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Performance Analyses of Deep Closed-loop U-shaped Heat Exchanger System with a Long Horizontal Extension

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ABSTRACT

Deep closed-loop U-shaped heat exchanger with a long horizontal extension (up to 5 km) is a new approach to harvest heat more sustainably. This system comprises two deep vertical boreholes which are connected using a long horizontal section. Such a closed-loop system avoids subsurface water contamination, greenhouse gas emission, seismic events, and scaling problems. Furthermore, it leads to mitigating pumping power, exploratory risk, and environmental footprint, which are associated with prolonged operation period and less uncertainty. However, the performance of this system is not yet characterized to observe its potential over conventional heat exchangers. In this study, the depth, horizontal extension, and diameter of boreholes, formation temperature gradient, flow rate, inlet temperature, thermal conductivity of formation, and length of insulation layer are considered as variable parameters to study the performance of the system. An in-house wellbore simulator, called MOSKITO, is used to calculate the outlet temperature and temperature and pressure distributions along the system, Then, the overall and sectional power output are optimized based on these parameters. According to the results, the temperature of the produced fluid is a nonlinear function of flowrate. This nonlinearity is due to the influence of flowrate on the displacement of the cooled region in the reservoir. To increase the power generation or output temperature while decreasing the flowrate it may be necessary to increase the insulation of the production well. It has resulted that for a particular range of flowrate, it is feasible to produce hot water with continuous temperature enhancement over 100 years of operation. Additionally, with simultaneous optimization of fluid velocity and geometrical factors, the continuous generation of 2.5 MW energy over one century is accessible. Finally, flowrate also has a nonlinear impact on the pressure drop and thermosiphon system since increasing flowrate magnifies the pressure loss due to friction in the horizontal section. However, it may increase the temperature difference between water columns in vertical wells. Further investigation of the results in both vertical and horizontal sections enables us to develop a conceptual multilateral wellbores system with a higher flow rate.

1. INTRODUCTION

Utilization of borehole heat exchangers seems to be a secure approach to harvest geothermal energy since it prevents subsurface water contamination and seismic events through hydraulic fracturing. This energy extraction method is characterized by no mass exchange between formation and wellbore and conductive heat transfer at the areas adjacent to the wellbores. Retrofitting abandoned wells (Caulk & Tomac, 2017) and harvesting shallow geothermal energy (Vieira et al., 2017) through borehole heat exchangers (BHE), as well-known examples of closed geothermal loops (Blázquez et al., 2017; Wang et al., 2021), got special attention in recent years. However, low profitability and economic viability are the main barriers to the spread of these systems.

Although the typical generated power of BHEs is less than 300 kW, deepening the system and extending the length of the horizontal section, accompanied by a more extensive heat exchange surface, can magnify the generated power significantly. Nevertheless, considerable construction costs and internal energy consumption elongate the payback period. It necessitates a comprehensive investigation of the performance of this system under various operational and geological conditions to make the system cost-effective.

The most comprehensive study evaluating the performance of deep closed-loop U-shaped heat exchangers is conducted by Song et al., 2018. However, simplifying the geological condition and lacking appropriate equation of state to update thermo-physical properties of water over a wide range of pressure and temperature were the notable imperfections of this research. This study is repeated by Sun et al., 2018 for carbon dioxide as a working fluid. Recently, Chen & Feng, 2020 used a temperature-dependent equation of state to improve the accuracy of other studies. Nevertheless, neglecting the impact of the casing and cement layers on the energy exchange between working fluid and surrounding areas made it difficult to rely on their results.

The first objective of this study is the coupling of continuity, momentum, and energy equations with proper equations of state to provide an accurate description of fluid flow and heat transfer in the system. Subsequently, we have investigated the impacts of geometrical/geological configurations and operational parameters on the system's performance. Finally, the importance of horizontal extension to magnify the generated power and some strategies to generate electricity are discussed elaborately.

2. NUMERICAL MODELING

2.1 Governing Equations

A finite element code, called MOSKITO (Gholami Korzani et al., 2019), has been developed by the second author using MOOSE framework (Gaston et al., 2009) to simulate non-isothermal transient flow in wellbores. This application couples conservation equations with appropriate equations of state to give an accurate estimation of fluid behavior in the system. The governing equations are listed below:

mass conservation:

$$\frac{\partial}{\partial t}(\rho) = -\frac{\partial}{\partial z}(\rho v) + m \tag{1}$$

where , ρ and m are velocity, density, and mass sink/source term in unit volume and unit time, respectively.

