Assessment of the footprint area required for heat extraction from borehole heat exchanger

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Abstract

Your abstract.

1 Introduction

With the growing interest in geothermal energy for domestic heating and cooling, borehole heat exchanger (BHEs) coupled ground source heat pump (GSHP) systems have been increasingly used worldwide (Chen et al., 2019). Shallow geothermal resources (<200m) are generally accessed using closed-loop system composed of single or multiple shallow vertical boreholes consisting of U-shaped tubes. During a heating cycle, a carrier fluid circulates through the loop of the heat exchanger and absorbs heat from the ground. The space between the borehole wall and the U-tubes is filled with grout material that ensures the good transmission of heat between the ground and the heat exchanger tubes (Bouhacina et al., 2015). Heat pumps are used to increase the temperature of the fluid and deliver the necessary heat load to the building. During a cooling cycle, the process is reversed and heat from the building is reinjected into the ground (Stylianou et al., 2017). Deeper boreholes (i.e. up to 2 km deep) allow accessing higher temperature found at greater depth according to the geothermal gradient. Using coaxial pipe BHE, the accessed heat can generally be directly used for cooling/heating buildings, without using heat pumps (Mottaghy and Dijkshoorn, 2012).

To support the design of GSHP systems, many studies have focused on evaluating the system performances (i.e. heat exchange rate between the soil and the BHE), its thermal response over time and the sustainability of heat extraction (i.e. how long can the outflow temperature be maintained for a specific extraction rate) depending on surrounding rock thermal properties and the required heat load. Chen et al. (2019) investigated the impact of grout, soil and pipe thermal conductivity, geothermal gradient and specific heat extraction rates, on the performance of the BHE system (i.e. change in outflow temperature over time) using the OpenGeoSys software. Results shows that the soil thermal conductivity is the most important parameter determining the system performance and that the main energy source for BHEs system is the heat stored in the soil. BHE-GSHP systems are generally assumed to last for a period of 30 years, knowing that the system will be constrained by lower temperature of the circulating fluid in the long term (Chen et al., 2019). Using an average geothermal gradient of 0.03 °C/m, a sustainable specific heat extraction rate of 100 W/m at the maximum was calculated (WHERE???). Following a sudden decrease in temperature during the first year, a quasi steady-state outflow temperature of 17.2 °C was reached after 20 years, indicating that the equilibrium between the heat extraction and recovery in the subsurface was reached. If the heat extraction rate is increased to 125 W/m, the minimum outflow temperature approached 0 °C reached after about 20 years of operation.

Lee and Lam (XXX) and Biglarian et al. (2017) analyzed the change in ground temperature away from the borehole after 10 years under a heat load of 4000 W. However, there is still a few studies focusing on the extent of heat depletion caused by a constant heat load extraction by heat exchangers. We here attempt to estimate the footprint area of extraction of a heat for a single house in the UK, and compare it to the available recharge to assess the sustainability of BHE-GSHP systems from the heat resource perspective.

2 Mathematical models

2.1 Energy consumption

The average energy consumption for a single house in the UK is 12 400 kWh per year, with a maximum of 18 000 kWh in winter and 8 000 kWh in summer. To satisfy this yearly demand, a heat pump would need to deliver an average heat load of 1415 W by extracting heat from the underground. This represents a total energy of $4.47 \times 10^{10} J$ over a year. In reality, the total heat load H delivered by a heat pump corresponds to the sum of the heat extracted from the ground G and the electric heat E required for air compression (Banks, 2008).

$$H = G + E$$

The coefficient of performances (COP) of GSHP is generally used to characterize the efficiency of the system. It can be used to calculate the total heat delivered by the heat pump H as a function of the electrical power E provided.

$$COP = \frac{H}{E}$$

Using an average COP of 3.4, the average heat that would need to be extracted from the ground to satisfy a heat demand of 1415 W is therefore:

$$G = H(1 - \frac{1}{COP}) = 1000W$$

This corresponds to a total energy of $3.16 \times 10^{10} J$ over a year. Considering a 40 m long borehole heat exchanger, the specific heat absorption from the rock (as defined in Banks, 2008) would here be 25 W/m.

