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Evaluating Heat Extraction Performance of Closed-Loop Geothermal Systems with Thermally Conductive Enhancements in Conduction-Only Reservoirs

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ABSTRACT

We investigated the impact of disc-shaped and linear thermal enhancements on performance of closed-loop geothermal systems using steady-state and transient COMSOL numerical simulations. Thermal enhancements refer to thermally conductive material introduced in the rocks surrounding a wellbore to compensate for the relatively low rock thermal conductivity and increase heat extraction. Materials proposed include composite cements with thermally conductive additives such as metals or graphite to obtain overall cement thermal conductivities of 10 to 100× the rock thermal conductivity. Our simulation approach was modeling a subsegment (e.g., 100 m long) of a wellbore with idealized (e.g., perfect disc-shaped) thermal enhancements, and we report results as relative increase in heat extraction with respect to systems without thermal enhancements. We did not evaluate technical feasibility or cost of installing thermal enhancements.

Simulations indicate that for 5-mm thick disc-shaped thermal enhancements with 5-m radius, repeated every 1 m along the wellbore and with thermal conductivity of 100× the rock thermal conductivity, the thermal output increases roughly 20% with respect to a closed-loop system without thermal enhancements. For fishbone structure thermal enhancements, we estimate a roughly 7% increase in thermal output for 5-m long radially outward pipes with half the radius of the main wellbore, repeated every 2.5 m, with thermal conductivity of 100× the rock thermal conductivity.

1. INTRODUCTION

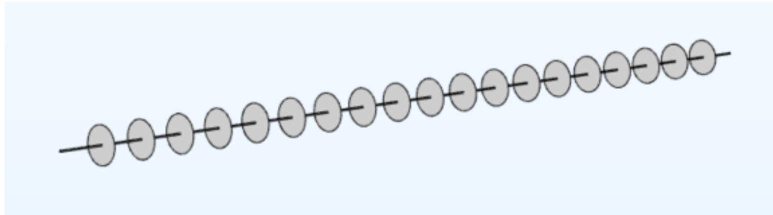
Prior research on the performance of closed-loop geothermal systems, including work done by the Closed Loop Geothermal Working Group (e.g., White et al. (2024); Beckers et al. (2022; 2023)), found challenging thermal performance in conduction-only reservoirs due to low rock thermal conductivity (i.e., 2 to 3 W/m/K) and limited heat exchange area for heat transfer between the circulating fluid and the rock. One approach to overcome these challenges and create multi-MW systems is developing very long wellbores and laterals, such as the Eavor 2.0 design studied in Beckers and Johnston (2022), requiring 80+ km of well drilling. Another approach for increasing thermal output is by artificially increasing the overall reservoir thermal conductivity by introducing highly conductive material into the rock surrounding the wellbore, also referred to as *thermal enhancements*.

Two proposed thermal enhancement designs in literature, which are discussed in this paper, are (1) existing or newly created fractures surrounding the wellbore filled with highly conductive material and (2) a "fishbone structure" where short wellbores are drilled radially outward from the main wellbore and filled with highly conductive material. A schematic of these two designs is presented in Figure 1, where in the first design the fractures are considered circular, and in the second design, the radially outward wellbores are assumed to have alternating orientations.

Cement compositions with thermally conductive additives have been proposed for thermal enhancement materials (Moncarz et al., 2018). Additives proposed include metals (e.g., iron), metal alloys (e.g., carbon steel), or other highly thermally conductive materials such as graphite or carbon nanotubes. Additive thermal conductivities vary from several 10's to 100's of W/m/K for metals and metal alloys and up to several 1,000's of W/m/K for graphite and carbon nanotubes. The cement composition may have an overall thermal conductivity of up to a few 100's of W/m/K, which is up to two orders of magnitude higher than a typical rock thermal conductivity (2 to 3 W/m/K).

Ahmadi and Taleghani (2017) studied the impact of highly thermally conductive material in a fracture intersected by a co-axial closed-loop well. For a 4-cm thick fracture intersected by a 100-m long wellbore with radius of 0.11 m, they find an increase in thermal output of 100× with thermal enhancement material thermal conductivity of 150 W/m/K. This increase appears much higher than our results (see Section 2). Their domain setup (Figure 2 in Ahmadi and Taleghani (2017)) is unclear as it appears they simulated a 2D axisymmetric model but with the wellbore potentially incorrectly modeled radially instead of axially.

Fowler and McClure (2021) compared thermal performance of three geothermal designs: closed-loop systems, closed-loop systems with thermal enhancements, and open-loop systems. The closed-loop system with thermal enhancements considered a 6-km long lateral at 3-km depth that is intersected by 400 fractures filled with highly thermally conductive material. The well is a monobore with 7" (0.18 m) outer diameter and 6.25" (0.16 m) inner diameter. Each fracture is 500 m long and 100 m wide. Two fracture apertures were considered: 2.5 mm and 5 mm. Values considered for the fracture material thermal conductivity are 1,000, 10,000 and 100,000 W/m/K. For the scenario with 5-mm thick fractures with thermal conductivity of 1,000 W/m/K, the thermal output increased by roughly 1% in comparison with the closed-loop system without thermally conductive fractures. For 2.5-mm thick fractures, the increase in thermal output is about 0.5%. For fracture thermal conductivities of 10,000 and 100,000 W/m/K, the thermal output increased by about 20% and 90%, respectively. The results provided in Fowler and McClure (2021) are in line with the findings presented in our paper.



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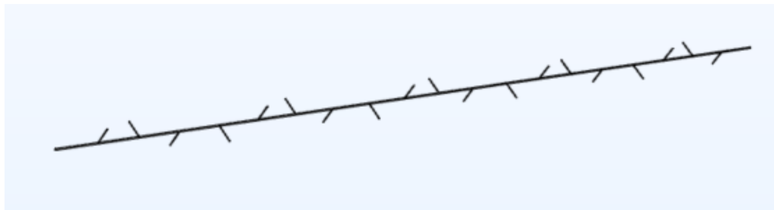

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Figure 1: Two thermal enhancement designs discussed in this paper: (a) disc-shaped fractures surrounding wellbore filled with highly conductive material and (b) "fishbone" structure with radially outward wellbores filled with highly conductive material. In both designs, the heat transfer fluid flows inside the wellbore, e.g., entering on the left side and exiting from the right. The wellbore shown only represents a subsection, e.g., a 1-km long horizontal segment of a total closed-loop system.

Fowler and McClure (2021) also presented a steady-state analytical model to estimate increase in thermal output Q (W) with thermal enhancements:

$$Q = NKWG\Delta T$$

where N is the number of fractures (-), K is the fracture thermal conductivity (W/m/K), W is the width of the fractures (m), G is a dimensionless geometric term (representing "perimeter of flow" divided by distance), and ΔT is the temperature difference between the injection temperature of the water and the farfield rock temperature (K). Fowler and McClure (2021) report comparable results for thermal output increase calculated with the analytical model and the numerical reservoir model.