Momentum conservation:

$$\frac{\partial P}{\partial z} = \rho g cos(\theta) \pm \frac{f \rho v^2}{2d} \pm \left[\frac{\partial}{\partial t}(\rho v) + \frac{\partial}{\partial z}(\rho v^2)\right] \tag{2}$$

where g is the gravitational acceleration, f is the friction factor, θ the inclination angle of the well, d the hydraulic diameter of the wellbore, and P is the fluid pressure. The sign of the terms in the momentum equation depends on flow and gravity directions.

Energy conservation:

$$\frac{\partial}{\partial t}\left[\rho\left(u + \frac{1}{2}v^2\right)\right] = -\frac{\partial}{\partial z}\left[\rho v\left(h + \frac{1}{2}v^2\right)\right] + \rho v g cos(\theta) - \frac{q}{A} + Q \tag{3}$$

where Q, q, h, and u are heat sink/source, lateral heat, enthalpy, and specific internal energy, respectively.

Transport species:

$$\frac{\partial}{\partial t}(\rho x) = -\frac{\partial}{\partial z}(\rho v x) + m \tag{4}$$

Coupling three equations of state (IAPWS (Wagner et al., 2000) for thermos-physical properties of pure water, Vogel equation (Huber et al., 2009) for water viscosity, and another empirical EOS to calculate brine properties) and the equations mentioned above enabled us to have a precise estimation of fluid behavior in the system.

The general equation to account for the energy exchange between working fluid and surrounding area (conductive heat transfer in casing/cement layers and convective heat transfer between fluid film and inside tubing wall) is:

$$q = 2\pi r_{to} U_{to}(T_f - T_{cf}) \tag{5}$$

where r_{to}, U_{to}, T_f, and T_{cf} represent the outside radius of tubing, overall heat transfer coefficient, fluid temperature, and temperature at the cement/formation interface, respectively. The overall heat transfer factor is governed by (Willhite, 1967):

$$\frac{1}{U_{to}} = \frac{r_{to}}{r_{ti} h_f} + \frac{r_{tox} \ln(r_{tox}/r_{tix})}{k_x} \tag{6}$$

where r_{ti}, k_x, r_{tox} and r_{tix} are the radius of inside tubing, thermal conductivity, outer and inner radii of layer x.

2.2 System Layout and Operation

Figure 1 shows the system configuration with all the casings and cement layers. The injected fluid exchanges heat with the formation around the wellbores. It gains energy at the areas around the injection and horizontal sections and loses heat in the regions adjacent to the upper part of the production wellbore. Therefore, the upper section of the production well should be adequately insulated to improve the system's performance. Additionally, the horizontal area is not equipped with any casing or cement layer to maximize the absorbed energy. While the direct exposition to the formation enhances the heat exchange rate, it promotes leakage probability through the horizontal well. Therefore, it is necessary to ensure that there is no contact between the horizontal section and any fault or fracture.

We set Dirichlet boundary conditions for pressure, temperature, flow rate, and salinity at the wellhead (Table 1). Also, the Neumann boundary is applied at the outlet to impose the open condition. Thermo-physical properties of casings, formation, and cement layer are addressed in Table 2.

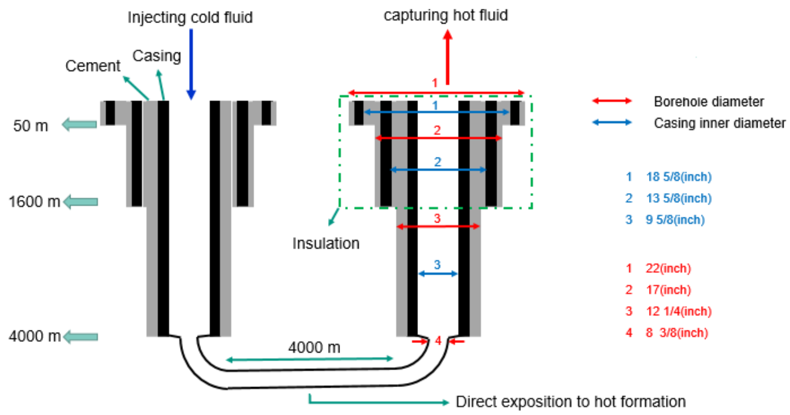

Figure 1: Schematic illustrating system configuration

Table 1
Boundary conditions

Wellhead pressure	Wellhead temperature	Flow rate	salinity
100 kPa	10 °C	5 L/s	0.25 m

