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Numerical Simulation of Heat Extraction and Heat Injection Processes Integrated with a Geothermal-Solar Heating System

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ABSTRACT

Long-term heat extraction from a closed-loop geothermal well results in a temperature decrease of formation around the well, which in turn lowers the outlet temperature of the heat extraction fluid (water). To improve this unfavorable situation, an integrated heat extraction–heat injection model has been developed in this study. The model is used to analyze formation temperature decline and its distribution after the first heating season, fluid temperature distribution in the well during heat injection, and fluid outlet temperature during the second heating season. The results indicate that during the first heat-extraction period, the formation temperature decreases under different flow rates reached a minimum value at depth of about 2860m. After 180 days of heat extraction, a plume-shaped low-temperature zone is developed around the borehole, with the maximum influence radius reaching about 12.6m at a depth of 2860m. During heat injection, the injected fluid in the inner pipe with a lower flow rate shows a U-shaped temperature profile. The upward flow in the outer pipe (annulus) transfers heat to the formation all the way during ascent when the flowrates are higher than 0.5kg/s, showing a monotonic decrease in temperature. A comparison of heat re-extraction shows that the heat-injection reduces the average temperature decline by about 50.8%. This study demonstrates that appropriate heat-injection, along with flow rate control, can significantly improve the temperature stability of formation around the geothermal well.

Keywords: closed-loop geothermal well, deep borehole heat exchanger, formation temperature decline, improvement due to heat injection, influence radius

NONMENCLATURE

Abbreviations	
CDBHE	coaxial deep borehole heat exchanger

Symbols	
t	day
T_{coni}	K
T_{out}	K
T_{soil}	K
$T_{consoil}$	K

1. INTRODUCTION

With the ongoing transition in the energy structure, the development of clean, stable, and renewable energy have become a central focus of global research. Geothermal energy has gained considerable attention for its strong stability, low sensitivity to climatic conditions, and ability to provide continuous energy supply around the clock.[1] Unlike intermittent sources such as wind and solar photovoltaics, geothermal resources provide reliable long-term baseload energy and show great potential for applications in heating, power generation, and integrated energy systems.

Among the various geothermal development methods, the coaxial deep borehole heat exchanger (CDBHE) has emerged as a representative design for geothermal heat extraction, owing to its simple structure, closed-loop circulation, and avoidance of formation fluid extraction.[2] The CDBHE is a typical closed-loop geothermal system, composed of an outer casing and a coaxially arranged inner pipe.[3]

Li et al. developed an analytical model of a CDBHE, which revealed the controlling influence of well depth and flow rate on outlet temperature.[4] Holmberg and Acuña validated, through numerical simulations and field data, the effects of different well depth and insulation measures on coaxial well performance, and suggested that optimized design can significantly increase heat output.[5] Chen and Tomac conducted a feasibility study on the geothermal system at the University of California, San Diego, and showed that coaxial wells could achieve

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approximately 600 kW of thermal output.[6] Sun explored the use of vortex generators to improve borehole heat transfer, raising the outlet temperature by 24.06% and thermal power by about 11.93%.[7] These studies demonstrate the engineering potential of CDBHEs and offer valuable references for future large-scale deployment.

However, prolonged unidirectional heat extraction gradually lowers the formation temperature, thereby constraining the sustainable use of the reservoir.[8] This phenomenon not only reduces the outlet temperature and energy supply capacity of wellhead fluids but also leads to reservoir thermal depletion, which limits the operational lifespan of geothermal systems. To address this issue, the thermal recharge strategy has attracted growing attention. This strategy involves injecting artificially heated fluids or using multi-energy complementary methods during the non-heating season to replenish heat in the formation and restore its temperature. Studies indicate that effective implementation of thermal recharge can significantly slow reservoir temperature decline and improve the long-term stability and efficiency of geothermal systems.[9]

This study develops an integrated heat extraction–heat injection model based on a coaxial borehole heat exchanger. It systematically simulates two operating conditions—heat extraction during the heating season and thermal recharge during the non-heating season—thereby revealing the dynamic heat exchange mechanisms between the wellbore and the formation. This modeling approach not only inherits the strengths of existing thermodynamic models but also broadens their application under coupled operating conditions. By using solar collectors to recharge the formation during the non-heating season, the model effectively alleviates thermal depletion and mitigates the decline in outlet temperature during the heating season.

