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Study of effective solar energy storage using a double pipe geothermal heat exchanger

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ABSTRACT

A reliable transient heat transfer model is used to ascertain the effect of solar thermal energy storage on a geothermal system. The proposed closed loop system is comprised of a double pipe heat exchanger, and is supplied with solar thermal energy during the summer months. The numerical simulations are based on cases that are common in northern climates (e.g. Canada). A conduction-advection based model is used to simulate heat transfer in the ground and in the heat exchange pipes for both heat extraction and heat injection scenarios. The constant power configuration is employed to accurately assess the effects of injecting thermal energy into a geothermal resource. The mass flow rate through the heat exchanger and the solar energy input are varied during summer cycles to investigate the influence on the uptake of thermal energy into the geothermal resource. The effects of rate of heat extraction and injection on the techno-economic performance of geothermal energy production have been investigated.

1. Introduction

The earth is plentiful with thermal energy waiting to be harnessed for human needs, assuming an average geothermal gradient of 25 °C/km, only 0.1% of the earth has a temperature below 100 °C [1]. This energy can be harnessed/stored as geothermal energy in many different ways. Currently, geothermal energy is gaining considerable attention due to its renewable nature, low environmental impact, independence from meteorological conditions, as well as its global accessibility. Geothermal energy is supplied at a relatively constant rate from the interior of the lithosphere, and is therefore recognized as a renewable source of energy. The independence of geothermal energy from meteorological conditions offers an important advantage over other types of renewable energies (e.g. solar, tidal, wind, etc.). From the period covering 1975 up until 2013, global installed geothermal capacity has increased from 1300 MWe to 11,765 MWe [2,3].

The energy harnessed from geothermal resources can be manipulated to provide power generation, heating/cooling with a heat pump, and a bevy of direct-use applications. Heating and cooling can be supplied by both indirect (i.e. heat pumps) and direct applications of geothermal energy. In Canada, residential space heating and hot water comprises 80% of the total energy consumed by the residential sector, with the residential sector accounting for 17% of the country's total energy demands [4]. Higher latitude countries would be expected to have similar heating needs, and geothermal heat pumps are an environmentally viable alternative to using electricity for heating.

Drilling a geothermal borehole is a risky and capital intensive enterprise, contributing up to 50% of the cost of the entire geothermal project [2]. By making use of seasonal thermal storage in the borehole, the productivity of the geothermal resource can be augmented without sacrificing sustainability. Seasonal thermal storage involves the injection of thermal energy to the geothermal system, so that the temperature of the geothermal resource can be supplemented for future use. The injected thermal energy can come from a solar collector, industrial waste heat, and/or various other sources in order to provide an extremely adaptable design. By storing thermal energy in the geothermal resource, there is the possibility of utilizing shorter boreholes or a higher rate of extraction from the borehole and a reduction of the influence on surrounding geothermal boreholes.

The idea of combining solar collectors and geothermal heat pumps was first proposed by Penrod in 1956 [5]. During the late 1970's two case studies were carried out within the United States [6]. During the 1980's, solar assisted geothermal research was

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concentrated to three conferences held in Ispra, Vienna [7], and Gothenburg [8–11]. The main conclusion reached from the aggregation of these three conferences is that it is economically advantageous to drill deeper boreholes rather than try to recharge the geothermal resource using solar energy. During the 1990's progress with solar coupled geothermal systems was limited to Germany [12,13], Austria [14], and Switzerland [15]. The projects developed during the 90's were experimental-based with the solar heated water used primarily as a supply for domestic hot water demand, and secondarily for recharging geothermal boreholes. Progress during the 2000's was fuelled by participation from Sweden, Germany [16], France, and Canada. SERC (Solar Energy Research Center at the University of Dalarna, Sweden) conducted research wherein a low temperature solar collector was developed in the test facility, an evaluation of the five Swedish systems available on the market was conducted [17], computer simulations were run using the TRNSYS (Transient System Simulation Tool) software [18], and the assessmentof a field test was conducted in Uppsala [19]. Additionally, there is a project in Anneberg, Sweden involving the heating of 50 residential units with solar collectors and geothermal boreholes (also used for thermal storage) [20]. The project in Anneberg has technical issues with leakage and instituting the heat pumps [21,22]. Furthermore, many Swedish single family dwellings have been outfitted with small solar assisted geothermal systems since 2000, but their diversity has stalled performance measurements and evaluations [23]. In France, Trillat-Berdal et al. analysed a solar-geothermal system that provided space heating/cooling and domestic hot water to a single family residence of 180 m^2 [24]. The Drake Landing Solar Community Project in Okotoks, Alberta consists of a community of 52 detached houses utilizing solar and geothermal energy for heating and seasonal thermal storage; and will reach above a 90% solar fraction after a few years of operation [25,26]. There has also been much research into numerically simulating the heat exchange associated with solar-geothermal systems [27–32]. According to Trillat-Berdal et al. [32], solar rejuvenation of a lone borehole for a single house is hardly justifiable as the energy consumption over 20 years is improved by only 3%. These results are shared by Bernier and Salim Shirazi who similarly conclude that there is no significant advantage to injecting solar energy into a single borehole [33].