In this paper, we present simulation results for the thermal output using disc-shaped and fishbone thermal enhancements for a range of conditions. We applied the COMSOL Multiphysics numerical simulator (version 6.1) for studying disc-shaped thermal enhancements using a two-dimensional axisymmetric model, and for studying fishbone structure thermal enhancements using a full three-dimensional model. We applied the Slender-Body Theory (SBT) Transient Heat Transfer Simulator (Beckers et al., 2015) for providing a test case to validate the COMSOL model. We did not investigate the technical feasibility or cost for developing thermal enhancements; rather, we focused on estimating the increase in thermal output when implementing thermal enhancements with respect to systems without thermal enhancements. Our objective was not to find an "optimum" design or explore the entire domain space, but rather to conduct a high-level assessment of performance boost with such systems and investigate the impact of a few key parameters. Disc-shaped thermal enhancements are studied in Section 2. Section 3 presents results for fishbone thermal enhancements. Conclusions are provided in Section 4.

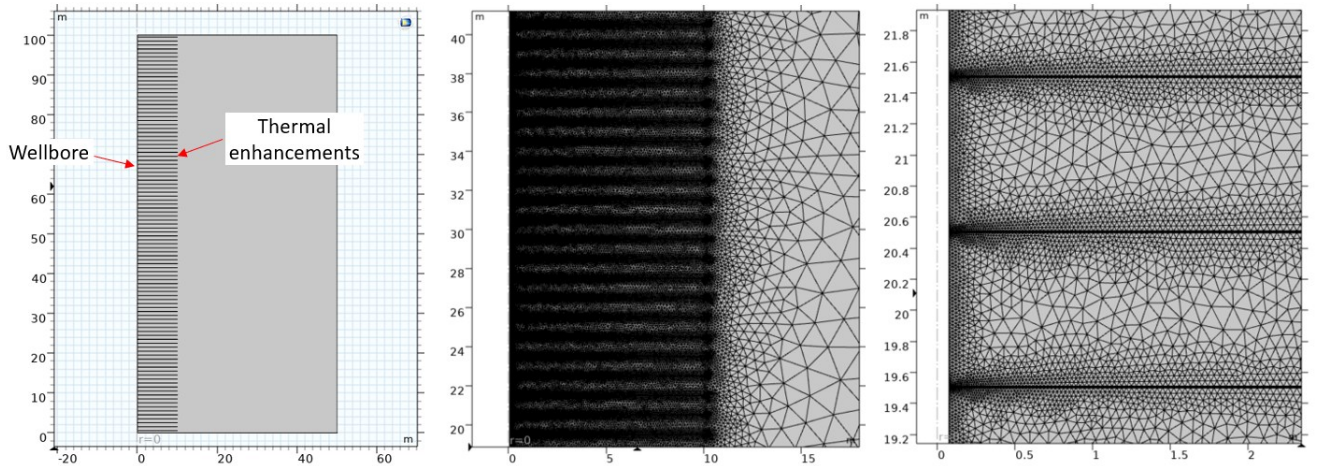
2. DISC-SHAPED THERMAL ENHANCEMENTS

We developed COMSOL steady-state and transient numerical models to investigate the impact of disc-shaped fractures filled with conductive material (Figure 1a) on increase in thermal output with respect to closed-loop systems without thermal enhancements.

2.1 Steady-State COMSOL Simulations

Thermal output with closed-loop systems exhibits a characteristic profile of a rapid initial decline followed by a relatively steady production temperature. By setting a constant far field temperature as boundary condition, this long-term behavior can be approximately simulated with a steady-state simulation, saving significantly on computational time, and allowing to run a large number of cases (e.g., for a sensitivity study). This observation agrees with the work by Fowler and McClure (2021), which found that a simple analytical steady-state model yields comparable results as a fully transient nummerical simulation for these type of systems.

We developed a steady-state axisymmetric model in COMSOL to investigate the relative impact of disc-shaped thermal enhancements on thermal output (Figure 2). The model is 100 m long and represents a segment of a lateral. The radius (with constant temperature as boundary condition) is set at 50 m, which is approximately the radial diffusion length of a thermal pulse due to an infinite line source in



(a) (b) (c)

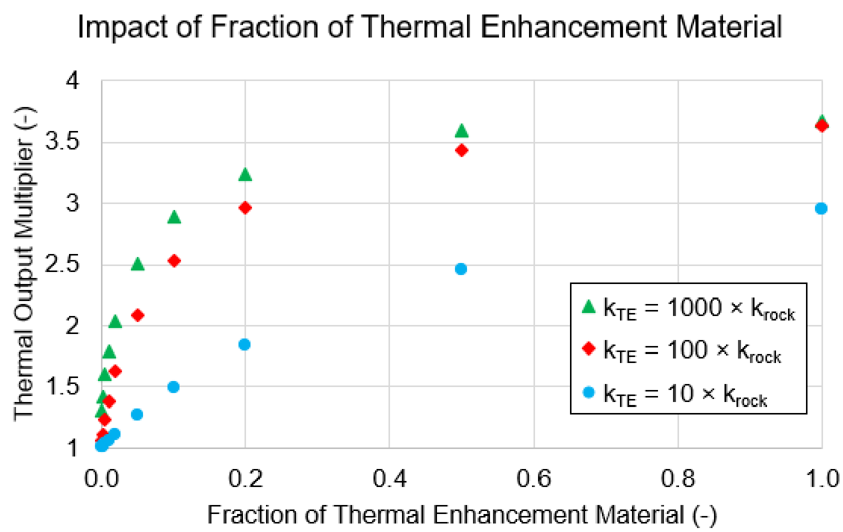
Figure 2: COMSOL model for steady-state simulations with disc-shaped thermal enhancements. (a) Model developed is 100-m long axisymmetric "segment" of a lateral with 100 equally spaced "fractures" or "discs" with radius of 10 m and made of highly conductive material. Fluid (i.e., water) flows axially along the segment (wellbore center located at r=0 and with wellbore radius of 0.0762 m). (b) Two-dimensional triangular mesh was assumed with fine elements along the wellbore and along the fractures, and coarse elements further away. (c) Close-up of mesh around the disc-shaped fractures.

Table 1: COMSOL model assumptions for studying disc-shaped thermal enhancements.

Parameter	Value
Model thickness	100 m
Model radius	50 m
Wellbore radius	0.0762 m
Fluid flow rate	2 kg/s
Fluid specific heat capacity	4,200 J/kg/K
Fluid density	1,000 kg/m^3
Fluid thermal conductivity	0.68 W/m/K
Fluid inlet temperature	50°C
Rock density	2,875 kg/m^3
Rock specific heat capacity	825 J/kg/K
Rock thermal conductivity	2.83 W/m/K
Rock initial temperature	100°C
Thermal enhancement shape	Disc-shaped fracture
Thermal enhancement radius	5 m; 10 m; 20 m
Thermal enhancement thickness	0.5 cm – 5 m
Number of thermal enhancements	5; 10; 20; 50; 100

a conductive medium after 20 years. Hence, our simulation results represent roughly a snapshot after 20 years of operation. The heat transfer fluid (i.e., water) flows through the wellbore and is assumed to have constant fluid properties. Hence, the orientation of the model and flow path (e.g., horizontal or vertical) is irrelevant. The wellbore center is located at r=0 and the wellbore radius is 0.0762 m (i.e., 3 inches). At the bottom and top of the model, a zero-heat flux boundary condition is assumed, to reflect the 100-m model being a segment of a longer wellbore or lateral. By assuming the fractures as circular and having constant thickness ("disc-shaped"), the model can be implemented as a two-dimensional axisymmetric model, significantly saving on number of mesh elements and computational time in comparison with a full three-dimensional model. The mesh size is fine along the wellbore and thermal enhancements, and coarse further away. The water flow through the wellbore is modeled using a separate one-dimensional model with constant flow velocity. The convective heat transfer coefficient is calculated using the Dittus-Boelter Nusselt correlation for turbulent flow in a pipe. Both models are coupled through the local fluid temperature and rock temperature at the wellbore wall, allowing to calculate the heat exchange between the two models. Full model assumptions are listed in Table 1.

