

Improved Heat Production from Upgraded Closed-loop Geothermal System with Multi-wing Fracture

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ABSTRACT

Closed-loop geothermal systems represent an emerging approach to geothermal energy utilization that operates without the need for sustained external fluid injection. However, their thermal performance is frequently constrained by the limited interfacial area available for heat transfer between the wellbore and the adjacent geological formation. Incorporating a thermally conductive fracture is a potential approach to improving closed-loop systems heat extraction. However, the heat extraction improvement effect of a multi-wing fracture has not been clarified yet. This work introduces an upgraded closed-loop geothermal system (UCGS) featuring a multi-wing fracture filled with thermally conductive proppants and connected to the well bottom, thereby improving heat transfer efficiency in the near-well region. A fully coupled three-dimensional hydrothermal numerical model is developed for the UCGS, on the basis of which a numerical study is conducted to evaluate heat extraction behavior under varying fracture dimensions and geometries. The results demonstrate that incorporating conductive fractures outperforms a conventional closed-loop system in terms of thermal production. Increase in fracture wing length and that in fracture height both lead to heat production improvement. For an identical fracture cross-sectional area, increasing fracture height is more effective in enhancing heat extraction than enlarging fracture thickness. As the number of fracture wings increases, both production temperature and cumulative net heat output increase at diminishing rates. Introducing a multi-wing fracture increases the 10-year cumulative thermal output by up to 19.23%. Results obtained from this study can inform improved design of closed-loop systems in future projects.

1. INTRODUCTION

The sustained reliance on fossil fuel extraction and utilization over recent decades has led to a growing range of environmental challenges, including greenhouse gas emissions, soil degradation, and water contamination (Kiran et al., 2017). Addressing these impacts necessitates the accelerated development of low-carbon and renewable energy alternatives. Among such options, geothermal energy has attracted increasing attention due to its stability and low environmental footprint. Conventional geothermal exploitation typically involves drilling wells into high-temperature formations, injecting a cold working fluid—most commonly water—into the subsurface, and recovering heated fluid or steam through production wells. Historically, this approach relied on open-loop configurations, in which sustained heat extraction requires a continuous and abundant supply of circulating fluid. Also, to maintain hydraulic integrity of wellbores in high-temperature subsurface environments, high-temperature resistant sealing materials are required for geothermal systems (Liu and Taleghani, 2024; Liu et al., 2025).

To improve subsurface fluid circulation, Enhanced Geothermal Systems (EGS) were introduced, wherein engineered fracture networks are created to facilitate water injection and heat exchange within hot rock formations (Liu et al., 2021; Ji et al., 2025; Zhang et al., 2026). In EGS operations, injected cold water flows through induced fractures, absorbs thermal energy from the surrounding rock, and is subsequently produced at elevated temperatures. However, the viability of EGS is strongly dependent on the availability of large volumes of water (Zhang and Zhao, 2020). In addition, injection-induced seismicity remains a critical concern, limiting deployment in regions sensitive to seismic hazards (Dahi Taleghani, 2013).

In response to these limitations, closed-loop geothermal systems have been proposed as an alternative that eliminates the need for continuous fluid injection into the reservoir. In such systems, the working fluid circulates entirely within a sealed wellbore, thereby preventing fluid loss and reducing the risk of induced seismicity. As a relatively recent technological development, closed-loop systems offer promising opportunities for broad application. Closed-loop systems are commonly classified into coaxial and U-loop configurations. Coaxial systems employ concentric tubing to separate injected and produced fluids, whereas U-loop systems consist of paired injection and production wells connected by horizontal laterals.

A few studies have investigated the thermal behavior of coaxial closed-loop systems. Bu et al. (2012) examined heat production from repurposed oil and gas wells, focusing primarily on the influence of the fluid circulation rate. Some studies assessed the role of convection in coaxial systems (Wang et al., 2021; Bidarmaghz and Narsilio, 2022), but these analyses relied on reservoir permeabilities rarely encountered at depth. Ahmadi and Dahi Taleghani (2016) incorporated conductive fractures into a closed-loop framework using a two-dimensional horizontal well model, while Liu et al. (2024) proposed an advanced closed-loop geothermal system that incorporated a vertically partitioned fracture into the fluid flow path.

