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Increasing the contribution of closed geothermal systems to green energy generation through designing a novel deep multilateral framework

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ABSTRACT

In contrast to typical forms of renewable energy like wind power and solar energy, baseload power is available everywhere throughout the whole year. However, its contribution to green energy generation is lower than its potential level. The primary factors restricting the spread of geothermal systems are subsurface water contamination, seismic events caused by hydraulic fracturing, and uncertainty in geothermal field characterization. Therefore, this study is dedicated to the planning of a new geothermal system that is capable of avoiding these potential hazards. The proposed closed multilateral system consists of several injection and horizontal wellbores and only one production wellbore. The special design of this system provides an extensive heat exchange surface for energy absorption from the surrounding environment. The results of the present study demonstrated that the circulation of a working fluid in this multilateral system results in the generation of megawatts of thermal power, which is comparable to those of open geothermal systems. The ratio of generated thermal power to the total length of the system is also higher than those of simple closed deep geothermal systems, indicating a shorter payback period. Nevertheless, operating with multilateral systems doesn't always result in higher performance than simple systems. It shows the necessity of filtering high-performance scenarios for operation in various geological conditions. The findings of this study indicate that the scenarios with the highest ratio of generated power to the total length are characterized by a particular relation between local vertical and horizontal flow rates. It is also found that the long-term performance of multilateral systems can be predicted based on their short-term performance. As an example, it is feasible to anticipate the extraction temperature and average generated power of the system after 100 years as functions of its extraction temperature after the first year of operation independent of the number of wellbores and flow rate. It gives insight for decreasing the risk of designing / operating with low-performance systems.

1. INTRODUCTION

With the increase of global energy demand, renewable energy sources are emerging as an alternative option to substitute fossil fuels. Geothermal energy is a reliable form of renewables that is available everywhere throughout the whole year. Indeed, the energy stored under the earth's surface can be incessantly supplied to either district heating networks or electric power grids. Many approaches are devised to facilitate and maximize energy extraction from the earth and increase the geothermal energy contribution to the global renewable capacity. The most successful methods rely on the direct exposition of the working fluid to the surrounding hot areas (i.e., open systems). The provided extensive heat exchange surface by faults and fractures enhances the heat absorption and allows for operating with large flow rates. Nevertheless, determining the location, orientation, and connectivity of the above-mentioned faults and fractures is uncertain, as our knowledge of subsurface structure is limited. This uncertainty endangers the project's success, which depends on the circulation of the working fluid through subsurface open spaces. Operating in regions with insufficient permeability requires thermal, chemical, or hydraulic stimulations to generate some flow paths in reservoirs. Hydraulic fracturing requires fluid injection at a high pressure that may prompt subsequent seismic events. It should also be taken into account that chemical stimulation is associated with subsurface water contamination and environmental pollution.

Fluid circulation in closed systems enables us to avoid the above-noted hazards since the flow path is already provided, and there is no mass exchange between wellbores and reservoirs (Beckers et al., 2022; Malek et al., 2022; Livescu and Dindoruk, 04252022). The longevity of these systems is also much better than those of open frameworks, as their extraction temperature is stable over time (Esmaeilpour et al., 2021). Nonetheless, these systems' heat exchange surface is restricted to the lateral area around the wellbores. Therefore operating with small flow rates is necessary to extract hot fluid at a reasonable temperature (Livescu and Dindoruk, 2021; 2022).

Multilateral wellbores can significantly improve the heat absorption performance of closed geothermal systems by enlarging the heat exchange surface. However, the performance assessment of multilateral closed systems with several injection/horizontal wellbores is rarely addressed in the literature (Esmaeilpour et al., 2022). Hence, this study is dedicated to the evaluation of the heat extraction mechanism in these systems. The main focus of this study is the characterization of thermal power production in injection/horizontal wellbores and finding the common features of high-performance systems.

2. NUMERICAL MODELING

A finite element code, called MOSKITO (Esmaeilpour et al., 2022; 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, 2021a; 2021b) in wellbores. This application couples conservation equations with appropriate equations of state to give an accurate estimation of fluid behaviour in the system. The governing equations are listed below:

mass conservation:

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

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

Momentum conservation:

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

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:

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

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

Transport species:

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

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 behaviour 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:

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

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) :

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

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.