A first set of simulations was conducted to explore the impact of the amount of thermal enhancement material along the 100-m wellbore (Figure 3). We assumed a model with 20 fractures, each having a radius of 10 m and varying the fracture thickness from 0.005 to 5 m and thermal conductivity of thermal enhancement material as 10×, 100× and 1000× the rock thermal conductivity. Results are expressed in Figure 3 as increase in thermal output with respect to a model without thermal enhancement material, versus fraction of thermal enhancement material along the wellbore. For example, a thermal output multiplier of 1.1 means a 10% increase in heat production for the system with thermal enhancements versus the base case scenario (no thermal enhancements). A fraction of 0.01 means 1% of the material along the wellbore is thermal enhancement material while 99% is the host rock. Figure 3a covers the entire fraction range of 0 to 1 while Figure 3b provides a close-up for a fraction in the range of 0 to 0.1. A fraction of 1 represents the scenario of an entire 100-m long hollow cylinder with 10-m radius made of highly conductive material (= 20 fractures of 5-m thickness). The scenarios with large fracture thickness do not represent realistic scenarios but allow investigation of the upper limit of performance with thermal enhancements. The only realistic scenario may be the case with a fracture thickness of 0.005 m, which provides a thermal output boost of about 6% with thermal enhancement material of 100× the rock thermal conductivity (and assuming 20 fractures along a 100-m segment). For small fractions, the thermal output multiplier scales linearly with the fraction of thermal enhancement material. For large fractions, the multiplier levels off at about 3.6.



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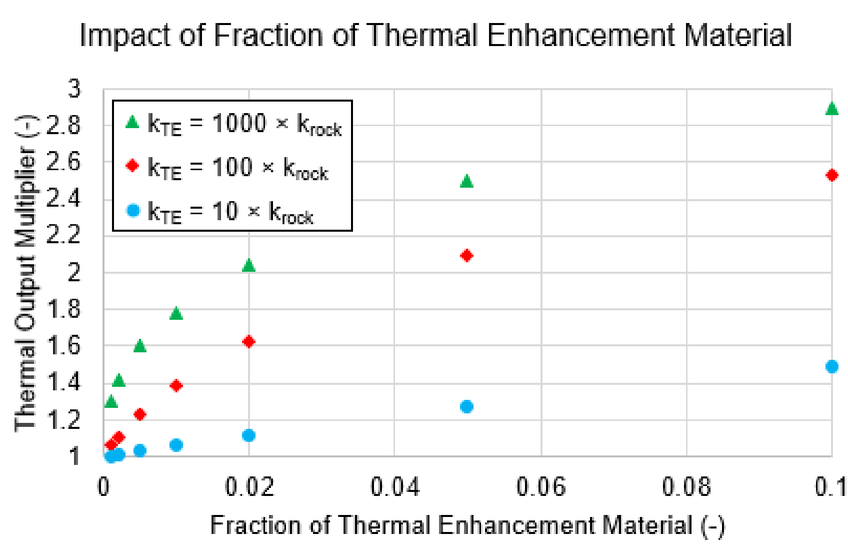


(b)

Figure 3: Impact of fraction of thermal enhancement material on thermal output for different thermal conductivities. Each simulation assumed 20 equally spaced "discs" with radius of 10 m in a 100-m long segment with disc thickness varying between 0.5 cm and 5 m. Results are expressed as increases in thermal output with respect to the scenario without thermal enhancements. (a) shows complete fraction range of 0 to 1 (100%) while (b) shows close-up with fraction varying between 0 and 0.1 (10%).

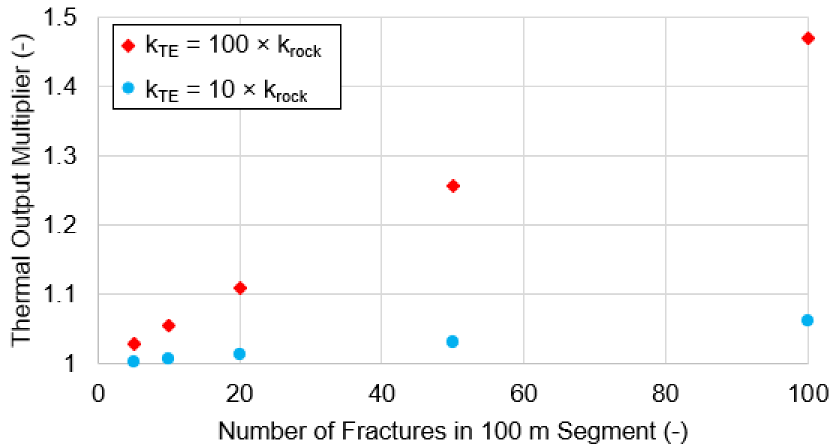


Figure 4: Impact of number of fractures on thermal output multiplier. Each fracture has a 10-m radius and is 1 cm thick. For the high thermal conductivity scenario, 100 fractures (with 1 cm thickness) would yield an increase of about 47%. Decreasing the thickness to 0.5 cm would halve the thermal output multiplier.

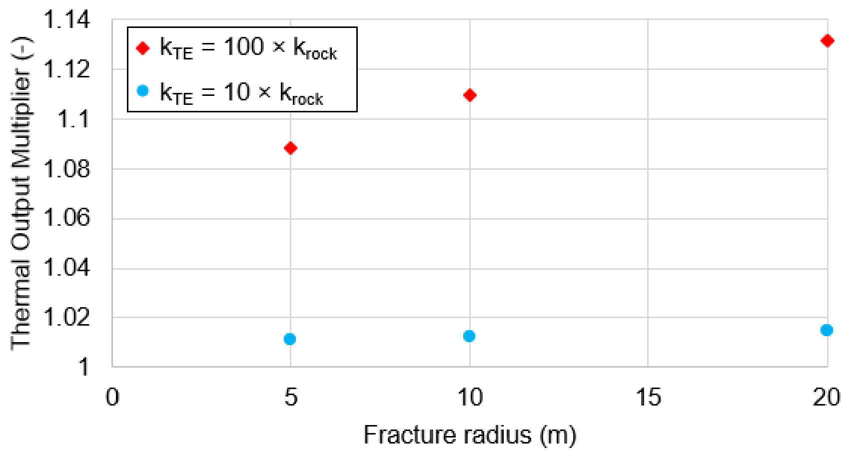


Figure 5: Impact of disc-shaped fracture radius on thermal output multiplier. Model assumes 20 equally spaced fractures with 1 cm thickness. Results indicate a negligible increase is obtained in thermal output when increasing the fracture radius from 5 m to 20 m for the low thermal conductivity scenario, while the increase is modest for the high thermal conductivity scenario.