Despite these efforts, heat extraction in closed-loop systems remains largely constrained by conductive heat transfer, as convective processes are minimal under typical deep-reservoir conditions. To address this limitation, U-loop systems with horizontal laterals have been proposed and examined. Song et al. (2018) developed a transient heat transfer model with variable coefficients to investigate U-loop

performance under different operational conditions. Additional studies explored the potential contribution of natural convection (Zhao et al., 2022), concluding that permeabilities on the order of 10 Darcy are required for convection to significantly enhance heat extraction.

Although substantial progress has been made, several important gaps remain. Closed-loop systems still exhibit limited thermal efficiency, hindering their commercial deployment. Most existing studies consider only fundamental configurations without fractures, and the potential benefits of modifying the near-wellbore region to enhance heat transfer have not been systematically evaluated. Also, the effect of multi-wing fractures on CLGS heat extraction has not been analyzed yet.

To address these knowledge gap, this study conducts a numerical investigation of an upgraded closed-loop geothermal system (UCGS). A three-dimensional, coupled hydrothermal model is developed in which a multi-wing fracture filled with thermally conductive proppants is introduced near the wellbore to improve heat transfer. Using this framework, the effects of fracture dimensions and geometry on heat extraction from the UCGS is explored.

2. MODELING OF UPGRADED CLOSED-LOOP GEOTHERMAL SYSTEM

2.1 Geometric model

Figure 1a illustrates the three-dimensional configuration of a conventional closed-loop geothermal system (CLGS), while Figure 1b presents a longitudinal cross-section from the ground surface to the well bottom to clarify its internal structure. The system is represented as a vertically oriented cylindrical assembly composed of multiple concentric components, including the host rock, cement layer, steel casing, and an inner insulation tube. The annulus between the casing and the insulation tube is designated as the injection channel, whereas the inner lumen of the insulation tube acts as the production pathway. Turbulent flow conditions are assumed for the working fluid in both the injection and production sections. Water, prescribed with a constant inlet temperature and mass flow rate, is injected into the well, absorbs thermal energy from the surrounding high-temperature formation, and is subsequently recovered at the production outlet in a heated state.

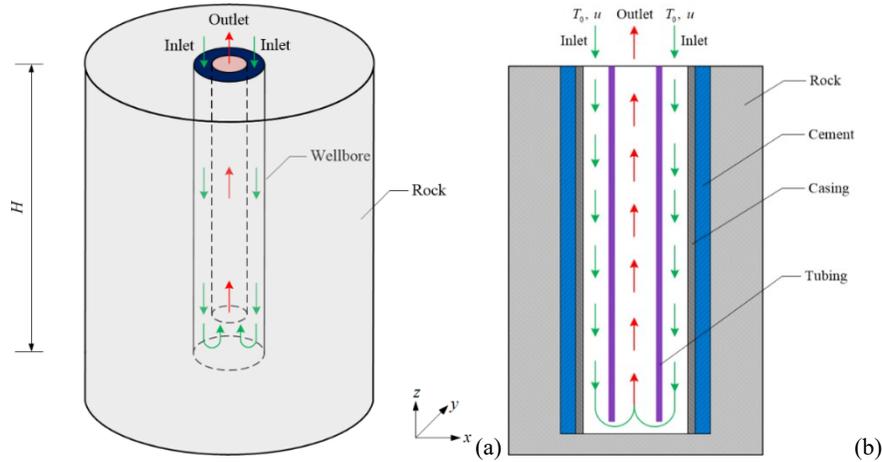


Figure 1: Basic closed-loop geothermal system: (a) 3D diagram; (b) xz cross-section.

On the basis of the basic CLGS configuration shown in Figure 1, an upgraded closed-loop geothermal system (UCGS) was constructed, as depicted in Figure 2. In this enhanced design, a thermally conductive multi-wing fracture is attached to the well bottom and incorporated into the original closed-loop layout. This multi-wing fracture can be generated through pulse fracturing techniques or hydraulic fracturing when horizontal in-situ stress difference is small (Liu et al., 2019; Yang et al., 2025a,b, 2026a,b). For improved visualization of the internal system layout, the surrounding rock formation is excluded from the schematic illustration. A Cartesian coordinate framework is adopted to describe the system geometry, where the xy -plane is perpendicular to fracture wings, and the z -axis denotes the vertical direction. The principal outputs extracted from the developed three-dimensional UCGS model include the produced-fluid temperature, defined as the temperature of the working fluid at the production outlet, and the net power, representing the effective heat extraction rate after accounting for the pumping energy required to sustain fluid circulation. The numerical investigation aims to evaluate the thermal recovery capability of the UCGS under a range of operating conditions, with the objective of elucidating the mechanisms controlling system thermal performance.