The total heat content of a rock mass can be estimated using the Eq. XXX.

$$Q = \rho_r V c \Delta T$$

with ρ_r the rock density, V the volume of the rock mass, c the specific heat capacity and ΔT the temperature change across the heat exchanger. Assuming ρ_r = 2650 Kg.m^{-3}, c = 950 J.kg^{-1}K^{-1} and ΔT = 5°C, the volume of rock required to provide a total heat load Q = 4.47 $\times 10^{10}$ J (i.e. energy for one year) is about 3700 m^3. Assuming that the heat is extracted radially from a borehole with a length h = 40 m situated in the center of a cylindrical volume, the radius of the cylinder would be about 5 m, corresponding to a surface area of 93 m^2. For Q = 3.15 $\times 10^{10}$ J, the required volume is about 2500 m^3, which corresponds to an area of about 63 m^2 (i.e. cylinder radius of 4.5 m).

GSHP are generally designed to cover 60% of the peak heat demand. Assuming that a 3000 W heat pump is used to cover for the peak heat demand of a single 90 m2 house, which generally averages 5000 W (i.e. energy flux of 56 $W.m^{-2}$), the actual specific thermal output for a 40 m long borehole would be 75 W/m. Using a COP = 3.4, the specific peak heat absorption from the rock, calculated using equation XXX, would instead equals 53 W/m (Banks, 2008).

2.2 Heat recharge

Alternatively, we can calculate the surface area that would be required to provide heat recharge to the BHE system. In the early stage of production, heat extraction from the ground will is expected to create a zone of depressed temperature around the borehole, leading to radial conduction of the heat stored in surrounding rocks toward the BHE. Over time, the cooling of the area will induce an increasing heat flow of solar energy from the surface that will eventually be balanced with the heat abstracted (Banks, 2008). The magnitude of this flow is a function of the temperature gradient between the ground temperature and the annual average surface temperature. Sustainable heat extraction can be reached over time if the heat load extracted is balanced by the rate of heat recharge.

We first assume that the heat is extracted from a vertical one-dimensional BHE and that recharge occurs from above (i.e. heat flux generated from solar energy) and below (i.e. geothermal heat flux). Where ground temperature has not been disturbed by heat production, heat conduction from or toward the surface depends on the effective surface temperature relative to the sub-surface temperature. In the shallow sub-surface, ground temperature is generally assumed to be equal to the mean annual air temperature. During winter, the ground temperature is higher than the average air temperature, and thus, the heat flux is directed from the ground toward the surface. In summer, the ground is colder than the air temperature and thus the heat flux is reversed, recharging the ground with heat.

The effective surface temperature depends on a complex combination of several factors, such as the amount of solar shortwave radiations, longwave radiations emitted from the ground or wind speed (i.e. convective heat flux from the air to the ground surface), that will impact daily/yearly heat recharge from the surface. Despite heat transfers to the ground can be affected by precipitation, water infiltration and evapo-transpiration processes, Fig 1 shows that shallow subsurface temperature tends to roughly follow the trend of the air temperature on a daily basis. Below a certain depth, the ground temperature is however no longer influenced by the yearly changes in surface temperature and tends to follow the local geothermal gradient.

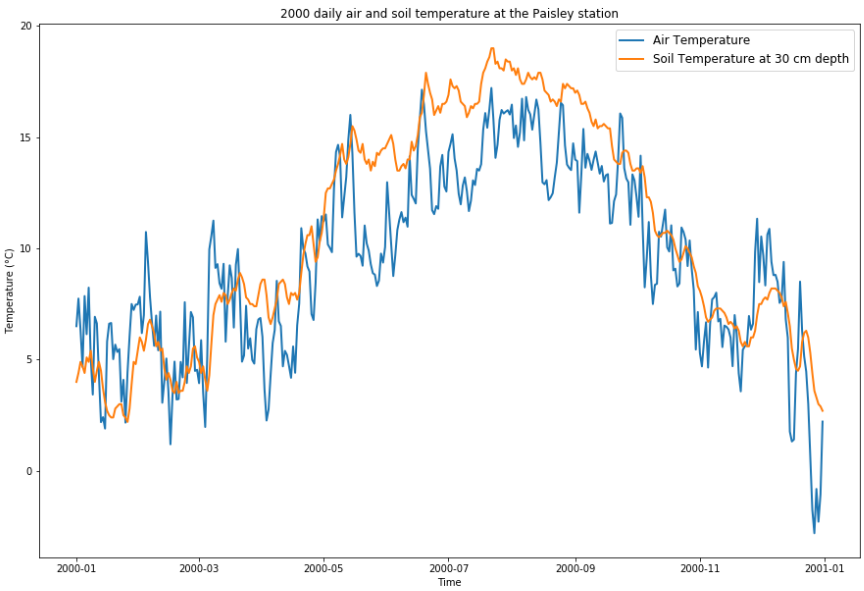

Figure 1: Daily air temperature and soil temperature measured at 30 cm depth at the Paisley station, Glasgow area, in 2000

