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Evaluation of the Advantages of Multilateral Closed Deep Geothermal Frameworks over Conventional Geothermal Systems

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ABSTRACT

Operating with typical geothermal systems may create seismic events, contaminate subsurface water, and cause other environmental hazards. However, multilateral closed deep geothermal (MCDG) systems can extract a considerable amount of energy in an environmentally friendly manner. Nevertheless, generated power, predictability, longevity, and payback period of these systems are controversial among scientists. Therefore, the primary purposes of this study can be categorized into three main groups: evaluation of the impact of operational parameters and system configuration on outputs, prediction of system's long-term behavior, and identification of the common features of high-performance MCDG systems. The findings of this study revealed that operating with MCDG systems doesn't always result in higher performance than simple closed deep geothermal systems. However, their longevity is much better than conventional open geothermal frameworks. Moreover, high-performance MCDG systems are distinguished by a specific relation between total flow rate and the number of injection/horizontal wellbores. Finally, it is found that the long-term performance of MCDG systems (i.e., extraction temperature and generated thermal power) is predictable as a function of their short-term behavior.

1. INTRODUCTION

The potential hazards of operating with open geothermal systems (e.g., induced seismicity and subsurface water contamination) necessitate developing new environmentally-friendly approaches to extract energy from the earth. The new technologies should be capable of producing thermal power without mass exchange between geothermal wellbores and surrounding areas to avoid the above-mentioned hazards. Therefore, it seems that a new form of closed geothermal systems should be designed to produce a significant amount of thermal power through conductive heat transfer.

In recent years, several studies have been carried out to investigate the performance of deep closed geothermal systems (Esmaeilpour et al., 2021; Beckers et al., 2022; Hu et al., 2020; Song et al., 2018; Sun et al., 2018; Wang et al., 2021). The researches show that the generated power of these systems can hardly compensate for drilling expenses. Indeed, the heat exchange surface provided by closed frameworks is much smaller than those of open geothermal systems, leading to the considerable reduction of generated thermal power. Nevertheless, the power production per meter of deep closed systems is much higher than shallow systems, resulting in a shorter payback period. Consequently, new upcoming technologies should focus on the performance enhancement of deep closed geothermal systems. 12345

Operating with multilateral structures is an interesting option to improve the heat absorption of conventional closed deep geothermal systems. The extensive lateral heat exchange surface of these systems can increase the ratio of generated thermal power to the total length of wellbores. Hence, the shorter payback period and notable generated power of this system can make it a solution for increasing the contribution of closed systems to geothermal power production. However, the geometrical configuration (i.e., number of wellbores, depth of the systems, length of horizontal section, wellbores' diameters, and the distance between parallel wellbores) and operational parameters (e.g., flow rate, injection temperature) should be designed carefully to maximize power generation and minimize relative drilling costs. It is worth mentioning that the geological condition and the purpose of operation (i.e., district heating or electric power production) can influence the system's design.

The main focus of this study is to investigate the impact of flow rate and wellbore configuration on the generated thermal power, extraction temperature, and relative payback period of MCDG systems. For this purpose, 160 different scenarios are designed, and the impacts of added vertical/horizontal wellbores on power generation and extraction temperature are elaborately analyzed.

2. NUMERICAL MODELING

2.1 Governing Equations

A finite element code, called MOSKITO (Maziar Gholami et al., 2019; Esmaeilpour et al., 2021), has been developed using MOOSE framework (Gaston et al., 2009; Permann et al., 2020) to simulate non-isothermal transient flow (Esmaeilpour and Gholami Korzani, 2021b; 2021a) 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:

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

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 (Kretzschmar et al., 2006) 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

As shown in Figure 1, an MCDG system consists of several deep injection wellbores connected to some long horizontal wellbores through manifolds. The final depth of the designed system and the length of the horizontal section are 4.1 km and 4 km, respectively. The optimum distance between parallel wellbores is 200 m to avoid any thermal interaction between them. It is worth mentioning that changing the operational parameters, project lifetime, and thermophysical properties can affect the distance between wellbores.