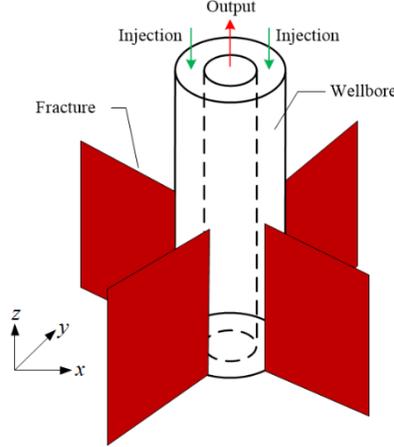


Figure 2: Upgraded closed-loop geothermal system.

2.2 Governing equations

The physical processes considered in this study primarily comprise fluid motion within the wellbore and heat transport throughout the coupled rock–wellbore system. Fluid flow is restricted to the annular space and the inner tubing of the well and is treated as incompressible, thereby satisfying mass conservation. The thermophysical properties of the circulating working fluid are assumed to remain constant and to be insensitive to temperature variations. Because the working fluid is confined to the wellbore, fluid flow within the surrounding rock matrix and fracture network is neglected.

Thermal transport represents the second key process and occurs throughout the entire system. Heat is conveyed through the reservoir rock, fracture, cement sheath, casing, and the fluid circulating in the wellbore. Two fundamental heat transfer modes are involved, namely conduction and convection. Heat transfer within the reservoir rock and fracture toward the wellbore wall is governed solely by conductive processes. In contrast, heat exchange between the wellbore wall and the moving fluid is dominated by convection induced by fluid motion, with conductive effects being insignificant. Heat transfer within the ECLGS is formulated using the corresponding energy conservation equations. For solid components, including the insulation tubing, casing, and cement sheath, the heat conduction governing equation is (Liu and Dahi Taleghani, 2022)

$$\rho_s C_{p,s} \frac{\partial T_s}{\partial t} - \lambda_s \nabla^2 T_s = 0 \quad (1)$$

where t is time; T_s represents solid temperature; ρ_s means solid density; $C_{p,s}$ is the solid heat capacity; λ_s denotes solid thermal conductivity. As for working fluid flowing in the well, its heat transfer equation is formulated as (Liu et al., 2023a)

$$\rho_f C_{p,f} \frac{\partial T_f}{\partial t} + \rho_f C_{p,f} \mathbf{u} \nabla T_f - \lambda_f \nabla^2 T_f = 0 \quad (2)$$

where T_f is fluid temperature; ρ_f is fluid density; $C_{p,f}$ is fluid heat capacity; λ_f is fluid thermal conductivity; \mathbf{u} means flow velocity. The second term in Eq. (2) represents the advective transport of thermal energy, reflecting the coupling between fluid motion and heat transfer.

The fracture intersecting the wellbore is assumed to be packed with fine-grained proppants possessing exceptionally high thermal conductivity. In the numerical implementation, the presence of this thermally enhanced fracture is represented by assigning an elevated thermal conductivity to the fracture region. Heat transfer within the reservoir domain, encompassing both the host rock and the conductive fracture, is modeled with porosity taken into account, and the reservoir is presumed to be fully saturated with groundwater. Within this domain, thermal transport is restricted to conduction alone; consequently, heat flow through the fracture is governed by the local temperature gradient in accordance with Fourier's law. The energy balance equations describing heat transfer in the rock matrix and in the fracture are given by Eqs. (3a) and (3b), respectively (Kaviany, 1995).