If we assume a geothermal heat flux of 0.06 W.m^2 and a solar heat flux allowing a recharge of 6 W.m^2 (XXX) half of the year, the area required to provide the necessary recharge to the BHE is about 330 m^2 (see Eq. XXX).

$$Area = \frac{1000W}{0.06 + 6 \times \frac{1}{2} W.m^{-2}} = 330m^2$$

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2.3 Heat mining

We then assume that heat extraction from BHE induces lateral heat flow from surrounding rock. Based on the estimated 63 m^2 footprint area required for heat consumption for one year, the geothermal heat flux and solar heat flux would contribute up to $0.06 \times 63 = 4W$ and $6 \times \frac{1}{2} \times 63 = 190W$ to the total heat recharge, respectively. That means that about 800 W will be mined from surrounding rocks. Assuming a borehole length of 40 m and a perimeter of 28 m (2πr with r=4.5m), the lateral heat flux would be in the order of 0.7 W.m^{-2} 2.

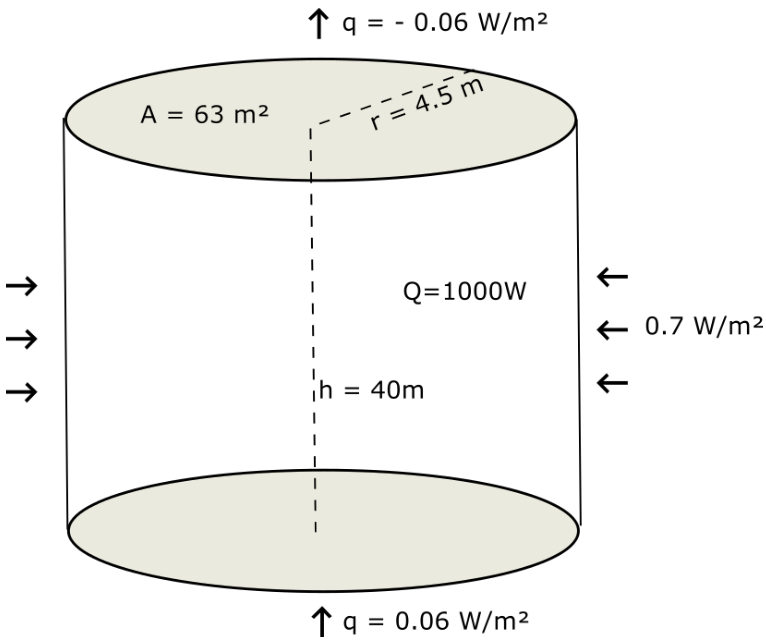

Figure 2: Conceptual model for the BHE with induced heat flux

3 Numerical approach

We use the OpenGeosys finite element modelling software to simulate the change in temperature within a volume under heat extraction and evaluate the impact of the recharge rate/parameters and available surface area on the temperature decline. We consider the borehole heat exchanger as a one-dimensional finite-element model consisting of a vertical line source composed of 4000 elements of 0.1 m in length. The BHE is treated as a homogeneous porous medium with a thermal expansion of $1 \times 10^{-5} {}^{\circ}C^{-1}$, specific heat capacity of 950 J/Kg.K and thermal conductivity of 3.0 W/m.K. The initial temperature distribution through the vertical line is defined by a geothermal gradient of 0.02 °C/m, corresponding to a surface temperature $T_0 = 7°C$ and a bottom temperature $T_z = 15°C$ at z = 400 m depth. Natural steady state conditions were calculated using constant top and bottom heat flux boundaries of -0.06 and 0.06 W/m2, respectively. Those are assumed to represent the geothermal heat flux entering the model from below, flowing through the BHE and coming out at the surface. They were defined accordingly to the geothermal gradient and the thermal conductivity, using Eq. XXX.

$$q = K\frac{dT}{dx}$$

In the long term, it is assumed that the flux coming in is equal to the flux coming out of the system through purely conductive heat transfers. A first simulation was run to ensure that the geothermal gradient within the model remains stable over a total duration of 30 years, using the constant heat flux boundaries.