Table 2
Thermos-physical properties of formation, casing, and cement layer

Formation density	Formation heat capacity	Formation thermal conductivity (upper layer)	Formation thermal conductivity (lower layer)	Cement thermal conductivity	Casing thermal conductivity	Ambient temperature gradient	Ground surface temperature
2400 kg/m^3	1000 J/kgK	2 W/mK	3 W/mK	0.7 W/mK	100 W/mK	30 °C/km	10 °C

3. RESULTS AND DISCUSSIONS

3.1 Impact of Geological Conditions

Three geological structures with various thermal conductivities (Table 3) are designed to evaluate the system's performance under different geological conditions. Figure 2 shows the production temperature over time. The immediate increase of outlet temperature derives from the displacement of residual hot fluid in the system. Subsequently, we can see the effect of lateral heat and boundary conditions, and the production temperature starts to decrease. While a higher thermal conductivity is accompanied by more intensive energy gaining in the injection and horizontal section, it magnifies energy loss at the upper part of the production well. However, raising outlet temperature for cases with higher thermal conductivities reveals the prevailing impact of energy absorption. It is worth mentioning that operating in regions possessing larger thermal conductivities improves the system's sustainability (Figure 2). The results also indicate that, even in the case with the uniform thermal conductivity of 2 W/mK, the production temperature is above 65 °C. It shows the reliability of this system to produce hot fluid over a hundred years of operation.

Table 3
Description of formation thermal conductivity for different cases

	Case 1	Case 2	Case 3
Thermal conductivity of upper 2 km	2 W/mK	2 W/mK	2 W/mK
Thermal conductivity of lower 2 km	2 W/mK	3 W/mK	4 W/mK

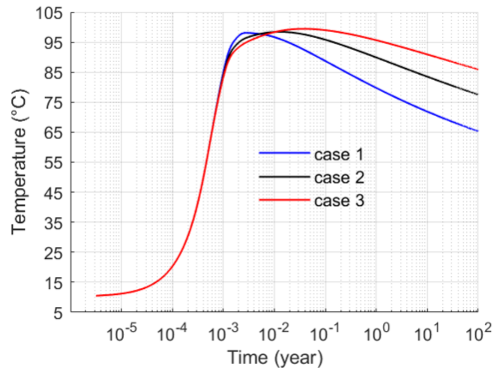

Figure 2: Impact of the geological condition (formation thermal conductivity) on the production temperature over time

Figure 3 exhibit the generated power of the system over time. Since the generated power in the vertical injection well is almost counterbalanced with the lost power in the production wellbore, the net generated power mimics the produced power pattern in the horizontal section. As time elapses, the temperature gradient between the working fluid and surrounding area decreases, leading to generated power reduction over time. Nevertheless, the generation of approximately 3 MW power over one century shows the advantage of this system over conventional BHEs with the produced power of below 300 kW for a shorter period.

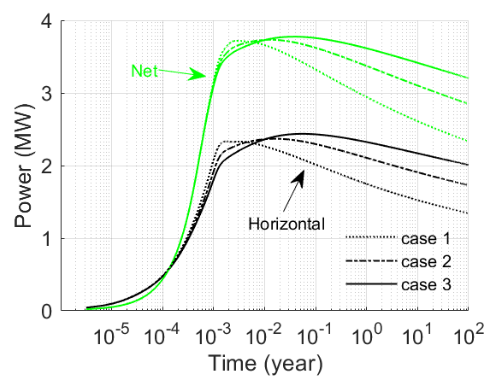

Figure 3: Generated powers in each section of the system for various formation thermal conductivities

3.2 Impact of Geometrical Configuration

As shown in Figure 4 and Figure 5, deepening the system is more beneficial than extending the horizontal section. Increasing the length of both horizontal and vertical wells results in a higher production temperature. However, this temperature enhancement is more considerable for deeper systems. The high outlet temperature, together with the more extensive length of vertical wells, escalate the difference between weights of water columns in the vertical wells, represented by a higher outlet pressure in Figure 5. Therefore, in this case, the remarkable enhancement of the generated power is associated with more significant mitigation of internal energy consumption.