2. MODELS

This study develops an integrated system for geothermal energy utilization and formation heat management based on a CDBHE. The system comprises an outer casing and a coaxially arranged inner pipe: the outer casing is in direct contact with the formation, whereas the inner pipe is insulated to minimize heat loss along the flow path. During operation, the working fluid circulates within the borehole and transfers energy with the formation via conduction, eliminating the need for extracting or reinjecting formation fluids. This closed-loop configuration prevents issues such as formation fluid loss, chemical scaling, and environmental pollution, thereby providing distinct advantages for urban heating, abandoned oil well repurposing, and deep geothermal energy exploitation. The system operates in two distinct modes depending on seasonal conditions:

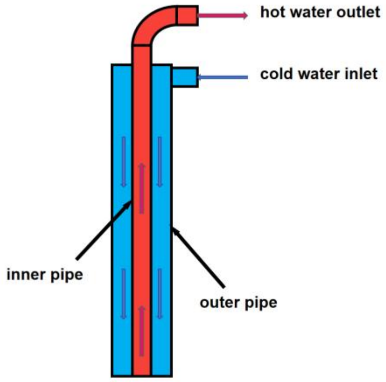

Fig.1 Heat extraction model

(1) Heating season — heat extraction mode

Fig.1 presents the schematic of the CDBHE operating in heat extraction mode during the heating season. In this mode, the low-temperature working fluid is injected from the surface into the wellhead, descends through the outer casing while exchanging heat with the surrounding formation, absorbs geothermal energy, and then enters the inner pipe at the well bottom before ascending back to the surface. Thanks to the effective insulation of the inner pipe, the temperature drop of the working fluid during upward flow is minimal, allowing it to reach a relatively high outlet temperature that can be used as a heat source for surface heating or other thermal applications.

(2) Non-heating season — heat injection mode

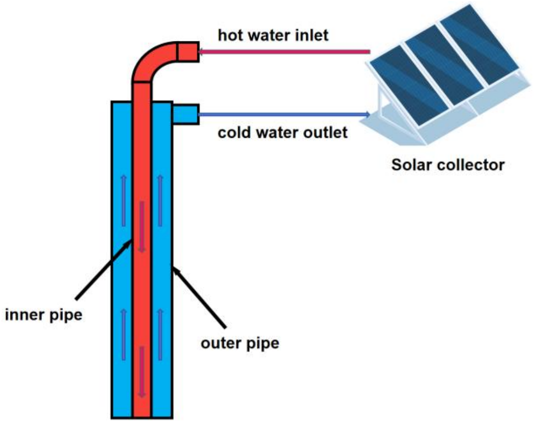

Fig.2 Heat injection model

Fig.2 presents the schematic of the CDBHE operating in heat injection mode during the non-heating season. In the non-heating season, the system operates in the reverse flow direction. Hot water heated by the solar collector is injected into the well bottom through the insulated inner pipe and returns via the outer casing, releasing heat to the formation during the process to provide thermal compensation for the reservoir. When constructing the heat transfer model, the heating-season CDBHE model can be directly applied, with only two key aspects requiring modification:

The fluid inlet boundary T_{coni} is set at the top of the inner pipe and assigned the hot water temperature provided by the solar collector output T_{out}. The outlet is defined at the top of the annulus, where the reinjected hot water exits, transferring heat radially through the well wall to the surrounding formation.