The injected fluid in vertical wellbores is redistributed in horizontal wellbores and finally collected through only one production wellbore. The vertical wellbores are equipped with some casing and cement layers, while the horizontal section is directly exposed to hot formation. The high temperature of formation and the direct explosion enhance the heat absorption in the horizontal part of the system. It is assumed that the injection of some chemicals and their penetration into the lateral area can seal the horizontal wellbore perfectly. For the detail of the casing program, refer to (Esmaeilpour et al., 2021).

The formation consists of two geological layers with a depth of 2 km and 2.1 km and thermal conductivities of 2 $W.m^{-1}.K^{-1}$ and 3 $W.m^{-1}.K^{-1}$, respectively. The subsurface temperature gradient is 30°C/km, and the surface temperature is assumed to be 10 °C. Other thermo-physical properties, operational parameters, and initial conditions are mentioned in (Esmaeilpour et al., 2021).

To acquire a deep understanding of the behavior of MCDG systems, 160 different cases with various configurations and flow rates are simulated. The number of injection and horizontal wellbores can be 1, 2, 4, and 8 (4×4 = 16 different configurations), while the flow rate can range between 5 L/s and 50 L/s with the interval of 5 L/s (10 different flow rates).

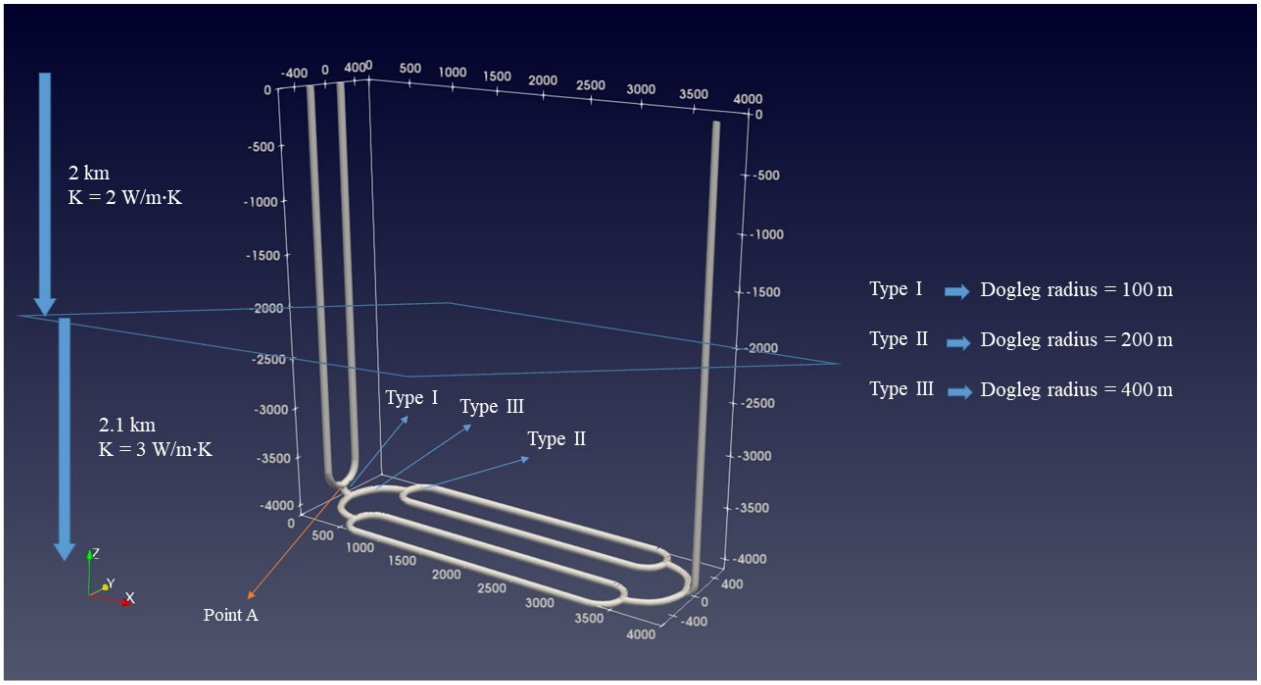

Figure 1: Schematic illustrating depth of MCDG systems, length of horizontal section, manifolds, and wellbores configuration.