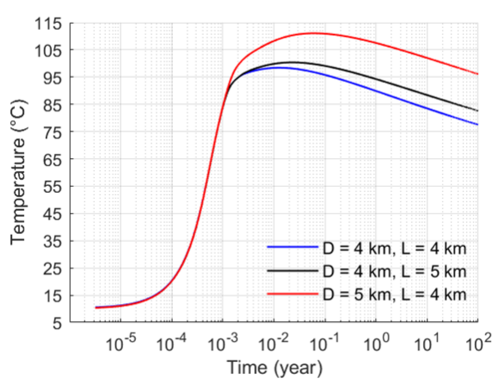

Figure 4: effects of length and depth of the system on outlet temperature over time

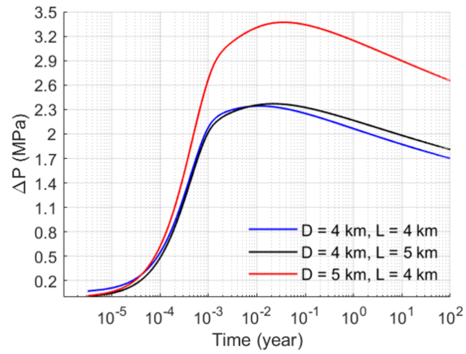

Figure 5: pressure difference between inlet and outlet as a function of depth and length of the system

3.3 Impact of Operational Parameters

Flow rate is the most crucial operating parameter influencing the performance of deep closed-loop U-shaped heat exchangers. Changing the flow rate at a constant cross-sectional area culminates in velocity variation. As the convective heat transfer factor is velocity-dependent, it is feasible to adjust the heat exchange rate by regulating the flow rate. It is a key factor in improving the system's sustainability. As shown in Figure 6, for the flow rate of 1 L/s, the outlet temperature is rising over time. This strange behavior of production temperature is related to the energy loss in the production well. For lower flow rates, we are losing a significant amount of energy in the production well. As time goes by, the heating effect at the upper part of the production wellbore prevents the vast temperature drop. Hence, the production temperature increases over time.

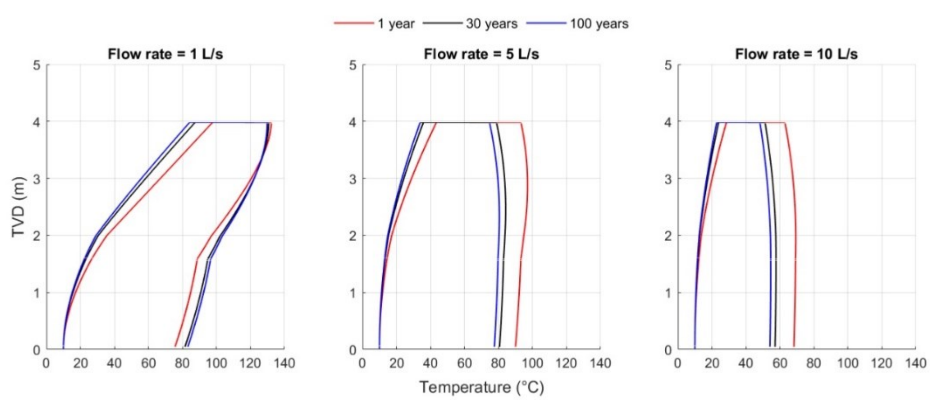

Figure 6: temperature distribution along the wellbore for different flow rates

Figure 7 shows the absorbed energy in each section of the system at the year 100. While the absorbed energy for the case with the flow rate of 10 L/s is higher than the other cases, its temperature is lower than the rest. Indeed, this energy is transferred to a higher amount of mass per time, leading to a smaller temperature enhancement over time. Increasing temperature and pressure can intensify the nonlinear behavior of thermo-physical properties (e.g., viscosity, density). It is the main reason for the nonlinear behavior of absorbed energy for the case with the flow rate of 1 L/s.

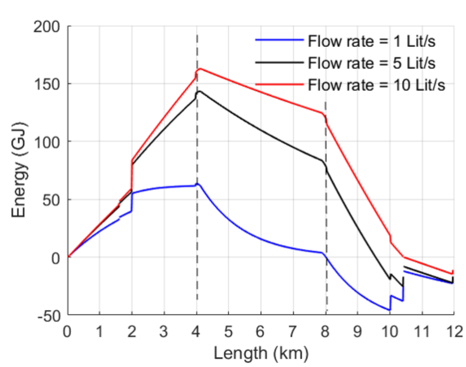

Figure 7: impact of flow rate on absorbed energy in each section of the system after one hundred years of operation

3.4 Importance of Horizontal Section

The horizontal section's contribution to the total generated energy after one hundred years of operation is plotted in Figure 8 to emphasize the importance of horizontal extension in magnifying generated power. Enhancement of convective effect (fluid velocity) decreases the difference between absorbed energies in vertical and horizontal sections. Therefore, the horizontal section's contribution to the net generated power reduces. It means the construction strategy to expand the horizontal area or deepen the system is linked to operational parameters like flow rate. As shown in Figure 8, decreasing wellbore diameter and increasing flow rate lead to the enhancement of vertical wells' contribution to the total generated energy, which is in good agreement with our interpretations. Eventually, it demonstrated that uniform enhancement of ambient temperature gradient has a negligible impact on the portion of absorbed energy by the horizontal well. Conversely, increasing the thermal conductivity of the lower layer of formation can change the contribution.