$$T_{coni} = T_{out} \tag{2.1}$$

The initial formation condition $T_{consoil}$ should be defined using the formation temperature T_{soil} distribution at the end of the heating season, rather than the natural steady-state reservoir temperature, to capture the temperature decline caused by long-term heat extraction.

$$T_{consoil}\big|_{t=0} = T_{soil}\big|_{t=180} \tag{2.2}$$

3. RESULTS AND DISCUSSION

3.1 The first heat extraction period

Fig. 3 presents the average formation temperature drop with depth within a 15 m radius under different flow rates. Under all operating conditions, the curves display a single minimum at about 2860 m, then rise almost linearly toward shallower depths and approach zero near the surface. With increasing flow rate, the average formation cooling becomes more pronounced, but the incremental cooling effect diminishes. increasing the flow rate from 2 to 8 kg/s enhances the temperature drop by about 1.2 K, whereas further increasing it to 14 kg/s yields only an additional about 0.2 K. Once the temperature difference at the well wall becomes large, further increases in flow rate mainly reduce convective resistance inside the pipe, while conductive diffusion in the surrounding rock remains constrained. The spacing between flow-rate curves is greatest in the 2100–2900 m interval, but they converge rapidly above 1500 m and nearly overlap in the shallow section. This indicates that higher flow rates primarily enhance deep heat transfer, with limited contribution to the shallow layers.

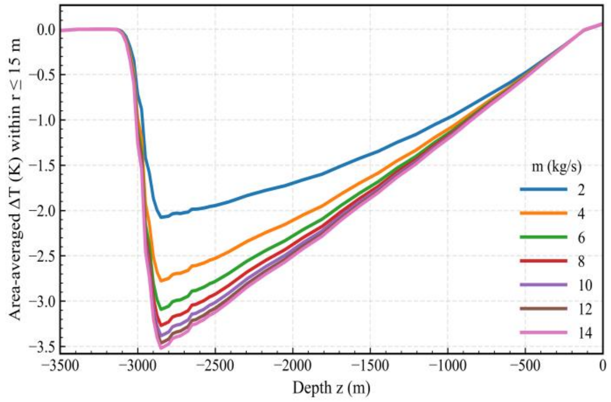

Fig.3 Formation temperature declines with depth under different heat-extraction fluid mass flowrates

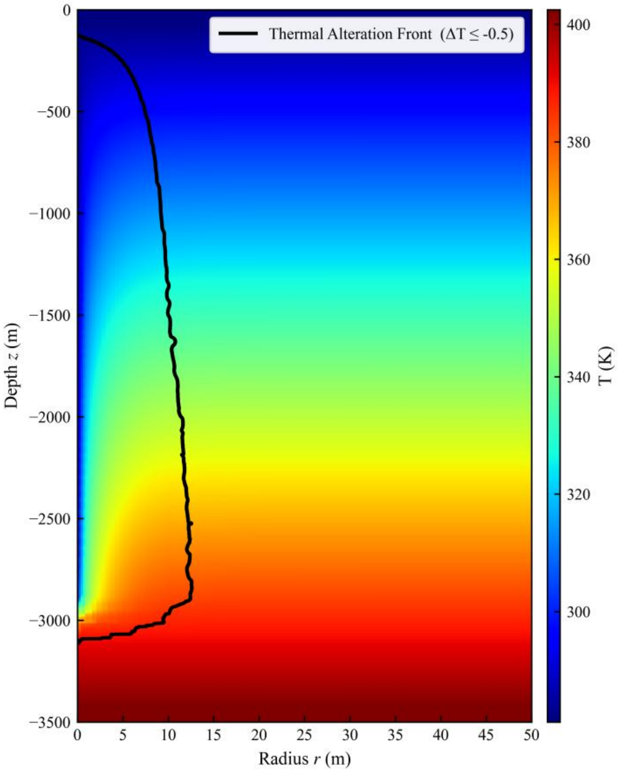

Fig. 4 Formation temperature distribution after 180 days heat extraction at a flowrate of 10 kg/s