We then use a series of transient simulations to determine the amplitude of the variations in the surface heat flux required to reproduce the change in surface temperature observed in Scotland. The average yearly temperature change in east Scotland is calculated from the data available on the UK Meteorological Office website. The mean annual temperature over the 1910-2019 period is 7°C, with a mean winter temperature of 2°C and a mean summer temperatures of 12 °C. Simulations are run using a series of different heat flux variations at the upper boundary. The yearly fluctuations in the surface heat flux are approximated using equation XXX,

$$-Asin(2\pi * \frac{\Delta t}{t}) - q$$

with A the amplitude of the variations, Δt the time increment (days), t the total duration (365 days x 30 years) and $q = 0.06$ W/m2 the geothermal flux from below.

Using an initial surface temperature of 7°C and values of amplitudes A ranging from 0.01 to 10 W/m2, we find that the expected yearly surface temperature changes can be simulated for $A =$ 6 W/m2 (Fig. 3.a). The change in the subsurface temperature under the effect of the fluctuating heat flux is simulated for a period of 20 years. Following a slight increase in the yearly average surface temperature, a fluctuating stead-steady temperature is reached at the surface after a period of about 9 years (Fig. 3.b). From there, it is assumed that the temperature profile is stable and no longer affected by the initial conditions. Thus, the output temperature profile from this simulation is used as initial conditions for the subsequent simulations.

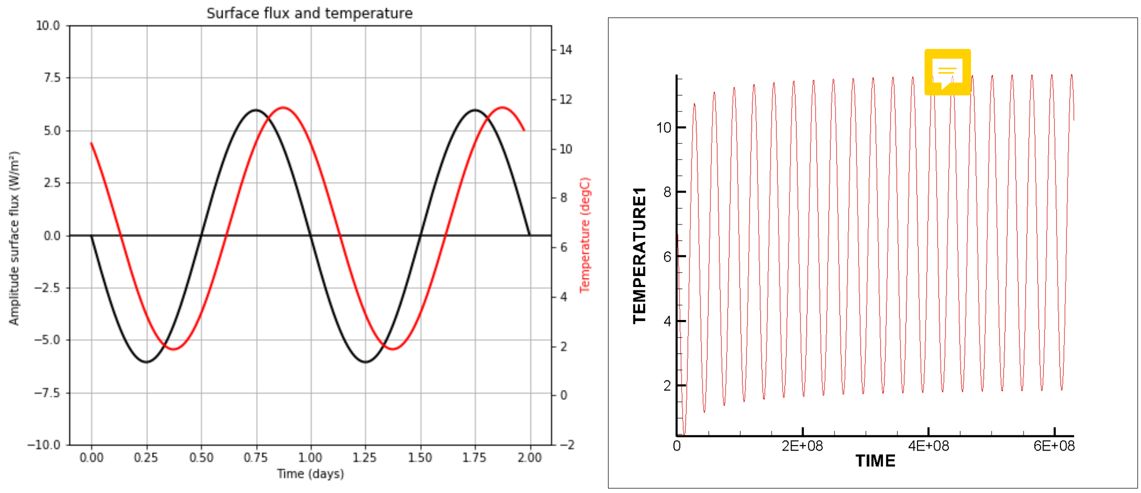

Figure 3: a) Surface heat flux input and resulting surface temperature change. The negative flux indicate flux from the ground to the surface (winter) and positive flux from the surface to the ground (summer) b) Temperature variation at the surface due to variation in the surface flux for 20 years

Temperature profiles displayed in Fig 4 shows that the impact of fluctuating surface heat flux does not extent further down to 27 m deep, where the average temperature is 7.4°C all year long.