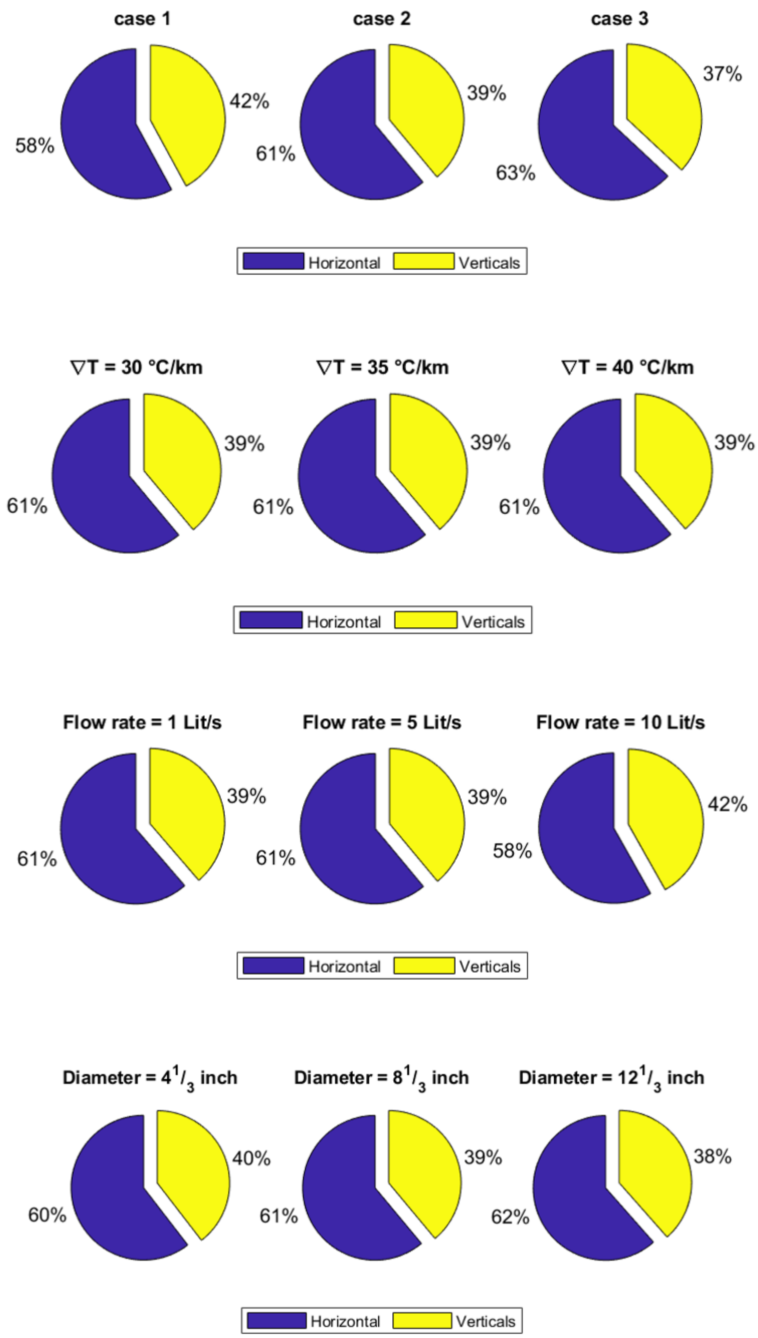

Figure 8: Impact of geological/geometrical/operational parameters on the contribution of the horizontal section to total generated energy

3.5 Utilization Strategy

Reinjection of hot water is a typical approach to generate electricity in geothermal applications. Nevertheless, as exhibited in Figure 9, even with the increase of inlet temperature to 70 °C, the production temperature is lower than 100 °C. Moreover, reinjection of hot fluid mitigates the mean temperature difference between vertical wellbores (Figure 10) and increases internal energy consumption. On the other hand, reducing the temperature difference between inlet and outlet reduces the absorbed energy by the system (Figure 11). Hence, it seems more rational to enlarge the structure or decrease the flow rate to enhance the outlet temperature and generate electricity.