$$(\rho C_p)_{eff} \frac{\partial T_r}{\partial t} - \nabla \cdot (\lambda_{eff} \nabla T_r) = 0 \quad (3a)$$

$$d_{fr} (\rho C_p)_{eff} \frac{\partial T_r}{\partial t} - \nabla \cdot (d_{fr} \lambda_{eff} \nabla T_r) = 0 \quad (3b)$$

where T_r is the temperature in rock; d_{fr} means fracture thickness. The effective heat capacity $(\rho C_p)_{eff}$ can be obtained as (Liu et al., 2023b)

$$(\rho C_p)_{eff} = \phi \rho_w C_{p,w} + (1 - \phi) \rho_m C_{p,m} \quad (4)$$

In this formulation, ϕ denotes the porosity of the reservoir, while ρ_w and ρ_m correspond to the densities of the pore fluid (groundwater) and the solid matrix, respectively. The symbols $C_{p,w}$ and $C_{p,m}$ represent the heat capacities of the groundwater and the rock matrix. The

parameter λ_{eff} refers to effective thermal conductivity, which is defined as a composite value obtained by averaging the thermal conductivities of the solid grains and the pore fluid, expressed as

$$\lambda_{eff} = \phi\lambda_w + (1 - \phi)\lambda_m \quad (5)$$

where λ_w and λ_m are respectively the thermal conductivities of the underground fluid and porous matrix.

Based on the prescribed mass flow rate of the circulating working fluid and the temperature differential between the injection and production streams, the overall rate of thermal energy recovery at the outlet of the production conduit can be determined using the following relationship (Hasan and Kabir, 2018).

$$W_{total} = \dot{V}\rho_f C_{p,f}(T_{out} - T_{in}) \quad (6)$$

Here, \dot{V} corresponds to the volumetric flow rate of the working fluid within the wellbore, T_{in} represents the temperature of the fluid at the injection point, and T_{out} denotes the temperature of the fluid at the production outlet. The mechanical power required to drive the fluid through the wellbore, overcoming frictional losses, is expressed as follows (Kundu et al., 2015).

$$W_{pumping} = \dot{V} \cdot \Delta p \quad (7)$$

Here, Δp is the pressure difference between the inlet and outlet. Net heat power acquired is calculated as

$$W_{net} = W_{total} - W_{pumping} \quad (8)$$

For numerical resolution, the governing equations are first spatially discretized employing appropriate shape functions. Subsequently, temporal discretization is applied to account for time-dependent behavior. The resulting set of finite element equations is ultimately solved through an implicit iterative procedure, utilizing the Newton-Raphson method for convergence.

3. RESULTS AND DISCUSSION

An examination of the UCGS configuration depicted in Figure 2 indicates several critical parameters that can significantly influence its heat extraction performance. To systematically investigate the effects of these parameters, a baseline numerical model was first established, forming the foundation for a comprehensive series of simulations. Table 1 summarizes the geometric, material, and boundary condition parameters adopted for the baseline model. The fracture was assigned a thermal conductivity of 44.91 W/(m·K) by referring to the effective thermal conductivity of copper-coated aluminum nitride proppants (40-70 mesh) measured by Al Balushi and Dahi Taleghani (2023).

Table 1: Parameters employed for upgraded closed-loop geothermal system simulation (OD: outer diameter; ID: inner diameter).

Parameter (Unit)	Value
Insulation tube OD (mm)	168.3
Insulation tube ID (mm)	114.3
Casing OD (mm)	244.5
Casing ID (mm)	215.9
Wellbore depth (m)	2000.0
Fluid flow rate (m ³ /h)	10.35
Injection temperature (°C)	40.0
Ground temperature (°C)	20.0
Rock temperature at bottom of wellbore (°C)	120.0
Length of fracture wing (m)	100.0
Thermal conductivity of fracture [W/(m·K)]	44.91
Thermal conductivity of cement [W/(m·K)]	0.8
Thermal conductivity of rock [W/(m·K)]	3.0
Density of rock (kg/m ³)	2800.0
Heat capacity of rock [J/(kg·K)]	920.0
Thermal conductivity of casing [W/(m·K)]	45.0
Thermal conductivity of insulation tube [W/(m·K)]	0.006

3.1 Effect of fracture dimensions

To quantitatively evaluate the influence of fracture dimensions on UCGS performance, a series of numerical simulations was conducted based on a UCGS with a dual-wing fracture. Five scenarios were considered: Case 0 with no fracture; Case 1 with $H_{fr} = 200$ m and $t_{fr} = 2$ cm; Case 2 with $H_{fr} = 200$ m and $t_{fr} = 4$ cm; Case 3 with $H_{fr} = 400$ m and $t_{fr} = 2$ cm; and Case 4 with $H_{fr} = 400$ m and $t_{fr} = 4$ cm, where H_{fr} and t_{fr} denote fracture height and thickness, respectively. The thermal conductivity of the fracture was maintained at 44.91 W/(m·K) for all cases. Results corresponding to these configurations are presented in Figures 3–5.