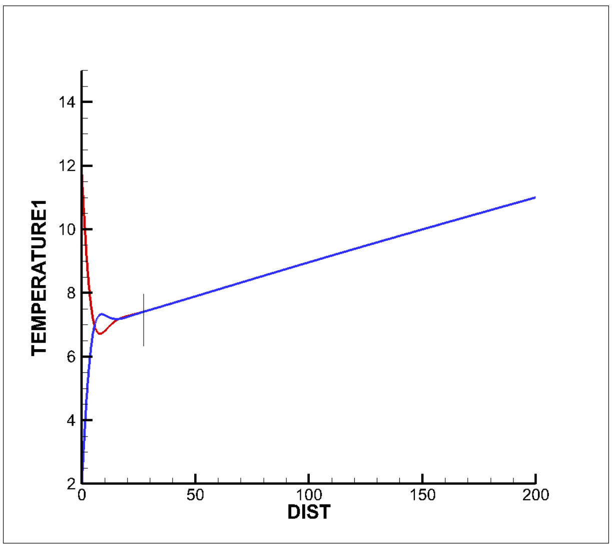

Figure 4: a. Winter (blue) and summer (red) temperature profiles

We then simulate the change in temperature in the rock mass over time due to heat extraction, using purely diffusive heat transfers within a porous medium. Heat is extracted from a BHE situated between 80 and 120 m depth. Two heat extraction scenarios that satisfy the thermal load of a single house are compared.

The first scenario assumes constant heat extraction of -1000W along the BHE. The second scenario considers seasonal heat extractions, which corresponds to a fluctuating source term, with a minimum of -1294 W in winter and a maximum of -706 W in summer, distributed along the 40m long BHE. The total heat load is calculated using Eq. XXX, with $A = 294$ W, the amplitude of the variations and $q = 1000$ W the average year heat load extraction (Fig. 5).

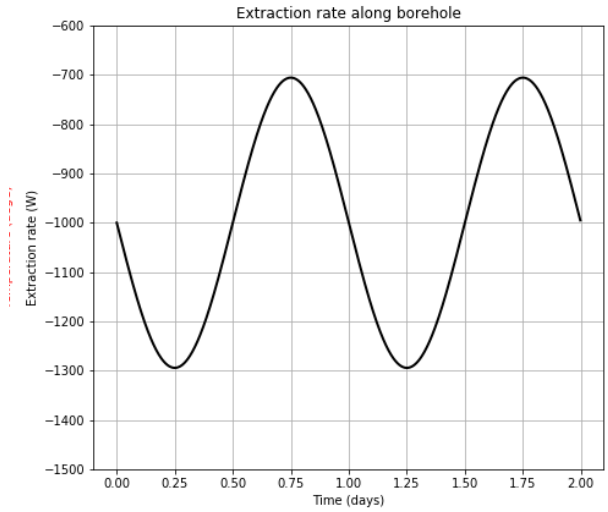

Figure 5: seasonal extraction

In addition, specific geometric areas of 200, 350 and 600 m2 are attributed to the line source. For each case, the solar and geothermal heat flux are scaled up appropriately and simulations are performed for constant and fluctuating extraction rates. After 30 years of extraction, similar temperature profiles are obtained for both scenarios, indicating that average yearly extraction rate is representative of a fluctuating extraction rate around this average (Fig. 6).