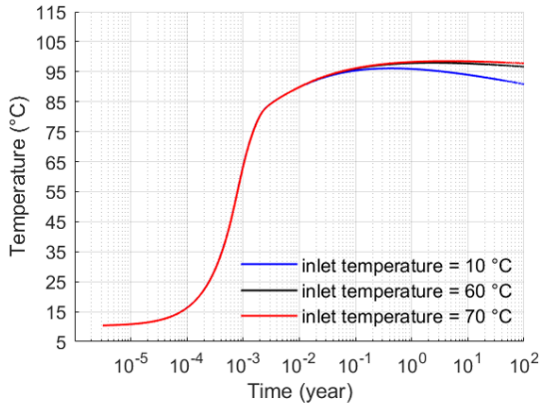

Figure 9: Effect of inlet temperature on the production temperature

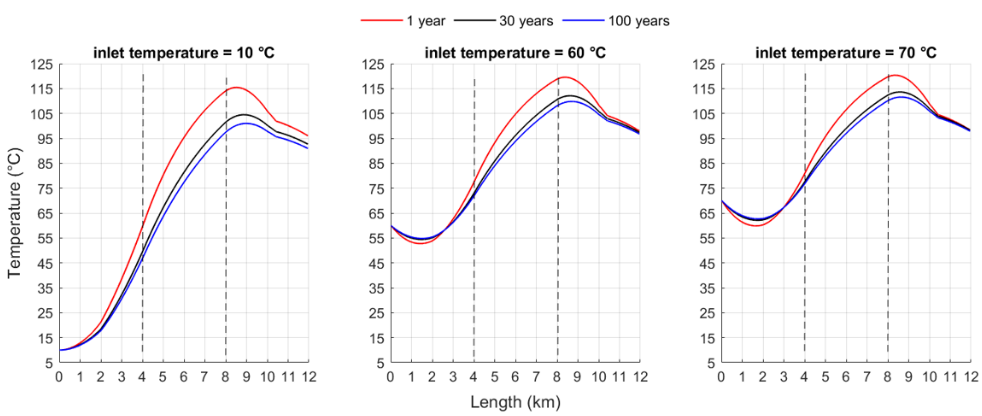

Figure 10: inlet temperature impact on the temperature distribution along the wellbore

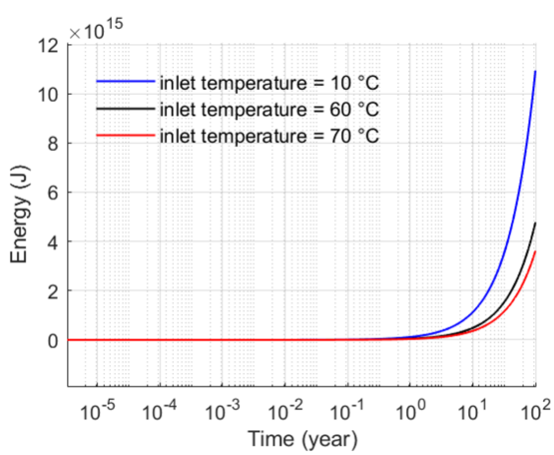

Figure 11: cumulative absorbed energy for different inlet temperatures

4. CONCLUSION

In this study, we have coupled continuity, momentum, and energy equations with proper equations of state to simulate fluid flow and heat transfer in a particular kind of closed geothermal systems accurately. While this system possesses long horizontal and deep vertical wellbores, using a special formulation of lateral heat decreased the computational cost significantly.

The generated powers in each section of the system are investigated separately to put emphasis on the importance of the horizontal section. The results indicate that for the operational/geological/geometrical parameters addressed in this paper, the horizontal section's contribution to the total generated energy can range between 58% and 63%.

The initial production temperature drawdown is a serious problem while dealing with closed geothermal systems. However, assessment of outlet temperature and produced power by this system revealed that operating under special conditions can lead to continuous production temperature enhancement over the project lifetime of one hundred years. It is worth mentioning that this system's generated power can exceed 3 MW, which is ten times higher produced power by typical BHEs.

Although the horizontal section has an undeniable impact on the absorbed energy, extending the length of vertical wells is of high importance to magnify the thermosiphon effect and decrease the internal energy consumption. Additionally, the results showed that deepening the system is more beneficial than extending the horizontal section to enhance the production temperature.

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