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## Abandoned petroleum wells as sustainable sources of geothermal energy

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### ABSTRACT

A reliable heat transfer model was developed to determine the performance of a double pipe heat exchanger retrofitted to an abandoned petroleum well. The proposed model is compared against an analytical heat transfer model and two numerical models, in order to determine the reliability and accuracy of the proposed model. Rock mass properties and well dimensions are based on realistic averages, with the geothermal gradient and depth of the well based on an abandoned well in the Persian Gulf. The proposed model makes use Fourier's diffusion law coupled with terms to account for the unsteady state of the model and the convective heat transfer. These three properties are coupled with the energy conservation equation and simulated with the finite element modeller FlexPDE. The proposed model was developed with a constant inlet temperature and a constant power configuration. The constant inlet temperature model is used to ascertain the effects of insulation, inlet fluid temperature, mass flow rate, thermal conductivity of the rock mass, geothermal gradient, and vertical groundwater flow. The constant power model is better suited to direct use and heat pump applications due to the requirement of a stable power source.

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### 1. Introduction

Geothermal energy is a renewable energy source that is showing considerable potential due to the low impact on the environment, very low greenhouse gas emissions, and its ability to be extracted from all over the globe. Furthermore, geothermal energy provides a stable source of energy as it can be exploited regardless of meteorological conditions, while alternative types of renewable energies are dependent upon meteorological conditions and supply intermittent energy (e.g. solar, wind, tidal, etc.). Presently, the global installed geothermal energy production capacity has increased from 1300 MWe in 1975 to 10,715 MWe in 2010 [1].

Geothermal energy can be harnessed to provide thermal energy for direct use applications (e.g. agricultural drying, zinc and gold ore recovery, etc.), for space heating and cooling, and to generate electricity. Space heating and cooling can utilize geothermal energy directly (e.g. greenhouse heating [2]), or indirectly through the use of a heat pump (e.g. melting snow/ice from bridges and roads [3]). Additionally, space heating/cooling can be supplied by a horizontally oriented geothermal heat exchanger (e.g. Esen et al. [4]) so as

to further eliminate the high costs associated with drilling a borehole. Power generation with a binary cycle requires an outlet temperature of at least 74 °C [5], while other methods require significantly hotter outlet temperatures.

When petroleum reservoirs are depleted beyond an economically feasible point, the wells are abandoned, decommissioned, and reclaimed. Petroleum wells that access a reservoir containing an economically unfeasible type or amount of petroleum are also abandoned, and are referred to as "dry" wells. Abandoned petroleum wells are an enduring liability to the companies that drill them, as the specific company is responsible for the possible environmental contamination and litigation in the case of a failed decommissioning of a well.

Abandoned petroleum wells present an interesting opportunity to be retrofitted as a geothermal system as they are generally deep enough to access higher temperature strata of the earth. The depth of exploratory and production wells for crude oil and natural gas (including dry holes) drilled in the US during the period from 1949 to 2008, vary from 945 m up to 2560 m in depth [6]. This range of well depths is a good indicator of petroleum well depths worldwide as the US has sunk over 2.5 million petroleum wells since the 1950's and is the country with the highest rate of oil and gas drilling in the world [7].

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Repurposing an abandoned petroleum well for a geothermal project can reduce the capital costs of the project by up to 50% [1], as well as making a constructive use for an enduring liability. The capital costs for a geothermal project can be further diminished by employing a closed loop configuration (i.e. closed circuit of pipes), as it can be retrofitted to a single borehole. Alternatively, an open loop configuration requires at least two boreholes to operate, namely an injection well and an extraction well. Additionally, a closed loop system does not require a water management system, compared to a compulsory water management system for open loop configurations. Closed loop configurations will also necessitate a lower pumping power compared to an open loop configuration, due to the thermosiphon effect present in the closed system. Moreover, closed loop configurations have the advantageous option of using a non-aqueous fluid with a lower boiling point than water to increase the heat exchange with the earth.

Another important aspect of retrofitting abandoned wells is the availability of large amounts of thermophysical data that is logged and available on existing wells. This data can be used to ascertain which wells will provide the highest bottomhole temperature and which are in proximity to the demand for energy. Likewise, the data can also be used to define resources and conditions pertinent to designing a closed loop geothermal heat exchanger. Abandoned wells can even be redrilled, in order to access superior conditions and resources, at a lower cost than drilling a new well [8].

The majority of work that has been done on retrofitting abandoned petroleum wells as a source for geothermal energy has been focused on open loop systems that repurpose the petroleum reservoir as a geothermal reservoir. There are a multitude of countries that have sponsored research and/or work specific to adapting an open loop design to abandoned wells, including: Albania [9], China [10], Croatia [11], Hungary [12], Israel [9], New Zealand [13], Poland [14], and the US [15]. Further work has been carried out by Sanyal and Butler [16] on the effects of different parameters concerning the extraction of geothermal energy using an open loop system.