Thermal energy storage can be attained by ground diffusive storage, earth storage, aquifer storage, and water storage. The principal heat transfer mechanism involved in the ground diffusive storage method is conduction, as the storage medium is the ground itself. Ground diffusive storage is normally realized with a vertical borehole heat exchanger (a.k.a. borehole thermal energy storage), and can command a very large volume of ground. Thermal storage supplied by solar energy is an attractive renewable option; however it does have some limitations. Firstly, a thermal store that is of a high temperature will result in a relatively high temperature fluid entering the solar collectors, thereby decreasing the efficiency of the solar collector (i.e. decreased thermal gradient). Secondly, heat losses from a high temperature energy storage system are relatively large, representing approximately 60% of the injected thermal energy [26]. The upper limit imposed on the ground diffusive storage does not mean that it is ineffective, merely that the average borehole storage temperature should be at a level that is close to the annual ambient temperature [27,28].

2. Model description

This model is a numerical representation of the heat transfer mechanisms that take place within a closed loop double pipe heat exchanger. The configuration of the double pipe heat exchanger is set so that the working fluid is pumped downwards through the annulus, and returned to the surface through the insulated inner pipe. A double pipe design was used in lieu of a u-tube configuration due to the higher surface area that the working fluid has to transfer heat through, as well as the capability of a higher mass flow rate. The model is based on that developed by Templeton et al. [34], which is validated by comparison with the analytical one-dimensional cylindrical source model as well as the numerical models developed by Kujawa et al. [35] and Bu et al. [2].

It is assumed that the heat transfer through the rock mass is dominated by conduction, so Fourier's three-dimensional diffusion should be employed for heat transfer inside the ground. However, there is also convective heat transfer occurring within the double pipe heat exchanger, so a more complex partial differential equation is developed. The energy conservation equation (c.f. Equation (1)) can incorporate the different heat transfer mechanisms, automatically balance the heat transfer between the borehole and the ground, and generate an equation that will accurately represent the heat flow. The left hand side of Equation (1) is the equivalent of Fourier's diffusion law in cylindrical coordinates. The advantage of converting to cylindrical coordinates is that the physical geometry can be described in two-dimensions, due to the symmetry about the z-axis (c.f. Fig. 1). Because of the axisymmetric nature of the model, the Θ (i.e. angular) components become zero-terms. The first term on the right side of Equation (1) is transient and accounts for the unsteady state heat transfer due to the flowing water within the heat exchanger. Subsequently, the second term on the right side of Equation (1) represents the advective and conductive effects of the working fluid within the heat exchanger.

$$\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)=\rho C_p\frac{\partial T}{\partial t}+\rho_{fluid}C_{p,fluid}U_z\frac{\partial T}{\partial z} \qquad (1)$$

where r is the radial coordinate, z is the vertical coordinate, T is the temperature at any given point within the model, k is the thermal conductivity, ρ is the density, C_p is the specific heat, and U_z is the velocity of water (uniform velocity profile). The specific values attributed to the variables in Equation (1) are dependent on the domain being evaluated (i.e. the density for the soil domain is different than the density of the fluid within the heat exchanger). For the purpose of this research, the U_z component is non-zero only within the borehole heat exchanger (i.e. positive U_z for fluid rising

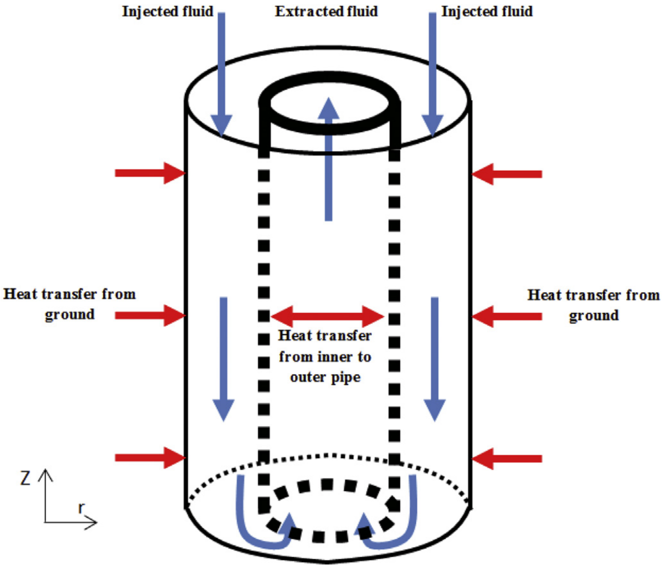

Fig. 1. Heat transfer through a closed loop double pipe heat exchanger.