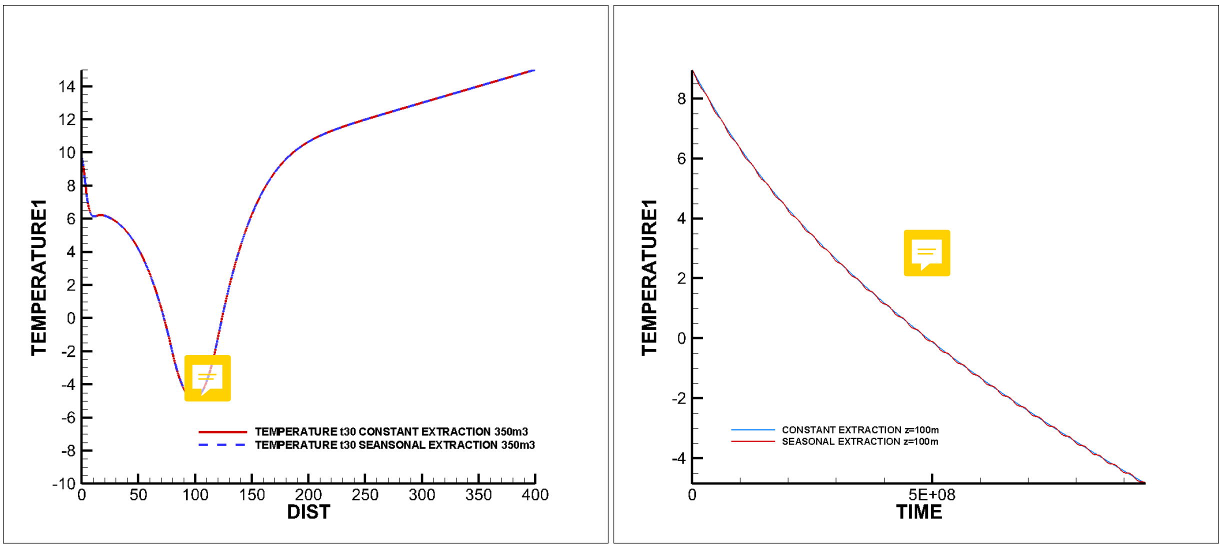

Figure 6: a) Temperature profiles and b) temperature changes at 100 m depth, after 30 years under constant and seasonal extraction (350 m2 line source)

Temperature profiles after 1 year and 30 years of production are therefore shown for a constant extraction rate in Fig. 7 for each line source area. In this vertical 1D model, recharge is assumed to occur only from the surface (half of the year, when the extraction rate is the lowest) and from below (all year long). However, as no lateral heat flux is allowed, no recharge occurs from neighboring areas. Thus, 1D models tend to overestimate the temperature decline and represent a most pessimist case. –> Coincides with mathematical model?

Additional simulations are made in order to assess the impact of different boundary conditions on the final temperature profile, using a constant surface and bottom temperature of 7 and 15

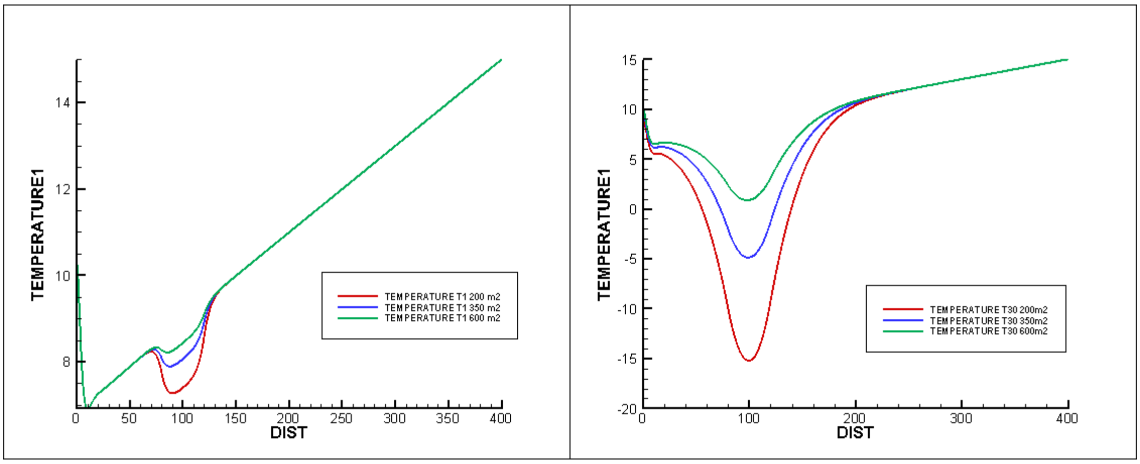

Figure 7: Temperature profiles after a) 1 year and b) 30 years, for a constant extraction rate of -1000 W

°C, respectively, a constant flux of -0.06 W/m2 and the seasonally fluctuating surface heat flux. Fig. 8 shows the temperature profiles for each scenario using a line source area of 350 m2, after a production period of 30 years, together with the temperature time series at a depth of 0 and 100m. As the BHE is located below the depth of influence of yearly solar variations, the temperature change at 100 m is not impacted by the surface boundary conditions. However, after about 15 years, the ground surface temperature starts to decrease due to the extension of the thickness of rock depleted in heat.