A second set of simulations was conducted to explore the impact of the number of fractures on the thermal output multiplier (Figure 4). Each fracture was assumed to be 1-cm thick with a radius of 10 m. With 100 equally spaced fractures (i.e., 1 m spacing between fractures) and thermal enhancement thermal conductivity of 100× the rock thermal conductivity, the thermal output increases by approximately 47%. Given the linear relation between thermal output and fraction of thermal enhancement material (Figure 3), decreasing the fracture thickness to 0.005 m would also halve the thermal output multiplier (i.e., 23.5%).

A third set of simulations explored the impact of fracture radius on thermal output multiplier (Figure 5). The model assumes 20 equally spaced fractures of 1 cm thickness with radius of 5 m, 10 m, and 20 m. Simulation results indicate that a negligible increase in performance is obtained for the low thermal conductivity scenario when increasing the radius from 5 m to 10 m or 20 m. For the high thermal conductivity scenario, the 20-m radius scenario has a thermal output multiplier of about 13%, while the 5-m radius scenario still achieves a thermal output increase of about 9%.

2.2 Transient COMSOL Simulations

Transient simulations were performed in COMSOL to conduct additional analysis on the impact of disc-shaped thermal enhancements on the thermal output of closed-loop systems. The first model studied considers a 1,000-m long wellbore placed in a rock domain with 100-m radius and five "disc-shaped" 10-m radius conductive fractures with 1 cm thickness (Figure 6). The setup is implemented as a two-dimensional axisymmetric model in COMSOL. Similar fluid and rock property values as in the steady-state model are considered (see Table 1). The time step starts at 1 s and grows exponentially. A 20-year simulation takes roughly 2,000 time steps. Water is injected at

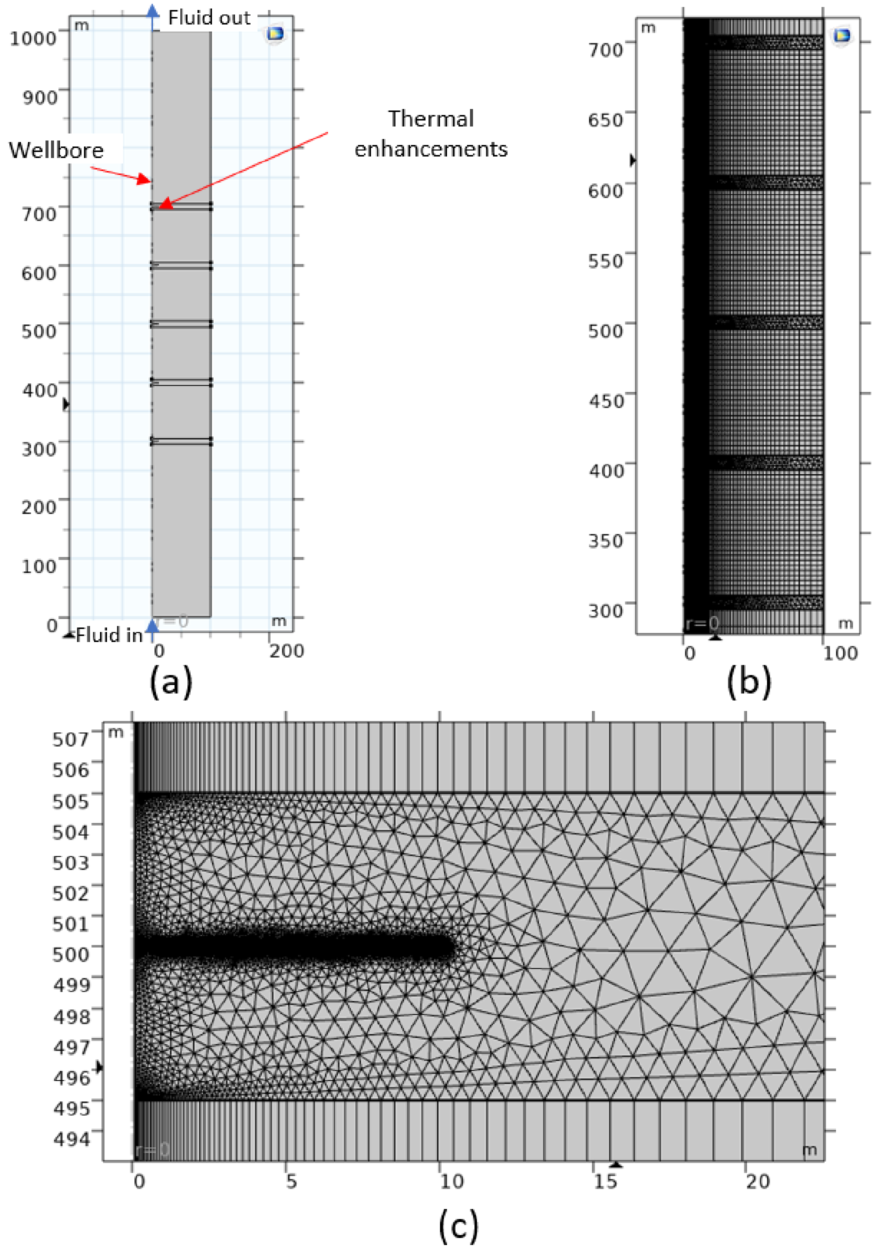


Figure 6: COMSOL model with disc-shaped thermal enhancements for transient simulations. (a) Model is set up as 1,000 m × 100 m two-dimensional axisymmetric model with five disc-shaped thermal enhancements. (b) Fine mesh elements are considered in the vicinity of wellbore and thermal enhancements. (c) Triangular mesh elements are considered in vicinity of thermal enhancements while rectilinear grid is considered elsewhere. No noticeable temperature gradient is present axially, away from the thermal enhancements, justifying the abrupt change from small triangular elements to long rectilinear elements.

50°C in the wellbore surrounded by rocks with an initial temperature of 100°C. The rock thermal conductivity is set to 2.83 W/m/K, and a range of thermal conductivities is considered for the thermal enhancement material from 1 to 5×10^5 times the rock thermal conductivity. The simulation time was set to 20 years. The mesh was made of triangular elements in the region along each fracture and rectilinear elements elsewhere. Fluid properties are kept constant; hence, the orientation of the model is irrelevant. While the fluid in the model appears to flow "upward," the model results are directly applicable to horizontal laterals (or laterals with any orientation).

A validation test was conducted where the thermal conductivity of the discs was set equal to the conductivity of the surrounding rock. Comparing the COMSOL transient simulation result over a 20-year period with the SBT model result indicates good agreement between these two models (Figure 7).