Figure 3 illustrates that increasing either H_{fr} or t_{fr} enhances both net power and extracted fluid temperature. This improvement arises because enlarging H_{fr} or t_{fr} reduces the thermal resistance associated with heat transport through the fracture, thereby allowing a greater heat flux to reach the working fluid per unit time. The expansion of the cooled region adjacent to the well, shown in Figure 5, corroborates this mechanism. A comparison of Cases 2 and 3 reveals that, for identical fracture cross-sectional areas, a taller fracture with smaller thickness produces higher heat output than a shorter fracture with greater thickness, indicating that increasing fracture height is more effective than increasing thickness for improving UCGS heat extraction. After 10 years, the fracture with $H_{fr} = 400$ m and $t_{fr} = 4$ cm delivers the highest extracted fluid temperature (55°C) and cumulative net thermal output (1.71×10^7 kWh), representing increases of 1.22°C and 9.62% , respectively, compared with the no-fracture baseline (53.78°C and 1.56×10^7 kWh).

These findings demonstrate that constructing a thermally conductive fracture with larger height or thickness is an efficient strategy to enhance UCGS heat recovery. To maximize both extracted fluid temperature and cumulative thermal output over the operational period, it is advisable to implement fractures that are both tall and thick. When the fracture cross-sectional area is constrained, for example by the available proppant volume, prioritizing increased fracture height over thickness is recommended. Nevertheless, the additional costs associated with fracturing operations and high-thermal-conductivity proppants must be carefully considered relative to the expected thermal gains during the system design process.

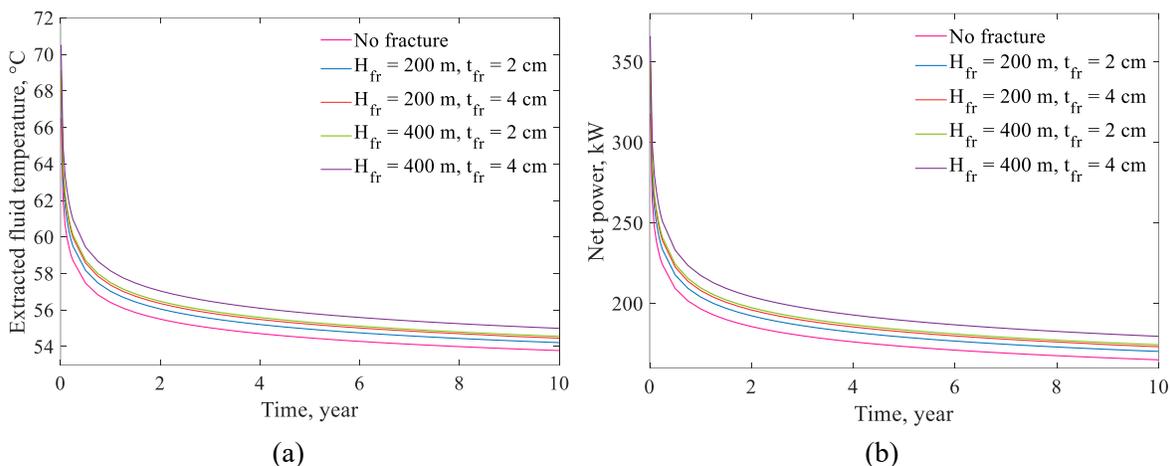


Figure 3: Effect of fracture dimensions on (a) extracted fluid temperature; (b) net heat power.