Fig. 4 presents the formation temperature distribution after 180 days of heat extraction at a flow rate of 10 kg/s. In the figure, color indicates temperature, with the horizontal axis representing depth (z) and the vertical axis representing radial distance (r). After 180 days of extraction, the formation retains its background geothermal gradient with depth, but a distinct low-temperature zone emerges near the borehole and spreads outward in a plume-like pattern along the wellbore. The figure highlights the formation region affected by heat extraction, generally exhibiting an arc-shaped pattern. The affected radius increases gradually, reaching a maximum of about 12.6 m at a depth of 2860 m, then decreases at greater depths, with the maximum depth of influence reaching about 3100 m. This indicates that in CDBHEs, radial heat transfer dominates the formation response: the temperature near the well wall drops rapidly and recovers monotonically outward. In the 2860–3000 m interval, continuous replenishment from deeper high-temperature formations reduces the radius of influence.

3.2 The heat injection period

Figs. 5 and 6 present the temperature distributions of the inner and outer pipes with depth under different heat-injection flowrates. When the injection flowrates are higher than 0.5kg/s, the inner-pipe fluid temperature decreases initially and then levels off with depth. When the injection flowrates are lower than 0.5kg/s, the inner-pipe fluid temperature decreases much faster so that its outlet temperature at the bottom of the well is lower than the formation temperature, forming U-shaped profiles; the lower the flowrate, the distinct the U-shape. The upward flow in the outer pipe (annulus) transfers heat to the formation all the way during ascent when the flowrates are higher than 0.5kg/s, showing a monotonic decrease in temperature (Fig.6). However, under lower flowrate conditions (<0.5kg/s), the upward annular flow temperature increases firstly (absorbing heat from the formation) at the bottom of the well; after the temperature reaches a maximum value, it decreases monotonically, implying a heat transfer from the fluid to the formation when the fluid's temperature becomes higher than the formation. Despite insulation of the inner pipe, radial heat transfer and axial conduction persist. At low flow rates, longer residence time enhances heat release from shallow fluid to the well wall and formation, causing rapid fluid cooling. Once the fluid temperature falls below the formation temperature at the same depth, heat flow reverses from the formation to the fluid, further reducing deep formation temperature. At high flow rates, heat loss per unit length is insufficient to significantly lower fluid temperature, enabling effective heat injection of the deep formation. When the flow rate reaches 0.5kg/s or higher, heat injection no longer causes adverse effects on deep formation recovery.

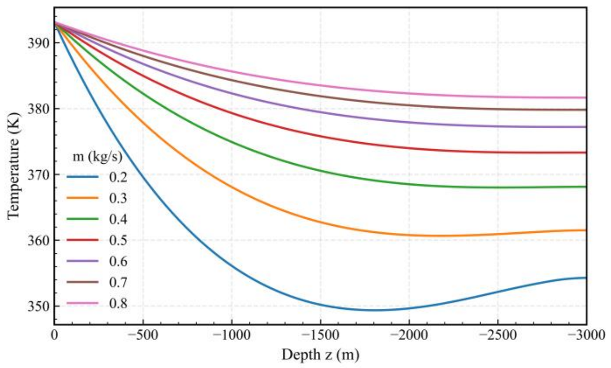

Fig.5 Temperature distributions of the inner-pipe fluid with depth under different injection flowrates rates

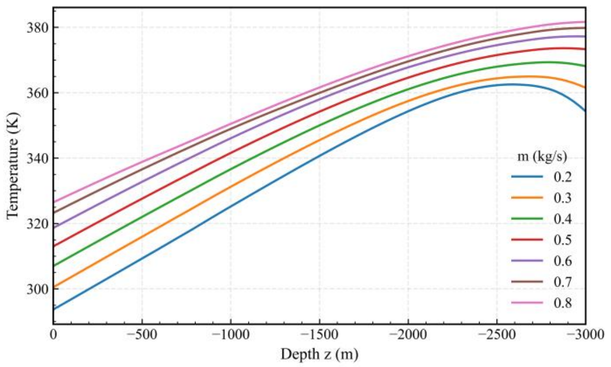

Fig.6 Temperature distributions of the outer-pipe fluid with depth under different injection flowrates