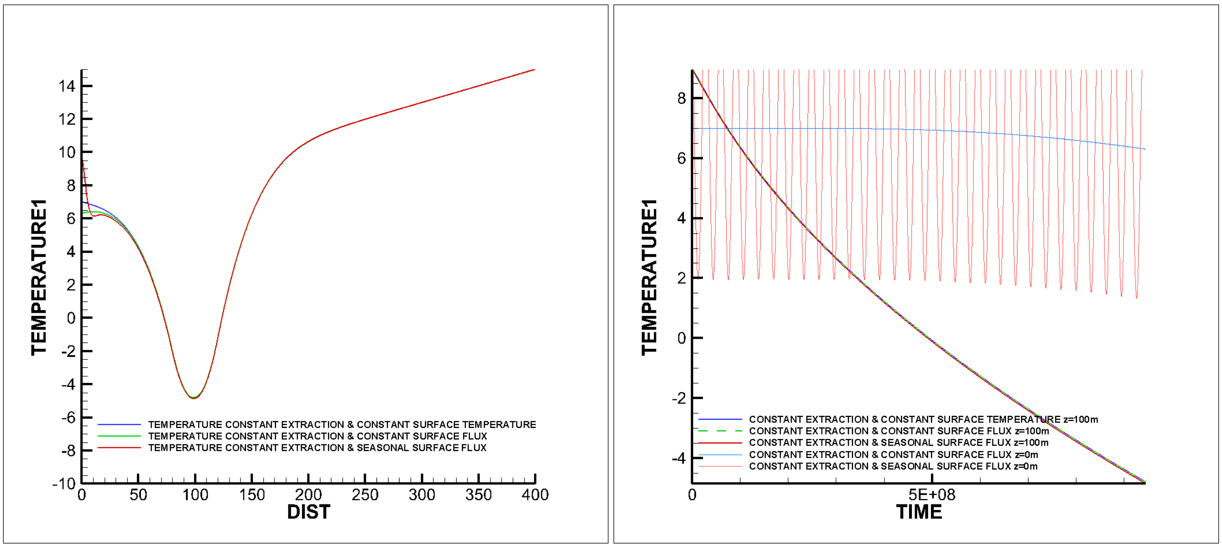

Figure 8: a. Temperature profiles and b. Temperature change at 0 and 100m depth for or different boundary conditions.

We finally assess the impact of the length of the BHE on the final temperature and the temperature distribution within the line source. By dividing the borehole size by two (i.e. extends from 80 to 100 m depth), the specific specific heat absorption of the BHE is increased by two (increases from 25 to 50 W/m). Simulations for a constant and seasonal extraction rates are done for a constant surface heat flux and results are displayed in Fig. 9. Results show that reducing the BHE length tends to increase the temperature decrease of the rock mass while maintaining the same thickness of rock affected after 30 years.

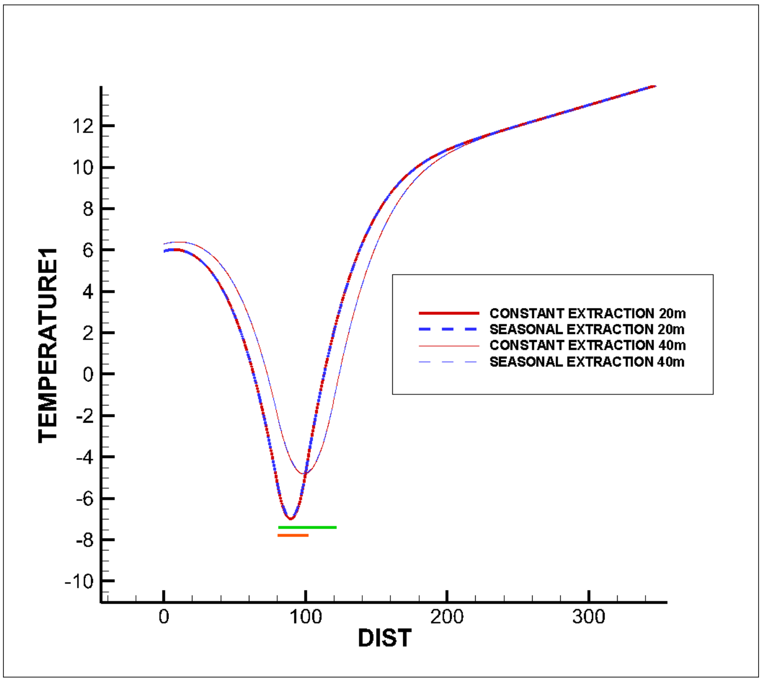

Figure 9: Temperature profile for a constant and seasonal extraction rate for 20m (orange) and 40m (green) long BHE after 30 years of production.

4 Conclusion

Shallow geothermal energy is described as a renewable energy resource but need large area to allow sufficient recharge. Vertical heat flux toward extraction zone increases over time, whilst the depleted area increases in depth, but need 3D model to assess lateral heat recharge. Deeper / longer borehole better to avoid depleting heat stored in shallow subsurface. Need to add GW flow?