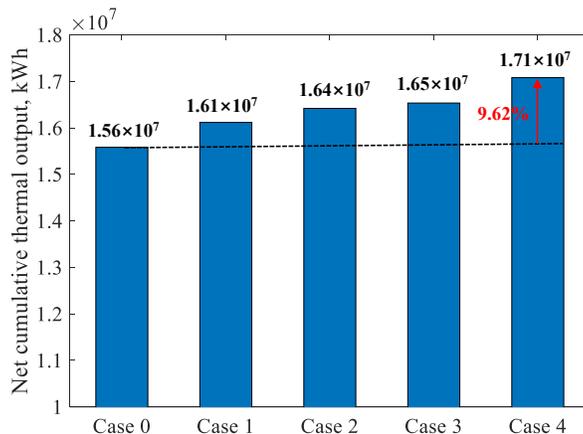


Figure 4: Effect of fracture dimensions on over-10-year net cumulative heat output.

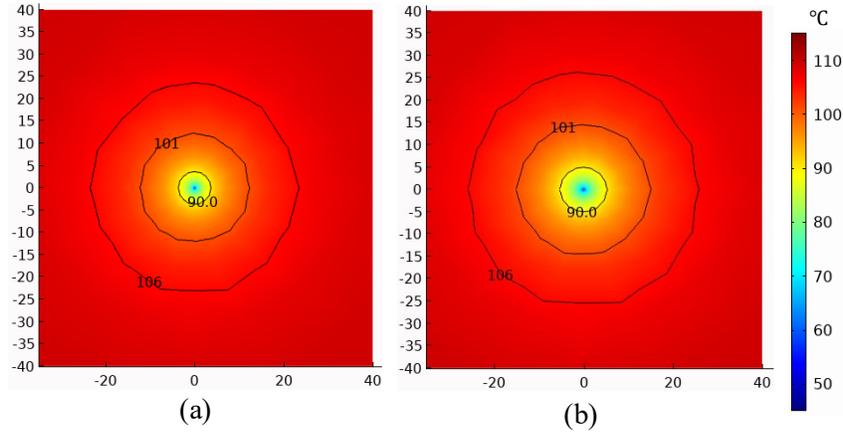


Figure 5: xy cross-sections of after-10-year temperatures for cases (a) without and (b) with fracture (cut at fracture's vertical middle).

3.2 Heat extraction with multi-wing fractures

The analyses discussed in the previous section focused exclusively on a dual-wing fracture configuration. Given the demonstrated heat extraction enhancement provided by fracture wings, it is reasonable to hypothesize that incorporating multiple fracture wings could further increase thermal recovery. Nevertheless, the effect of multi-wing fractures on improving heat extraction in CLGSs remains insufficiently understood. To address this, numerical simulations were conducted to evaluate the thermal performance of a UCGS as a function of the number of fracture wings. The number of fracture wings (NFW) was varied from 2 to 6, with configurations exceeding two wings classified as multi-wing fractures. The respective fracture geometries for these cases are illustrated in Figure 6, showing that the phase angle between adjacent wings, inversely related to NFW, decreases from 180° to 60° .

The simulation results in Figure 7 indicate that increasing NFW significantly enhances heat extraction from the UCGS. As NFW rises, both the extracted fluid temperature and net power improve, although at a slightly diminishing rate over time. This enhancement occurs because additional fracture wings reduce the overall thermal resistance between the formation and the well, promoting more efficient heat transfer into the circulating fluid. The temperature distributions in Figure 9 confirm this effect, showing an expanded cooled region near the well as NFW increases, particularly when increasing from 2 to 3 wings, which allows heat to be extracted from a larger volume of the reservoir. The slight decline in marginal gains with higher NFW is attributed to thermal interference among adjacent conductive fracture wings, which compete to transfer heat to the wellbore. Nevertheless, even when increasing NFW from 5 to 6, substantial improvements in heat production are observed. Figure 8 shows that the net cumulative thermal output generally increases with NFW, though at a gradually diminishing rate. After 10 years, the configuration with six fracture wings achieves an extracted fluid temperature of 56.24°C and a cumulative thermal output of 1.86×10^7 kWh, representing respective increases of 2.46°C and 19.23% relative to the no-fracture case.

In summary, integrating additional fracture wings represents an effective approach for further enhancing the thermal performance of a UCGS. For maximizing both extracted fluid temperature and cumulative thermal output over the operational period, implementing multiple fracture wings near the wellbore is recommended. Furthermore, employing a multi-wing fracture may serve as a viable alternative to constructing a taller and thicker dual-wing fracture, offering comparable or improved heat extraction benefits.