3.3 The second heat extraction period

Fig. 7 presents the variation of inner pipe outlet temperature with extraction time for the first extraction period and the second period, with and without heat injection. All three curves display a rapid initial decline, followed by a gradual decrease. Compared with the first heat-extraction period (first heating period), the average outlet temperature in the second heat-extraction period (second heating period) is consistently lower, due to substantial thermal depletion of the formation after the first heat-extraction period. During the second heat-extraction period, the outlet temperature with the heat-injection mode remains higher than that without heat-injection, although the difference gradually narrows over time. This occurs because the reinjected heat during heat heat injection establishes a higher initial temperature and gradient around the well, providing a greater usable

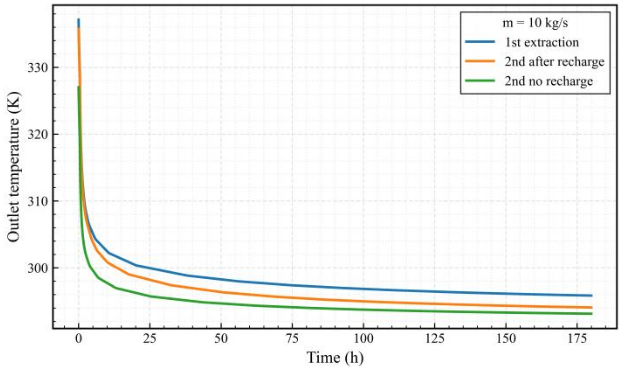

Fig. 7 Outlet temperature variations of heat extraction with time under three operation conditions

temperature difference and conductive replenishment in the re-extraction period, which raises the outlet temperature and suppresses the early sharp decline. The average outlet temperature is 298.02 K in the first period, and 296.22 K and 294.57 K in the second period with and without heat injection, respectively. In the second period, the average outlet temperature decreases by 1.792 K with heat injection and 3.643 K without heat injection, showing that heat injection reduces the average decline by about 50.8%.

4. CONCLUSIONS

To investigate the formation temperature change during geothermal well operation and to evaluate the long-term effects of heat injection, an integrated heat extraction and heat injection model using a deep coaxial borehole heat exchanger was established. Based on this model, the processes of heat extraction, heat injection, and subsequent heat re-extraction in the second heating period were systematically analyzed, leading to the following conclusions:

(1) During the initial heat extraction stage, the most pronounced average temperature decrease occurs within a 15m radius at a depth of about 2860m. In contrast, rapid convergence of temperature profiles is found at shallower depths (≤1500 m). Increasing flow rate enhances heat extraction at deeper depths but contributes little to shallower depths.

(2) After 180 days of heat extraction with a mass flowrate of 10kg/s, a plume-shaped low-temperature zone develops along the borehole axis. The maximum influence radius is approximately 12.6m at 2860m depth, while the maximum influence depth extends to 3100 m.

(3) During the heat injection process, lower flow rates result in longer residence times and higher unit-length heat losses, leading to excessively low fluid temperatures in the deep section of the well and consequent heat depletion from the formation. The upward flow in the outer pipe (annulus) transfers heat to the formation all the way during ascent when the flowrates are higher than 0.5kg/s, showing a monotonic decrease in temperature.

(4) Compared with the first heat extraction period (first heating period), the average outlet temperature of the heat extraction fluid during the second heat extraction period (second heating period) remains consistently lower, indicating a progressive thermal depletion in the formation. Heat injection substantially enhances the heat re-extraction performance by reducing the average temperature drop from 3.643K to 1.792K, representing an improvement of about 50.8%. Moreover, heat injection can effectively suppress the sharp temperature decline typically observed at the startup stage.

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