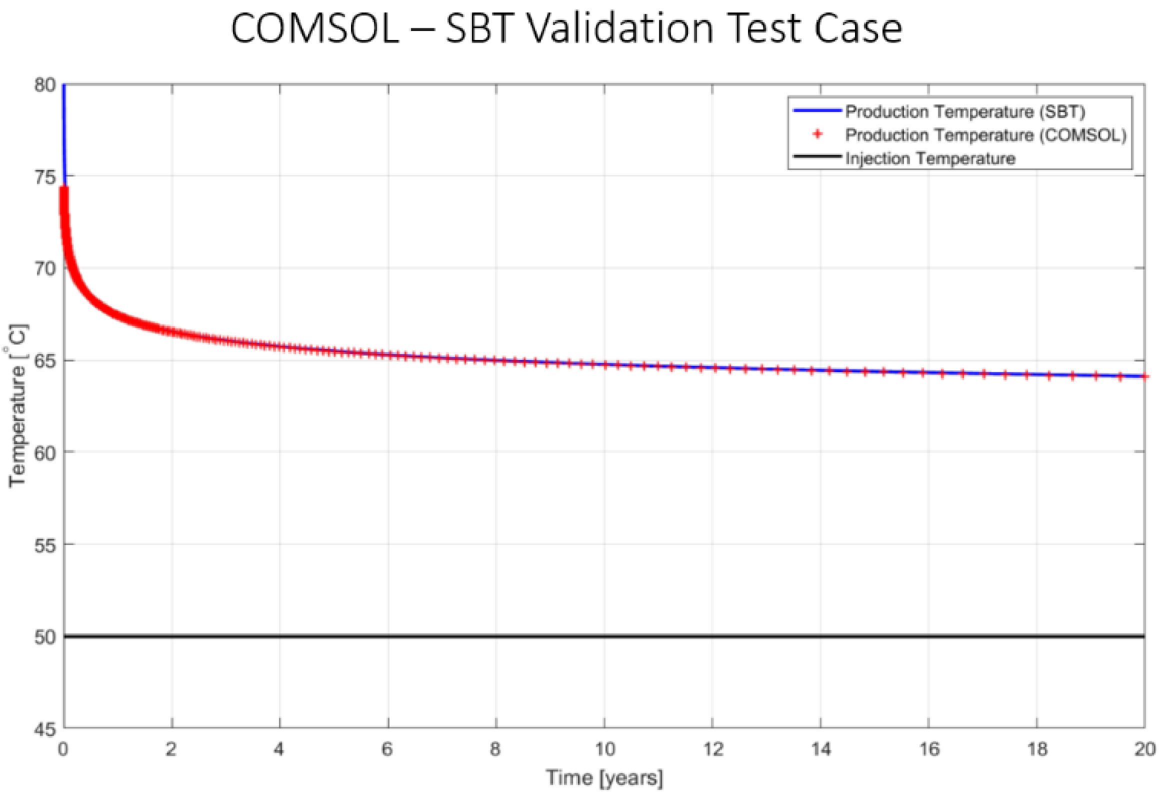
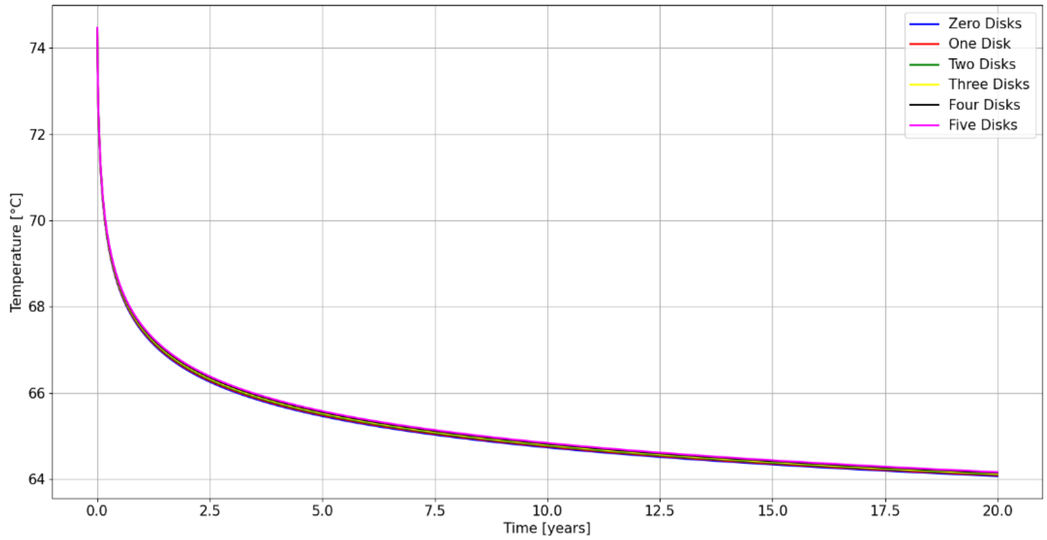


Figure 7: Comparison plot of COMSOL simulation result and SBT simulation result indicating good agreement between the two models. Setup considers 1,000-m lateral with water injected at 50°C and initial rock temperature at 100°C (see Figure 6) and with fracture thermal enhancement material set identical to the rock material (i.e., scenario without thermal enhancement).

Various simulations were run to explore the impact of number of thermal enhancements and thermal conductivity of thermal enhancements on the production temperature (and thermal output). Figure 8 presents a first set of simulation results showing the impact of number of thermal enhancements (from one to five) on production temperature with thermal enhancement thermal conductivity set to 1,000× the rock thermal conductivity (i.e., 2,830 W/m/K). A thermal conductivity of 1,000× the rock thermal conductivity would be the upper theoretical limit (e.g., using carbon nanotubes or diamond). More realistic thermal conductivities for thermal enhancements are likely in the range 10× to 100× the rock thermal conductivity. Results indicate a linear trend between increase in thermal output and number of thermal enhancements, in agreement with steady-state modeling results. For five thermal enhancements, the thermal output increases by approximately 0.7% and is fairly steady across the lifetime.

A second set of simulations was conducted to explore the impact of thermal enhancement thermal conductivity on production temperature and thermal output profile (Figure 9). For the 1,000-m model with five disc-shaped thermal enhancements (Figure 6), the thermal conductivity of the thermal enhancement was varied between 1 to 5×10^5 times the rock thermal conductivity. Results indicate increasing the thermal conductivity also increases thermal output but with diminishing returns for thermal conductivities beyond 10,000× the rock thermal conductivity. The 10^5 and 5×10^5 curves nearly overlap, indicating that they approach a "maximum" value where there is no further increase in heat extraction by increasing the conductivity. Realistic values for thermal conductivity of the thermal enhancement material likely fall in the range 10× to 100× the thermal conducivity of the rock (i.e., ~30 to 300 W/m/K).