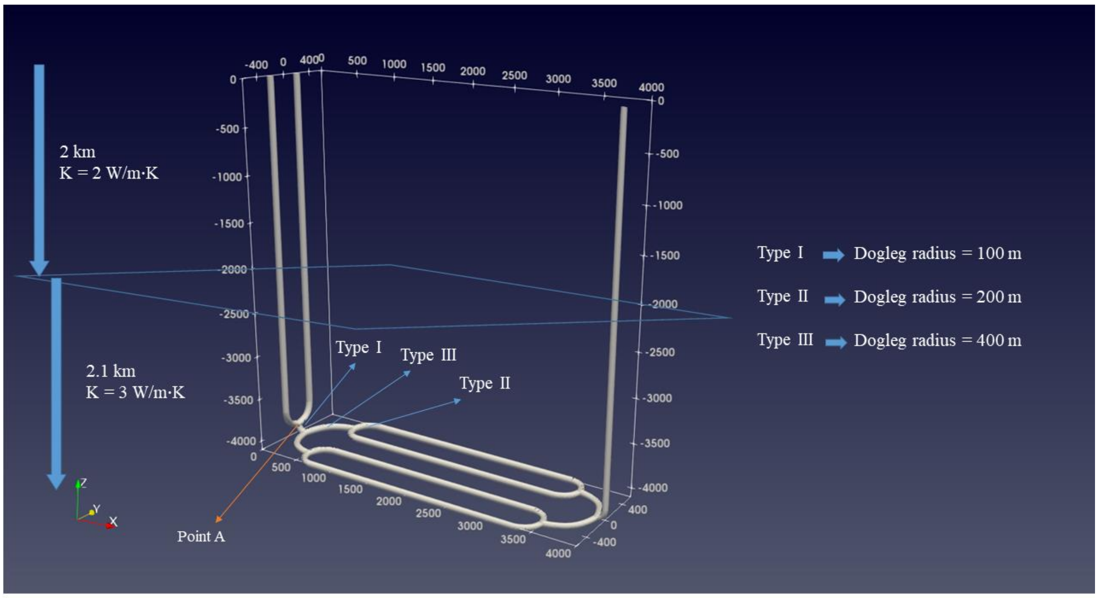
3. SYSTEM LAYOUT AND HEAT EXTRACTION MECHANISM

As shown in Figure 1, a multilateral closed deep geothermal (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 behaviour 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).



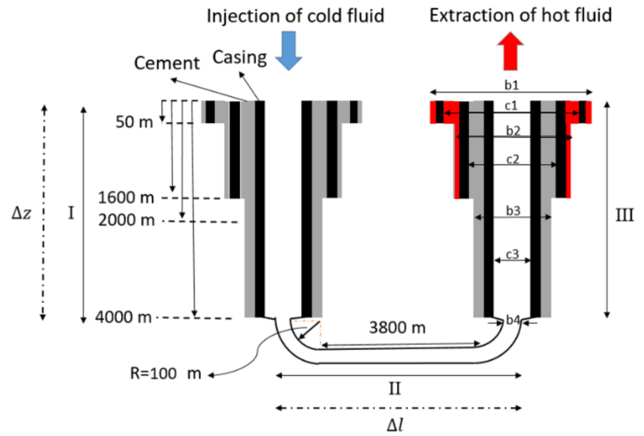


Figure 1: Schematic illustrating depth of MCDG systems, length of horizontal section, manifolds, and wellbores configuration

4. RESULTS AND DISCUSSIONS

4.1 characterization of thermal power production in vertical and horizontal wellbores

The increase of the number of wellbores provides a larger heat exchange area and improves the energy absorption by the working fluid. Therefore, it will be possible to operate with a higher flow rate. Nevertheless, the operating flow rate cannot be unlimitedly increased as it may lead to a considerable decline of the extraction temperature. The generated thermal power is a function of flow rate and the temperature difference between injection and extraction points. Therefore, the increase of flow rate is reasonable when it prevails the extraction temperature reduction and enhances the power production.

Drilling risks and construction expenses are also the main barriers to the increase of the number of wellbores. Indeed, it is rational to work with MCDG systems when the enhancement of thermal power production compensates for the excess drilling costs.

Figure 2 and Figure 3 show the impact of flow rate and system configuration on the generated thermal power in injection and horizontal wellbores of different MCDG frameworks, respectively. As mentioned before, for each flow rate, 16 various configurations are modeled. Hence, the ranges of boxplots exhibit the impact of systems configuration on the outputs.

The notable sensitivity of generated thermal power to specific flow rates, ranging between 5 L/s and 25 L/s, shows the necessity of operating with higher flow rates to enhance power production. However, a further increase of the flowrate has a negligible impact on the thermal power while it decreases the extraction temperature. Moreover, the increase of the number of wellbores can significantly improve power production at high flow rates. As an example, the generated thermal power in injection and horizontal wellbores are 0.7 and 1.2 while operating with a flow rate 50 L/s. This thermal can be magnified to 4 MW and 8 MW when the MCDG system possesses 8 injection/horizontal wellbores. Nonetheless, it doesn't make sense to work with multilateral systems at low flow rates (e.g., 5 L/s) as the added extra wellbores cannot enhance the power production significantly. It is also worth mentioning that generated thermal power in the horizontal wellbores is higher than those produced in the injection side since the horizontal section of the systems is directly exposed to the hottest formation. In fact, the smaller thermal resistance and higher temperature difference between the working fluid and the surrounding environment result in more significant heat absorption in horizontal wellbores.