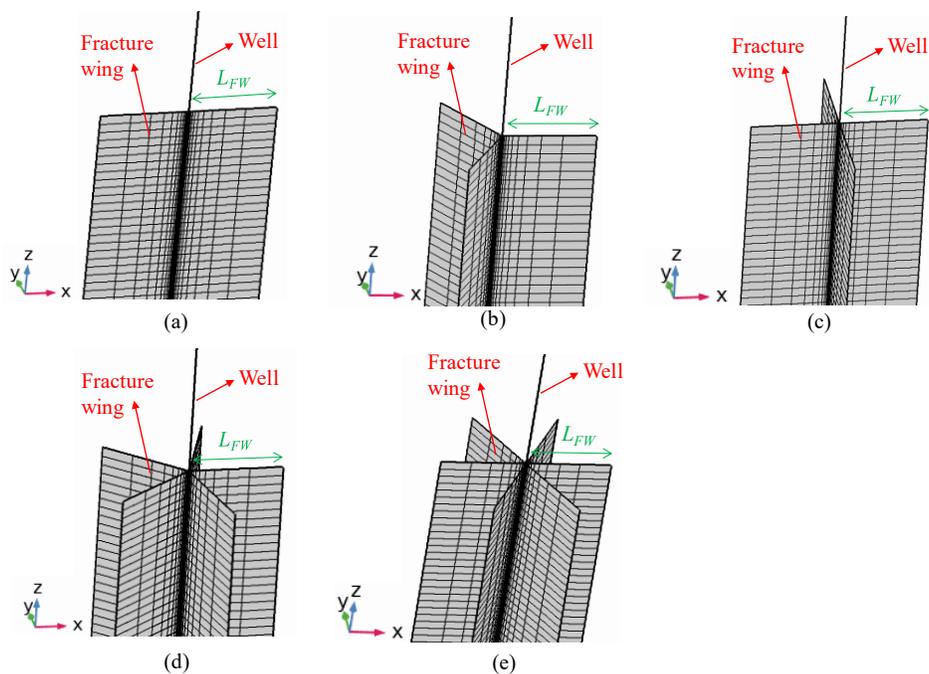


Figure 6: Configurations of fractures with (a) 2, (b) 3, (c) 4, (d) 5, and (e) 6 wings (L_{FW} : length of fracture wing).

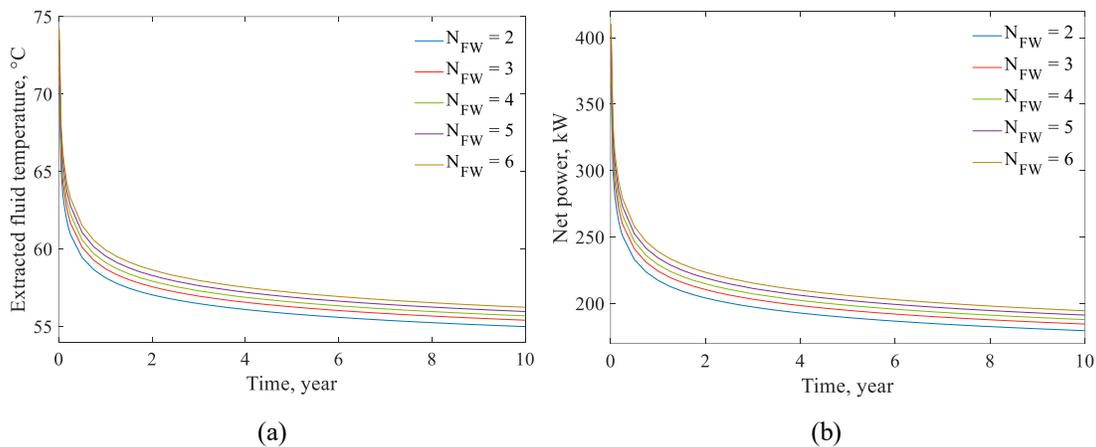


Figure 7: Effect of fracture wings number on (a) temperatures of extracted fluid; (b) net heat power (N_{FW} : fracture wings number).