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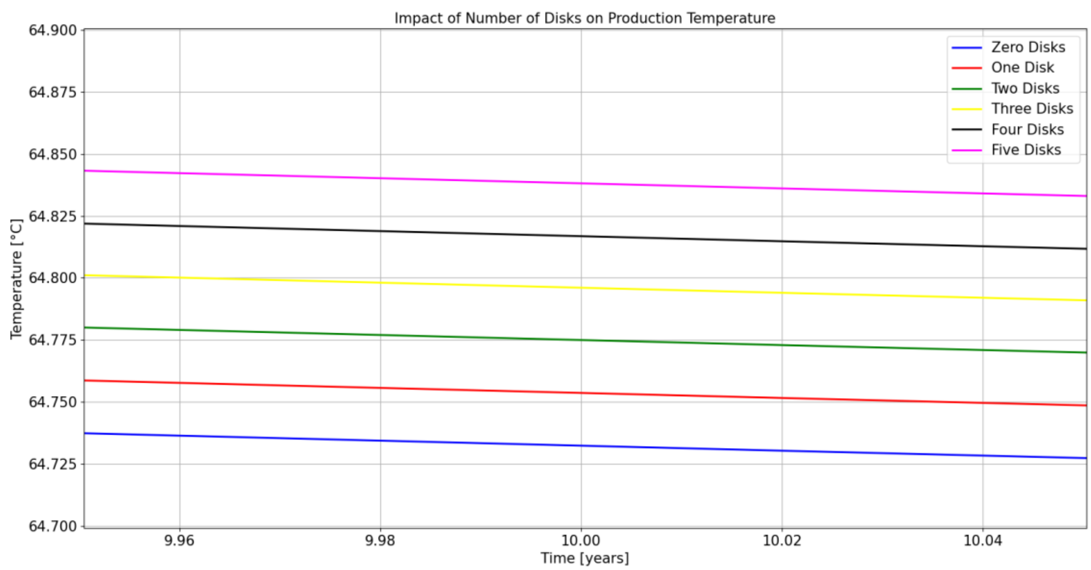


(b)

Figure 8: Production temperature profile over 20 years (a) and close-up at 10-year mark (b) for 1,000-m wellbore model presented in Figure 6 as a function of number of disc-shaped thermal enhancements. Thermal conductivity of thermal enhancement material is set to 1,000× rock conductivity. Thermal output increases linearly with the number of thermal enhancements. For five discs, thermal output increases by approximately 0.7% in comparison with the base case scenario (zero discs).

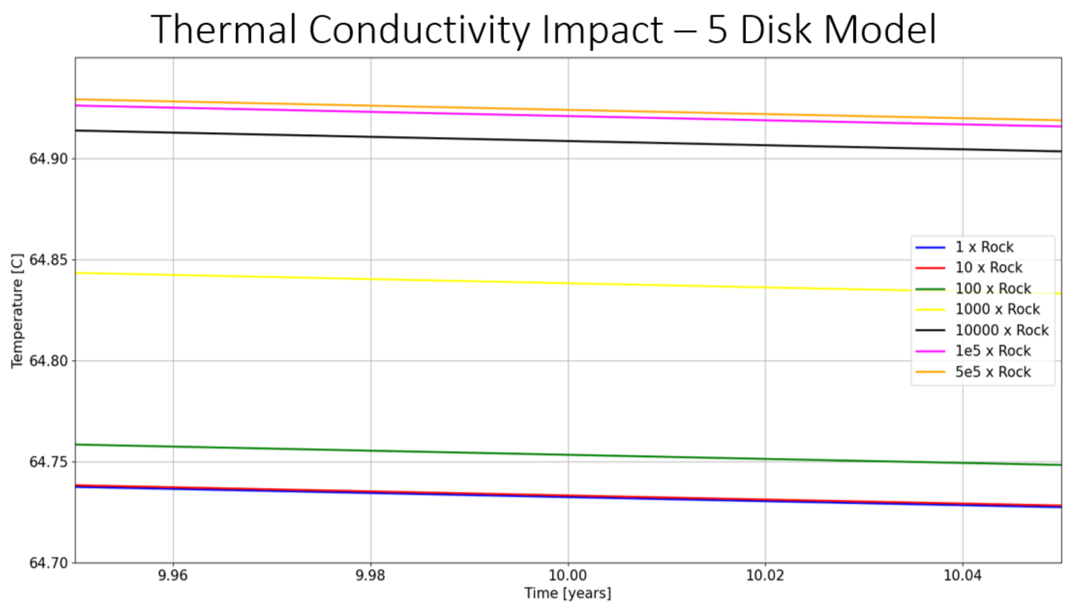
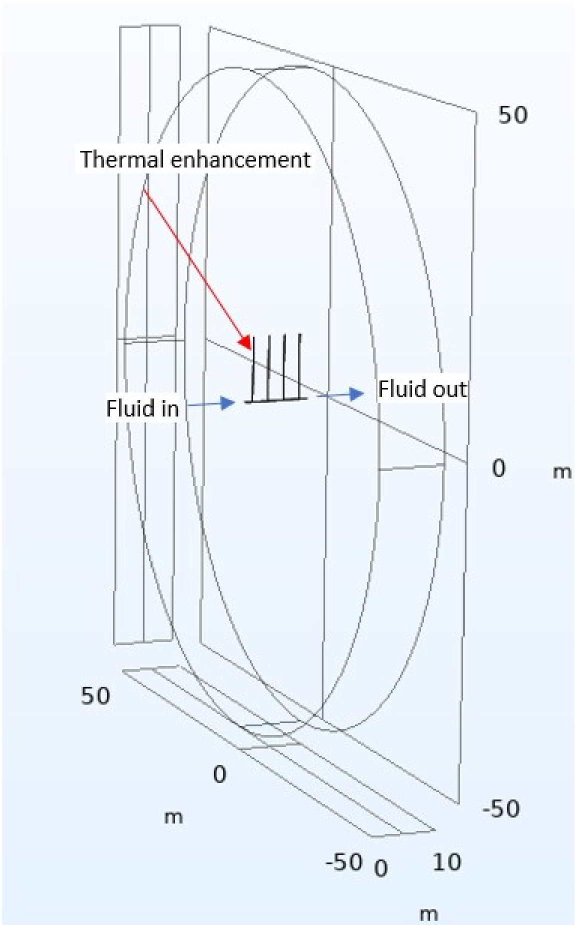


Figure 9: A close-up of the 10-year mark of production temperature profile over 20 years for the 1,000-m wellbore model presented in Figure 6 as a function of thermal conductivity (expressed as multiples of rock thermal conductivity). The number of discs is five for each case. Thermal output increases quickly until it approaches an asymptote. At 5×10^5 rock thermal conductivity, the increase in thermal output is approximately 1.3% with respect to the base case scenario (no thermal enhancement).

3. FISHBONE THERMAL ENHANCEMENTS

3.1 Steady-State COMSOL Simulations

COMSOL steady-state simulations were conducted to explore the impact of linear thermal enhancements using a fishbone structure (Figure 1b) on thermal performance of closed-loop geothermal systems. We followed a similar approach as with fracture-based thermal enhancements (Section 2): A short segment of a lateral was simulated with results reported as relative increase with respect to a system without thermal enhancements. The model simulated represents a 10-m long segment of a lateral with water as heat transfer fluid and one to four radially outward cylindrically shaped, thermally conductive pipes (i.e., filled up with thermally conductive material), also referred to as “linear thermal enhancements” (Figure 10a). To approximately translate these results to a full closed-loop system, the linear thermal enhancement would have to be repeated every 10 m along the entire wellbore or lateral. The model simulated has a 50-m radius with constant temperature boundary condition, approximately representing the temperature field after ~20 years of continuous operation. On both ends of the rock domain (axially at 0 m and 10 m), the boundary condition is a zero-heat flux boundary condition. All model assumptions are listed in Table 2. The setup was implemented in COMSOL using a three-dimensional model with tetrahedral mesh elements. The COMSOL solver relative tolerance was set to 10^{-6}, and the number of mesh elements ranged from about 500,000 to over 2,000,000 depending on number and length of the linear thermal enhancement. A close-up of the mesh at the interconnection of the wellbore and a thermal enhancement is shown in Figure 10b.



