulated shell and tube geothermal heat exchangers installed in abandoned oil wells was created with a closed loop design. Using a finite element modeller, the model was solved for many situations in order to simulate the performance of the shell and tube heat exchanger in an abandoned well. The insulation is added along the entire length of the inner tube, and to part of the length of the shell. The depth and geothermal gradient of the abandoned well was based on an abandoned onshore well in Persian Gulf. A sensitivity analysis was carried out on the inlet temperature and the mass flow rate, so as to find the optimal design parameters for power production. The optimum inlet temperature was found to be 70°C, and the optimum mass flow rate was determined to be 1.3 kg/s. With these properties the abandoned well was modelled to be able to produce an outlet temperature of 84°C and a steady state power of 80 kW. We used a conservative value of 2 W/m·K for the thermal

conductivity, and resources with higher thermal conductivities will produce higher outlet temperatures along with more steady state power.

The effectiveness of the shell and tube geothermal heat exchanger retrofitted to an abandoned petroleum well has been demonstrated with this model, and shown to be able to sustainably produce hot enough outlet temperatures for power generation. The trade-off from producing higher temperature outlet fluid is a smaller steady state power. However, power generation isn't the only use for this design and lower temperature water could be used for direct use heating applications. Depending on the immediacy of the thermal demand/load, direct heating may or may not be feasible. Supplying direct heating applications with this well has the potential to make use of a greater portion of the thermal power compared to producing electricity. Making use of the lower temperature outlet temperatures would allow more power be extracted from the resource, and insulation would not have to be applied to the well's casing.

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