3. RESULTS AND DISCUSSIONS

3.1 Comparing Power Production in Horizontal and Vertical Wellbores

As mentioned before, the higher temperature difference between the working fluid and surrounding area and the direct exposition to the hot formation enhances the heat absorption in the horizontal part of MCDG systems. As can be seen in Figure 2, the maximum power production in a vertical wellbore is limited to 0.7, while it can exceed 1.5 MW in a horizontal wellbore. Consequently, adding an extra horizontal wellbore is more beneficial than including an extra vertical wellbore in terms of power production. Nevertheless, it should be taken into account that the drilling cost of a horizontal wellbore may be higher than those of an injection wellbore. Hence, the strategy for the development of MCDG systems depends on relative drilling costs of horizontal wellbore compared to vertical wellbore drilling expenses.

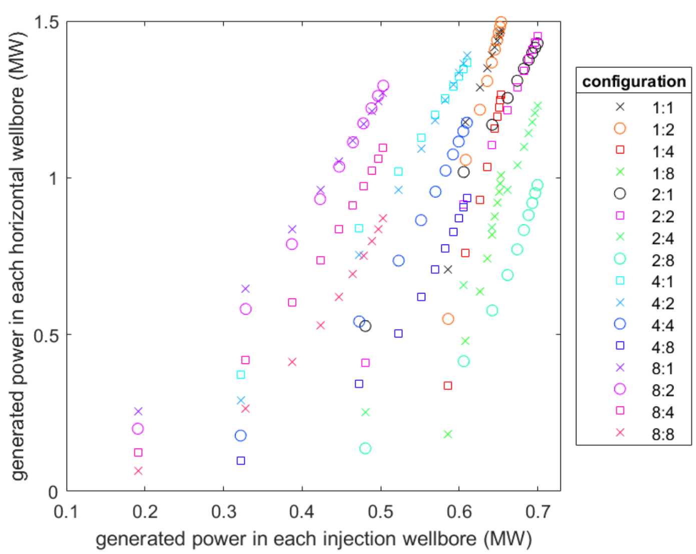

Figure 2: Generated thermal power in each horizontal and vertical wellbore of simulated MCDG systems. The project lifetime is 100 years. The first and second numbers in the configuration box indicate the numbers of injection and horizontal wellbores.

3.2 Importance of Power Production in Horizontal Wellbores

Figure 3 exhibits the average extraction temperature over the generated power in horizontal wellbores. Clearly, the simulated cases are categorized into four different groups since the derivative of average extraction temperature over generated power in the horizontal part can possess four different values. In each group, operating with a higher flow rate increases the power production in horizontal wellbores. However, it causes the extraction temperature to take smaller values. In these cases, the increase of mass flow rate prevails the decrease of the temperature difference between the beginning and end of horizontal wellbores. Switching from one group to another one happens when the extraction temperature and power increase simultaneously. The main reason for this jump is that the increase of flow rate avoids heat loss at the single production wellbore. Therefore, the increase of power generation in horizontal wellbore accompanies a higher extraction temperature.

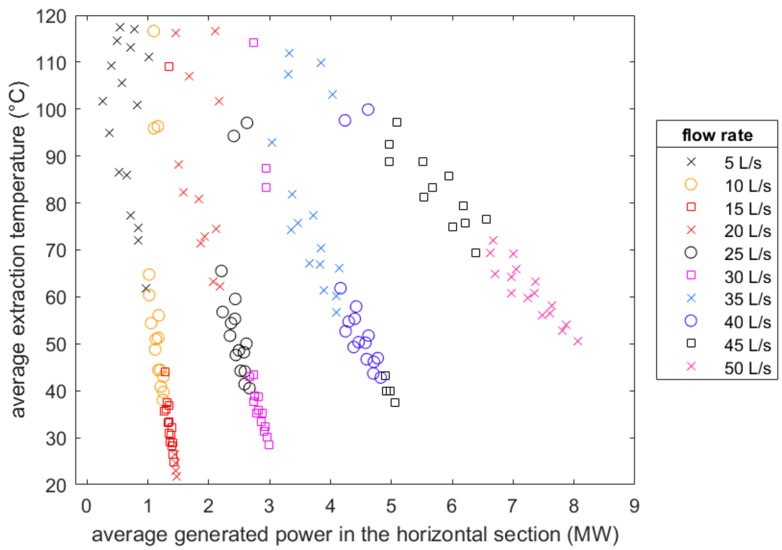

Figure 3: Average extraction temperature of simulated cases over 100 years of operation versus the generated power in horizontal wellbores of MCDG systems.