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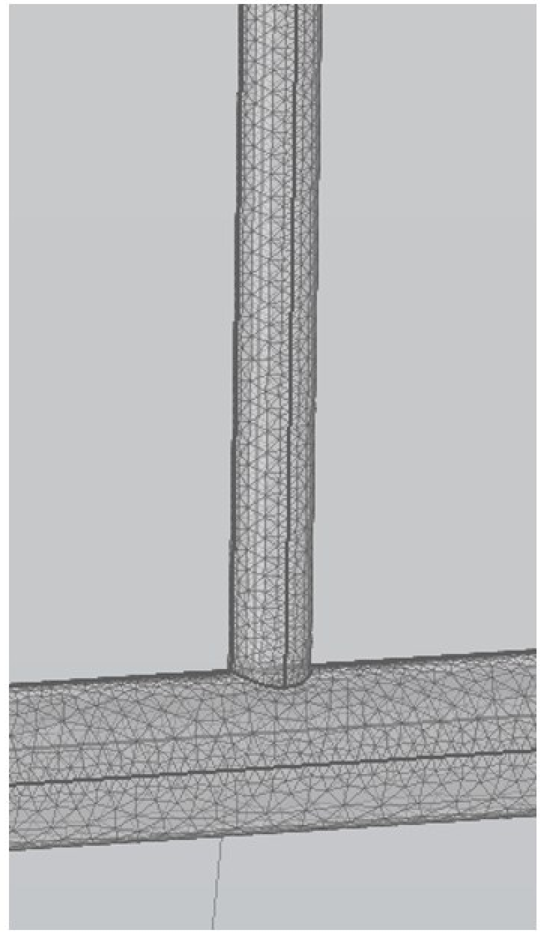

(b)

Figure 10: (a) COMSOL three-dimensional model for simulating linear thermal enhancements. A short segment of a lateral is simulated with one to four radially outward thermal enhancements. (b) Close-up of mesh at connection of thermal enhancement to lateral.

Table 2: COMSOL steady-state model assumptions for simulating fishbone structure thermal enhancements.

Parameter	Value
Model thickness	10 m
Model radius	50 m
Pipe radius	0.0762 m
Fluid flow rate	2 kg/s
Fluid specific heat capacity	4,200 J/kg/K
Fluid density	1,000 kg/m
Fluid thermal conductivity	0.68 W/m/K
Fluid inlet temperature	50°C
Rock density	2,875 kg/m^3
Rock specific heat capacity	825 J/kg/K
Rock thermal conductivity	2.83 W/m/K
Rock initial temperature	100°C
Thermal enhancement shape	Radially outward pipe
Thermal enhancement radius	0.0381 m (= 0.5 × 0.0762 m)
Thermal enhancement length	1m; 2m; 5 m; 10 m; 20 m
Number of thermal enhancements	1; 2; 4

We investigated the impact of thermal conductivity, length, and number of linear thermal enhancements on the increase in thermal output with respect to the design without thermal enhancements. Figure 11 represents the relative increase in thermal output as a function of thermal conductivity of the thermal enhancement (expressed as multiples of rock thermal conductivity k_{rock}) with a single 10-m long thermal enhancement. For anticipated thermal conductivities of 10× to 100× k_{rock}, the thermal output increases by 1% to 2 %. For an "infinite" thermal conductivity, the thermal output levels off at about 13%. Figure 12 suggests that short lengths are sufficient (e.g., 2 m to 5 m when thermal enhancement material thermal conductivity is 100× the rock thermal conductivity) to obtain the resulting increase in thermal output. Figure 13 indicates thermal output increases linearly with the number of linear thermal enhancements.

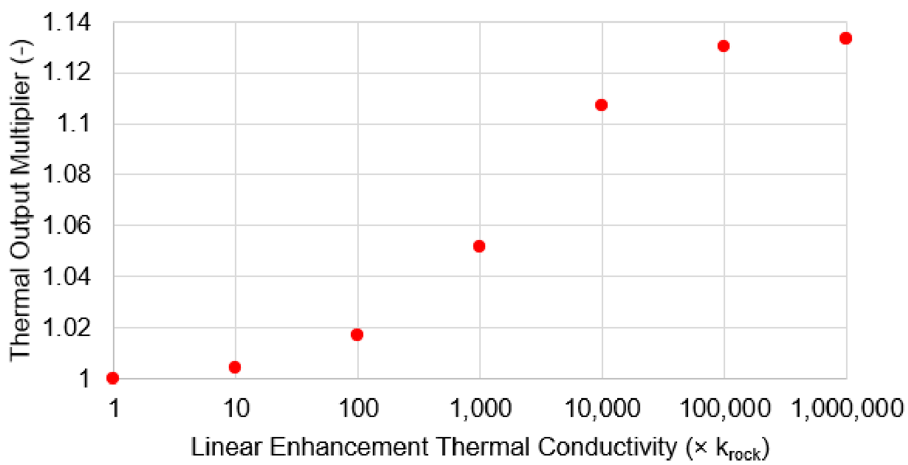

Figure 11: Impact of the thermal conductivity of the linear thermal enhancement on thermal output multiplier. Thermal conductivity is expressed as multiples of rock thermal conductivity. Setup is for one 10-m long linear thermal enhancement within a 10-m segment.

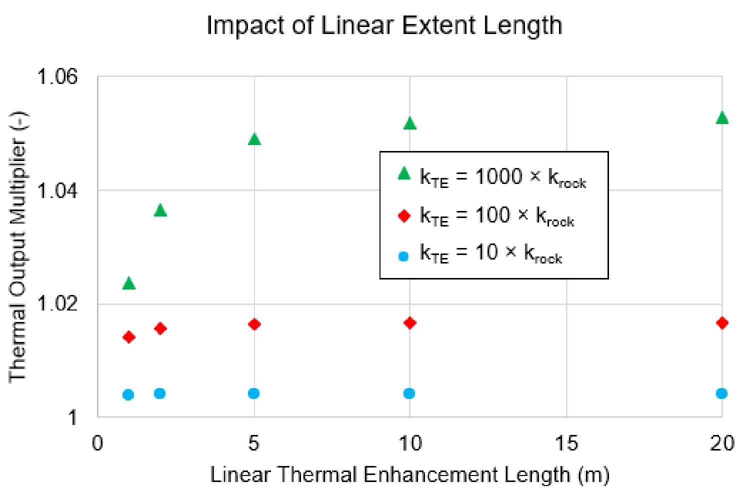

Figure 12: Impact of the length of linear thermal enhancement on thermal output multiplier. Setup assumes one linear thermal enhancement along a 10-m segment.