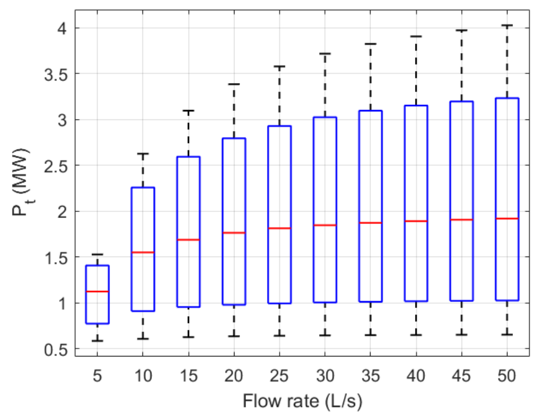


Figure 2: Generated thermal power in the injection wellbores of MCDG systems for different flow rates and systems configurations.

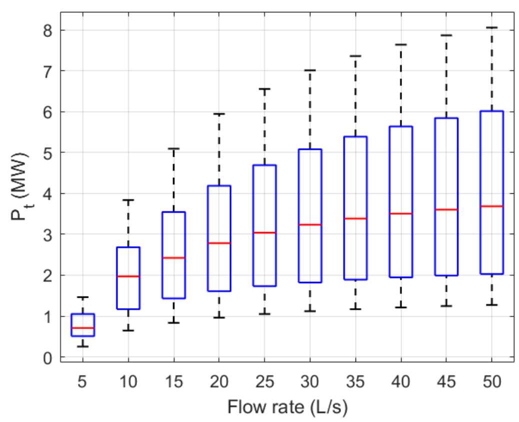


Figure 3: Generated thermal power in the horizontal wellbores of MCDG systems for different flow rates and systems configurations.

4.2 Flow rate impact on the stabilization of extraction temperature

One of the most important advantages of closed geothermal systems over open frameworks is the stability of extraction temperature. The only heat exchange mechanism of closed structures is conductive heat transfer. Therefore, the volume of the cooled region around the wellbores is limited. It means the heat extraction through closed geothermal systems doesn't cool down the reservoir quickly, resulting in a stable extraction temperature over a long period. The operating flow rate can noticeably affect the extraction temperature stability and the system's longevity. The heat extraction by the working fluid is controlled by the Nusselt number and the duration in which the fluid is exposed to hot formation. Both of these two factors are adjusted by the fluid velocity. Figure 4 and Figure 5 show the impact of fluid velocity on the stability of extraction temperature and average temperature loss in the production wellbore over 100 years of operation. In the case of low flow rates, the injected fluid gains a lot of energy in the injection wellbore and loses a considerable amount of heat in the production side, represented by a huge temperature drop in the

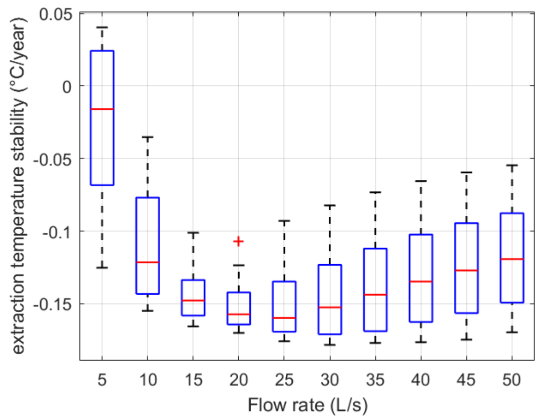


Figure 4: impact of flow rate on the stability of extraction temperature calculated by $(\frac{T_{100} - T_1}{99})$

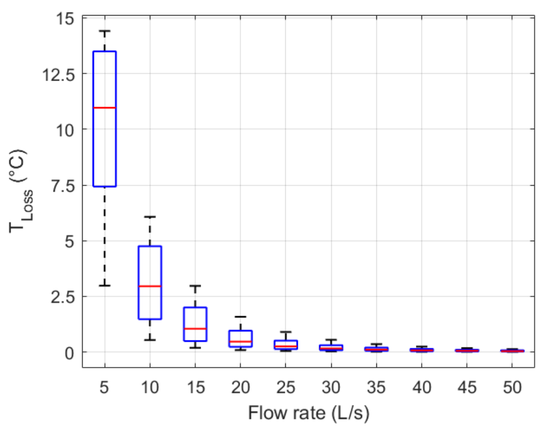


Figure 5: impact of flow rate on the temperature loss in the production wellbore

production wellbore (Figure 5). Nevertheless, as time elapses, the heated area around the production wellbores prevents the temperature drop, represented by positive stability values (i.e., increase of extraction temperature over time). In the case of high flow rates, the extraction temperature is smaller than other cases and doesn't considerably decrease over time. Consequently, the cases with moderate flow rates reneging between 15 L/s and 30 L/s experience the highest temperature drawdown over time.