It is necessary to define an index and compare the performance of different cases against each other in terms of the ratio of generated thermal power to the equivalent total length, as shown in Figure 3.

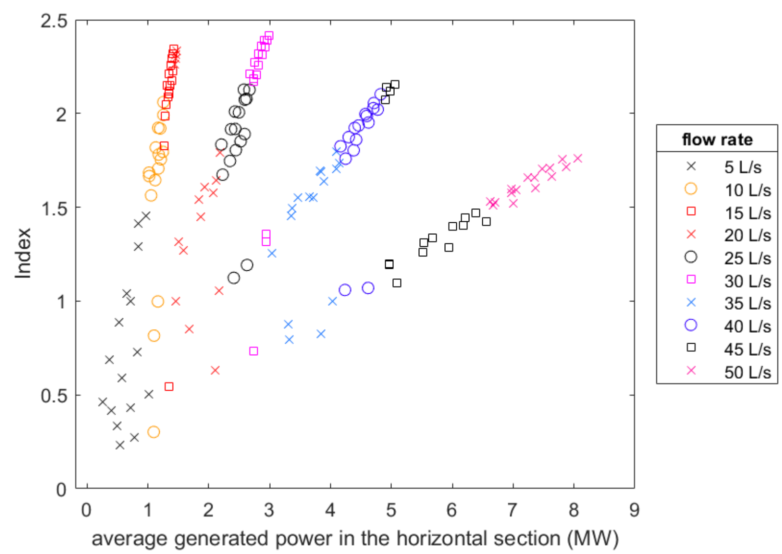

Figure 4: Index of simulated cases over the generated power in horizontal wellbores of MCDG systems. The project lifetime is 100 years.

$$index = \frac{\frac{generated\ power}{equivalent\ total\ length}}{\frac{generated\ power_{reference\ case}}{equivalent\ total\ length_{reference\ case}}} \quad (7)$$

The reference case used in this equation is a simple closed structure with an injection wellbore, a horizontal wellbore, and a production wellbore. The operating flow rate of the reference case is set to be 5 L/s, and its generated thermal power is roughly 1.3 MW. The equivalent total length is also a simplified/normalized indicator of drilling costs, defined by:

$$Equivalent\ total\ length = total\ length\ of\ vertical\ wellbores + 2 \times total\ length\ of\ horizontal\ wellbores + Length\ of\ production\ wellbore \quad (8)$$

It is assumed that the horizontal wellbore's drilling cost is two times that of a vertical wellbore. The index of higher than 1 shows the increase of the ratio of generated thermal power to the equivalent total length of the system compared to the reference case. On the other hand, it doesn't make sense to operate with the multilateral system when the index is lower than 1.

Like Figure 3, all the cases are divided into four groups in Figure 4. In all the groups, the increase of the generated thermal power is associated with a higher index. Nevertheless, the rise in power production has a more substantial influence on the index when operating with lower flow rates. Indeed, the working fluid loses a considerable amount of energy in the production wellbore when the fluid speed is low. In these cases, the increase of flow rate enhances power production in the horizontal wellbores and avoids the temperature loss in the production wellbore represented by a higher derivative of extraction temperature over the power generation in the horizontal wellbores.

3.3 Importance of Average Extraction Temperature

Even for district heating purposes, the extraction temperature should be higher than 100 °C. However, it is possible to use heat pumps and increase the temperature of the extracted fluid. Regardless of the importance of extraction temperature for the using purpose (i.e., district heating or electric power generation), the temperature of the produced fluid is of high importance for the prediction of the behavior of MCDG systems. As shown in Figure 5, the extraction temperature experiences the highest drawdown when its average value is about 70 °C.