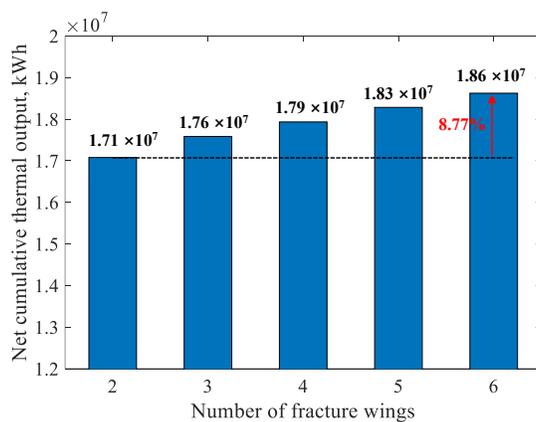


Figure 8: Effect of fracture wings number on over-10-year net cumulative heat output.

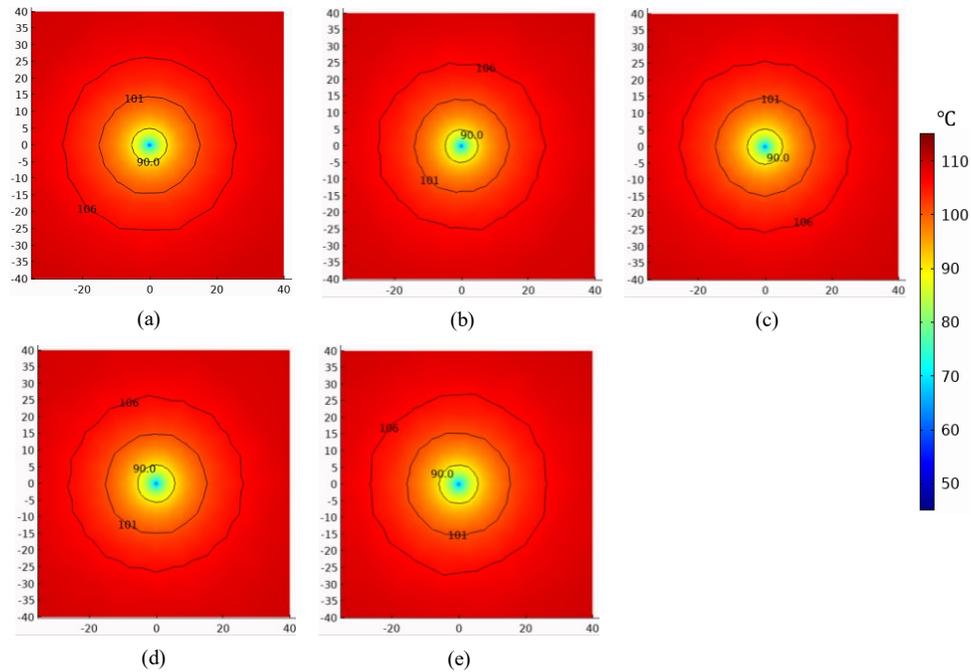


Figure 9: xy cross-sections of after-10-year temperatures for cases having (a) 2, (b) 3, (c) 4, (d) 5, and (e) 6 fracture wings.

4. CONCLUSIONS

This study introduces a UCGS that integrates a multi-wing thermally conductive fracture to enhance heat transfer in the near-well region and thereby improve overall heat extraction efficiency. A three-dimensional numerical framework coupling wellbore fluid flow with heat transport was developed to simulate the UCGS. Using this model, extensive parametric simulations were conducted to evaluate system performance under varying fracture geometries and configurations. The principal conclusions are summarized as follows.

Compared with a conventional closed-loop system without fractures, the UCGS incorporating a dual-wing conductive fracture achieves superior thermal performance, with the extracted fluid temperature and net cumulative heat output after 10 years increased by 1.22 °C and 9.62%, respectively. Enhancing either fracture height or thickness leads to improved heat recovery; however, for a fixed fracture cross-sectional area, increasing fracture height is more effective than enlarging fracture thickness. An increase in the number of fracture wings (NFW) leads to near-linear improvements in both produced fluid temperature and net power over time. The presence of a multi-wing fracture raises the net cumulative thermal output by up to 19.23%, and this enhancement further increases to 73.08% when a thermo-socket is additionally employed. Overall, these results demonstrate the strong thermal advantages of the proposed UCGS and establish it as a promising advancement in closed-loop geothermal technology. The considerable improvements in heat extraction highlighted in this work provide valuable guidance for the future design and optimization of high-performance closed-loop systems.

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