U-tube and double pipe heat exchangers are the focus of the research that has been carried out on closed loop systems retrofitted to abandoned petroleum wells. There is one paper that proposes a numerical model to determine the performance of a u-tube heat exchanger in an abandoned well, and it refers to the need to take into account the convective heat flow through the porous medium surrounding the borehole [17]. The few papers available concerning the design and performance of a double pipe system retrofitted to an abandoned well include: Davis and Michaelides [18], Bu et al. [1], and Kujawa et al. [19]. Alternatively, there are a plethora of papers concerning the design of u-tube and double pipe heat exchangers with new geothermal wells (e.g. Al-Khoury & Bonnier [20], Wang et al. [21], Garbai & Méhes [22], Zhongjian & Zheng [23]).

The paper by Kujawa et al. [19] examines the feasibility of retrofitting an existing deep production well with a closed loop double pipe heat exchanger to harness geothermal energy. The paper concludes that the flow rate, inlet fluid temperature, and insulation on the inner pipe have a significant influence on the performance of the heat exchanger. The model proposed by Kujawa et al. [19] simplifies the heat flow surrounding the borehole, by modelling a time dependent radius beyond which the influence of geothermal energy extraction is inconsequential. This assumption is an empirical simplification describing the heat transfer in the earth surrounding the borehole. Davis and Michaelides [18] propose a model to explore the feasibility of power production using geothermal power obtained from an abandoned oil well. Their double pipe heat exchanger uses an organic fluid in lieu of water. The simulations consider the effects of the temperature of the well,

injection pressure, and flow rate of the organic working fluid. Davis and Michaelides' [18] model assumes that the ground temperature is not transient which therefore results in an overestimation of the power production capacity. The model proposed by Bu et al. [1] examines the potential effects of the working fluid's flow rate and the geothermal gradient on the heat extraction and potential power generation of a double pipe heat exchanger (closed loop) retrofitted to an abandoned petroleum well. Both Davis and Michaelides [18] and Bu et al. [1] simplify the convective heat transfer coefficient they employ by making use of the Dittus–Boelter correlation [24]. The Dittus–Boelter relation was designed for smooth isothermal tubes (i.e. exhibiting constant heat flux through the tube walls), and loses accuracy when there is a large temperature difference. The Dittus–Boelter correlation is inapplicable to scenarios where the temperature of the tube wall is transient due to the simplifications assumed in the derivation of the correlation. Moreover, the Dittus–Boelter correlation was not designed to be applied to heat transfer through an annulus, so there will be inherent uncertainty in the results obtained by Davis and Michaelides [18] and Bu et al. [1].

Double pipe heat exchangers boast the advantages of having a higher surface area to exchange heat and containing a higher volume of fluid through which to exchange heat, over u-tube heat exchangers. Retrofitting a double pipe heat exchanger to an abandoned well will also require less pumping energy and significantly less grout compared to adapting a u-tube heat exchanger to an abandoned well. The double pipe design's higher cross sectional area means that for an identical flow rate the fluid velocity will be lower compared to a u-tube design. A lower fluid velocity requires less hydraulic pressure to circulate the fluid, resulting in a lower amount of pumping energy. The double pipe design requires enough grout to seal the bottom of the well, whereas the u-tube design necessitates a large volume of grout to facilitate the heat transfer from the surrounding rock mass.

The purpose of this study is to develop a reliable model in order to simulate the heat transfer through the surrounding rock mass to the heat exchanger, as well as the heat transfer occurring inside of the double pipe heat exchanger. Additionally, this model will be used to demonstrate the feasibility of extracting geothermal energy from abandoned petroleum wells. To accomplish this, the effects of using an insulation jacket and variable versus constant rates of heat loading will be carried out. Also, in order to attain a sustainable rate of heat extraction over the long term the effect of the heat extraction rate on the outlet fluid temperature is studied.

## 2. Model description

This model proposes using a closed loop heat exchanger based on a double pipe design. The configuration of the double pipe is that the water is pumped downwards through the outer annulus, and returned to surface through an insulated inner pipe. The double pipe design was adopted instead of a u-tube arrangement because of the higher cross sectional area that can be used for fluid flow (i.e. efficient use of the volume within the borehole). Assuming that the heat transfer through the rock mass to the heat exchanger is controlled by conduction, Fourier's three dimensional diffusion law (c.f. Equation (1)) can be used to describe the heat conduction throughout the model.

$$\vec{q} = -k\nabla T \quad (1)$$

where  $\vec{q}$  is the heat flux vector,  $k$  is the thermal conductivity, and  $T$  is the temperature at any given point within the model. Equation (1) can be incorporated into the energy conservation equation to generate the partial differential equation necessary to accurately

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