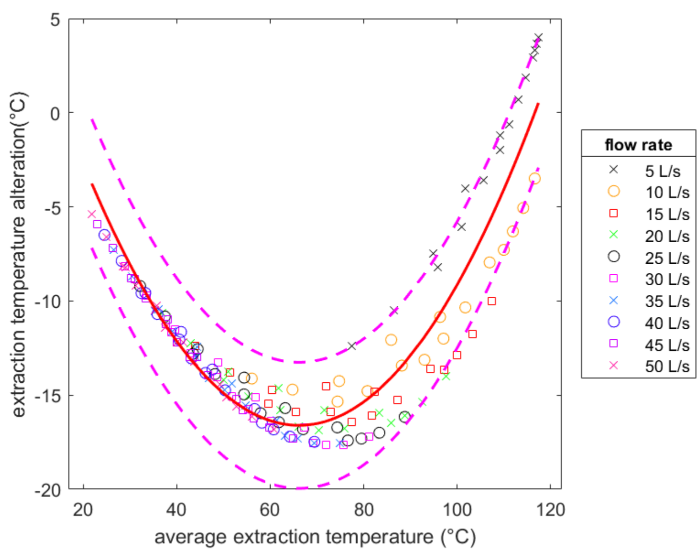

Figure 5: variation of extraction temperature over 100 years of operation versus the average value of extraction temperature in this period.

Figure 6 shows the index of simulated cases over their average extraction temperature in the period of 100 years. The high extraction temperature is achievable when the MCDG system possesses a lot of injection/horizontal wellbores, or the flow rate is low. The increase of the number of wellbores is associated with a higher equivalent total length, and the reduction in the flow rate leads to the generation of a smaller thermal power. Therefore, both of these two factors reduce the ratio of generated thermal power to the equivalent total length of the system. It can be claimed that the payback period of MCDG systems is shorter when it is designed for district heating purposes. It is also worth mentioning that all the calculations of this study are conducted with the assumption that the drilling cost of a horizontal wellbore is two times that of a vertical wellbore. However, changing this ratio can influence the results provided for the evaluation of the index of MCDG systems and alter the construction strategy.

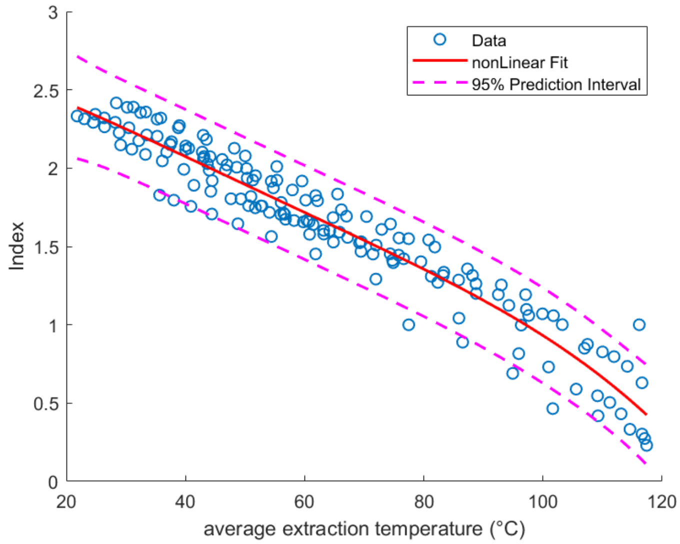

Figure 6: Alteration of the index of MCDG systems versus the average extraction temperature over the projects' lifetime f 100 years

4. CONCLUSION

The primary purpose of this study was to evaluate the performance of multilateral closed deep geothermal systems. The designed multilateral systems possess several injection and horizontal wellbores and only one production wellbore. The heat exchange between different components of the system (i.e., working fluid, casings, cement layers, and formation) is included as a source term in the energy equation. Then, the energy equation is coupled to mass and momentum equations to provide an accurate mathematical description of the problem. Subsequently, the impact of vertical and horizontal wellbores on thermal power production and the behavior of extraction temperature are discussed. The main results of this study are listed below:

1. Since the horizontal wellbores are exposed to the hottest formation and are not surrounded by any casing and cement layers, they have a higher thermal power generation capability than vertical wellbores.
2. There is a nonlinear relation between average extraction temperature and extraction temperature alteration over time when operating with MCDG systems. The highest temperature drop is observed for the average extraction temperatures ranging between 60 °C and 80 °C.
3. High extraction temperature is achievable when there are many injection/horizontal wellbores, or the flow rate is low. Both of these factors decrease the ratio of generated thermal power to the equivalent total length of the system. Consequently, the MCDG systems designed for district heating purposes have a shorter payback period than those designed for electric power generation.

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