4.3 Characterization of best operation scenarios

The main idea of designing MCDG systems is to enhance the heat absorption per meter of the system. However, operating with MCDG systems doesn't always result in a better performance than simple closed geothermal structures. Therefore, an index called specific power is defined to compare the performance of various MCDG systems in terms of the ratio of generated thermal power to relative drilling expenses.

$$P_s = \frac{generated\ power}{equivalent\ total\ length} \quad [7]$$

Where equivalent total length is normalized/simplified indicator of relative drilling costs.

$$Equivalent\ total\ length = total\ length\ of\ vertical\ wellbores + 2 \times total\ length\ of\ horizontal\ wellbores \quad [8]$$

It is assumed that the construction expense of horizontal wellbores is two times that of injection wellbores. Nonetheless, drilling technology, length of the wellbores, their diameter, casing program, and other complicated parameters can change this factor of two. For a simple closed deep system operating with a flow rate of 5 L/s (Esmaeilpour et al., 2021), the value of specific power is 70.81 W/m. Therefore, it is reasonable to operate with an MCDG system when its specific power is higher than 70.81 W/m.

Figure 6 shows the average temperature drop in the production wellbore and the specific power of different MCDG systems. The cases with minimum temperature drawdown in the production wellbore are capable of producing hotter fluid that leads to a higher specific power.

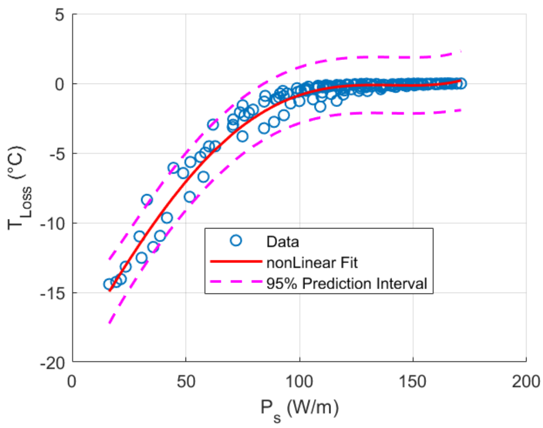


Figure 6: average temperature loss in the production well of various MCDG systems versus their specific power.

The high specific power doesn't guarantee that an MCDS system is appropriate for the operation. Reasonable extraction temperature is another important factor that should be taken into account when designing multilateral systems.

Figure 7 shows specific flow rates of MCDG systems defined by:

$$Q_s = \frac{flow\ rate\ (L/s)}{NIW + 2 \times NHW + 1} \quad [9]$$

Where NIW and NHW are the numbers of injection and horizontal wellbores, respectively.

As an example, the cases with an average extraction temperature of higher than 60 °C and specific power of bigger than 70.81 W/m are assumed to be convenient for operation and highlighted by red color in Figure 7. It seems that a specific flow rate of smaller than 2.25 is an accurate indicator of high-performance MCDG systems. A higher specific flow rate causes the extraction temperature to be smaller than 60 °C.

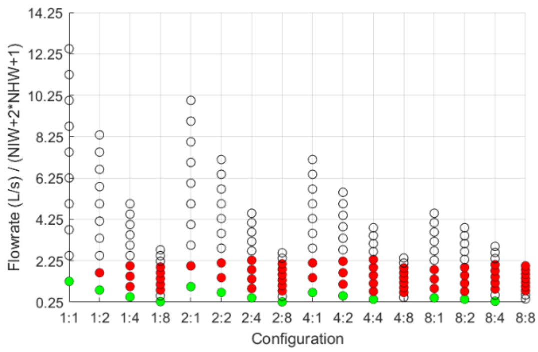


Figure 7: specific flow rates of various MCDG systems. Green pints show the cases with a flow rate of 5 L/s that have been excluded from our investigation.

5. CONCLUSIONS

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

1. The operating flow rate of MCDG systems should be high enough to extract the maximum thermal potential of the system, increase the generated thermal power and compensate for its notable drilling expenses. However, exceeding a critical value leads to the reduction of the extraction temperature

and doesn't change the power production considerably.

2. Operating flow rate plays a key role in the extraction temperature stabilization of MCDG systems. The Nusselt number and the thermal exposure duration (i.e., the period in which the working fluid is exposed to the surrounding formation) depend on fluid velocity. The results of this study revealed that operating at a specific range of flow rate can stabilize the extraction temperature.
3. Operating with MCDG systems doesn't always result in a better performance than simple closed deep geothermal systems. The high-performance MCDG frameworks are characterized by a special relation between flow rate and the number of injection/horizontal wellbores.

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