5 Supplementary Material

5.1 Personal notes - solutions of heat equation

The analytical solution for temperature change in a semi-infinite half space under periodic heating / seasonal change in temperature $T_s = T_0 + \Delta T cos(wt)$ (Turcotte and Schuber, XXX) is:

$$T = T_0 + \Delta T + \exp{(-y\sqrt{\frac{w}{2\alpha}})} cos(wt - y\sqrt{\frac{w}{2\alpha}})$$

with $w = \frac{2\pi}{\Theta}$.

For a instantaneous cooling / heating of a semi-infinite half-space, where a constant temperature T_0 is applied on the top boundary condition of a domain of initial temperature T_1, with $T_1 < T_0$, the temperature profile or temperature change can be calculated at a time t or distance z from the boundary using the following equation (Dirichlet heat conduction problem, with q = 0 on the lower boundary):

$$T = T_1 + (T_0 - T_1) erfc(\frac{z}{\sqrt{4\alpha t}})$$

with $erfc$ the complementary error function and $\alpha = \frac{\lambda}{c\rho}$ the thermal diffusivity (m2/s).

In case of a heat flux boundary condition, the change in temperature on the surface T_s and at a distance z, T_z in the half space can be defined as follow (using $T \rightarrow T_1$ as $y \rightarrow \infty$):

$$T_y = T_1 + \frac{2q_0}{k}(\sqrt{\frac{\alpha t}{\pi}} \exp{(\frac{-z^2}{4\alpha t})} - \frac{z}{2} erfc\frac{z}{\sqrt{4\alpha t}})$$

and

$$T_s = T_1 + \frac{2q_0}{k}\sqrt{\frac{\alpha t}{\pi}}$$

The temperature field around a line source model with constant injection rate q can be written as a function depending on time t and radius r (Carlslaw and Jaeger 1959). The heat transfer is dominated by conduction (i.e. heat diffusion), with no groundwater flow.

$$\Delta T = \frac{q_0}{4\pi\lambda} E_1 \frac{r^2}{4\alpha t}$$

with q_0 the extraction rate on the BHE (i.e. the quantity of heat produced per unit time and unit length of the line source in W/m or J/m.s). r represents the radial distance from the center of the coordinate system or the line source/heater (m), ΔT is the temperature difference between the measured temperature and the background temperature at a radial distance r away from the line heater at time t, and E_1 is the exponential integral function. The solution proposed by XXX suggest an approximation of the exponential integral function for large values of $\frac{\alpha t}{r^2}$, resulting in the following equation:

$$\Delta T = \frac{q_0}{4\pi\lambda} ln(\frac{4\alpha t}{r^2}) - \theta$$

With θ the Euler's constant = 0.5772.

For an instantaneous heat-pulse applied to an infinite line source in a homogeneous and isotropic medium at a uniform initial temperature (Carslaw Jaeger, 1959):

$$\Delta T = \frac{Q}{4\pi\alpha t} exp(\frac{-r^2}{4\alpha t})$$

Q is the finite quantity of heat liberated by the line source (m^2C), as $Q = \frac{q}{\rho c}$, with q the quantity of heat liberated per unit length of heater (J/m).

Marshall (1958) proposed the following analytical solution for the application of an instantaneous line source of heat along the z-axis in an isotropic medium:

$$\Delta T = \frac{Q}{4\pi\alpha t} exp(\frac{(x - V_h t)^2 + y^2}{4\alpha t})$$

with ΔT the difference between the temperature at position (x, y) before application of the heat-pulse and a time t (s) after application of the heat pulse, Q (K m2) defined as the temperature to which the amount of heat liberated per unit length of the line would raise a unit volume of the substance, D the thermal diffusivity (m2/s),and Vh the heat pulse velocity (m/s).

Benchmarks: The equation for a constant boundary condition:

$$(erfc(\frac{x - vt}{\sqrt{4\alpha t}}) + \exp(\frac{xv}{\alpha}) * erfc(\frac{x + vt}{\sqrt{4\alpha t}}) * \frac{T_0}{2}$$

The solution for a pulse equation:

$$(erfc(\frac{x - v(t + \Delta t)}{\sqrt{4\alpha(t + \Delta t)}}) + \exp(\frac{xv}{\alpha}) * erfc(\frac{x + v(t + \Delta t)}{\sqrt{4\alpha(t + \Delta t)}}) * \frac{T_0}{2}$$

References