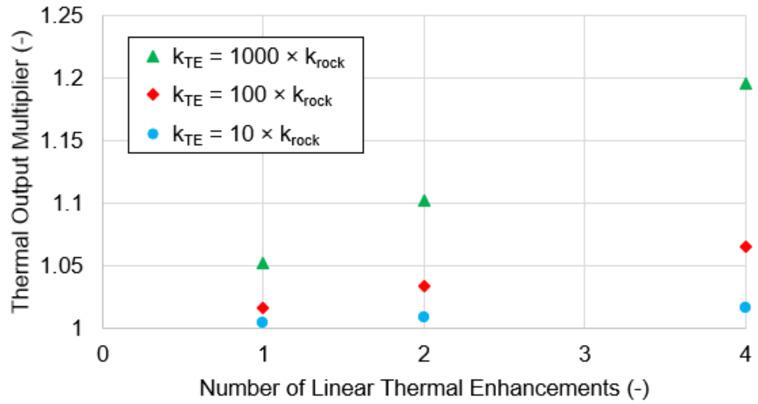

Figure 13: Impact of the number of linear thermal enhancements on thermal output multiplier. Setup assumes each enhancement is 10 m long and the enhancements are equally spaced along the 10 m lateral. Figure 10a represents the setup for four linear enhancements.

3.2 Transient COMSOL Simulations

Using the COMSOL model in Figure 10, we conducted transient simulations to investigate the impact of fishbone thermal enhancements on heat extraction. We assumed a single 5-m long linear thermal enhancement with conductivity ranging from 1× to 1,000× the rock thermal conductivity. Similar to the transient simulations for fracture thermal enhancements (Section 2.2), we increased the rock domain radius from 50 m to 100 m and set the outer boundary condition to a zero-heat flux boundary condition. The model height was kept at 10 m with a zero-heat flux boundary condition at the bottom and top to reflect that the model represents a subsection of a larger wellbore or lateral. Other model parameters are the same as in Table 2. The computational time for each simulation is about 2 hours on a personal computer.

Figure 14 presents the output temperature profile over a 20-year period as a function of thermal enhancement thermal conductivity. The increase in thermal output using thermal enhancements stays steady over the system lifetime. The increase in thermal output is comparable to the steady-state results: After 20 years, the heat output is approximately 0.4%, 1.7%, and 4.9% higher than the base case thermal output (without thermal enhancement) for a thermal conductivity of 10×, 100×, and 1000× the rock thermal conductivity, respectively. For the steady-state results (Section 3.1), the corresponding increase in thermal output was 0.4%, 1.6%, and 4.9%, respectively. The steady-state output temperature matches the transient temperature after operating for about 24 years.

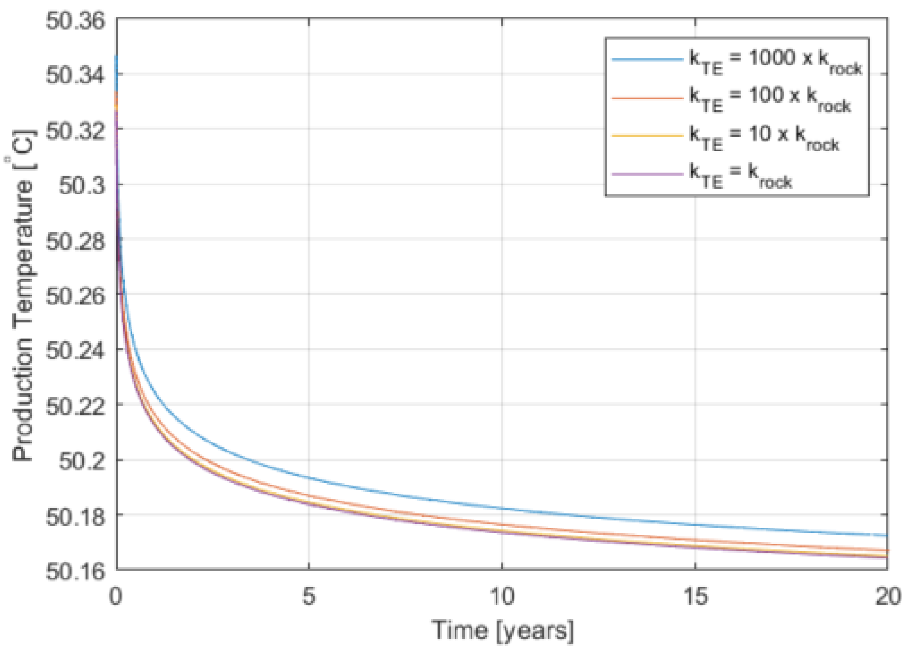

Figure 14: COMSOL results for production temperature for 10-m long segment with one linear thermal enhancement (similar to Figure 10) with different thermal conductivities. Model parameters are listed in Table 2 with domain radius set to 100 m instead of 50 m. With a thermal enhancement thermal conductivity of 1,000× the rock thermal conductivity, the heat production increases by about 5%.

4. CONCLUSIONS

We investigated the impact of disc-shaped and linear thermal enhancements on performance of closed-loop geothermal systems. Thermal enhancements have been proposed to compensate for the relatively low rock thermal conductivity and increase thermal output with co-axial or U-loop type closed-loop geothermal systems. Thermal enhancement materials considered include composite cements with additives that have high thermal conductivity (e.g., metals, graphite), to obtain a cement thermal conductivity that is 10× to 100× higher than the rock thermal conductivity.

Both steady-state and transient simulations were performed using the finite element simulator COMSOL. Our approach was modeling a short section of a lateral or wellbore (e.g., 100 m long), and we present results as relative increase in heat extraction when using thermal enhancements versus systems without thermal enhancements. We explored the impact of thermal conductivity, quantity, and size (e.g., fracture radius or wellbore length) of thermal enhancements. A validation test was conducted by comparing a base case scenario (i.e., without thermal enhancements) with the corresponding SBT simulation result.

For disc-shaped thermal enhancements with thermal conductivity of 100× the rock thermal conductivity, a roughly 20% boost in thermal output requires 5-mm thick disc-shaped fractures with 5-m radius repeated every 1 m along the wellbore or lateral. For a thermal enhancement material thermal conductivity of 10× the rock thermal conductivity, the boost in thermal output drops to about 2% to 3%. For fishbone structure thermal enhancements, a roughly 7% boost in thermal output is obtained for 5-m long radially outward wellbores with half the radius of the main wellbore, repeated every 2.5 m, with thermal conductivity of 100× the rock thermal conductivity. The boost drops to about 1.5% for a thermal enhancement thermal conductivity of 10× the rock thermal conductivity.

For the designs studied and considering realistic thermal conductivities, our results suggest a small boost (on the order of ~1% to ~20%) in heat production can be obtained with thermal enhancements for closed-loop geothermal systems. We only considered idealized geometries, a small number of scenarios, and heat conduction-only in the rock. These findings are in line with prior work such as by Fowler and McClure (2021). Future work could consider different designs, convection in the rock, as well as investigate technical feasibility and costs of installing thermal enhancements downhole in the wellbore.

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