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Research Paper

Research progress on temperature field evolution of hot reservoirs under low-temperature tailwater reinjection

Xin Wang[1,3], Guo-qiang Zhou[1,4,5*], Yan-guang Liu[1,2,3*], Ying-nan Zhang[1,3], Mei-hua Wei[4,5], Kai Bian[1]

[1] *School of Earth science and Engineering*, *Hebei University of Engineering*, *Handan* 056038, *Hebei*, *China*.
[2] *Institute of Hydrogeology and Environmental Geology*, *Chinese Academy of Geological Sciences*, *Shijiazhuang* 050061, *China*.
[3] *Technology Innovation Center of Geothermal & Hot Dry Rock Exploration and Development*, *Ministry of Natural Resources*, *Shijiazhuang* 050061, *China*.
[4] *Shanxi Key Laboratory for Exploration and Exploitation of Geothermal Resources*, *Taiyuan* 030024, *China*.
[5] *Shanxi Geological Engineering Exploration Institute*, *Taiyuan* 030024, *China*.

Abstract: This paper focuses on the study of the evolutionary mechanism governing the temperature field of geothermal reservoir under low-temperature tailwater reinjection conditions, which is crucial for the sustainable geothermal energy management. With advancing exploitation of geothermal resources deepens, precise understanding of this mechanism becomes paramount for devising effective reinjection strategies, optimizing reservoir utilization, and bolstering the economic viability of geothermal energy development. The article presents a comprehensive review of temperature field evolution across diverse heterogeneous thermal reservoirs under low-temperature tailwater reinjection conditions, and analyzes key factors influencing this evolution. It evaluates existing research methods, highlighting their strengths and limitations. The study identifies gaps in the application of rock seepage and heat transfer theories on a large scale, alongside the need for enhanced accuracy in field test results, particularly regarding computational efficiency of fractured thermal reservoir models under multi-well reinjection conditions. To address these shortcomings, the study proposes conducting large-scale rock seepage and heat transfer experiments, coupled with multi-tracer techniques for field testing, aimed at optimizing fractured thermal reservoir models' computational efficiency under multi-well reinjection conditions. Additionally, it suggests integrating deep learning methods into research endeavors. These initiatives are of significance in deepening the understanding of the evolution process of the temperature field in deep thermal reservoirs and enhancing the sustainability of deep geothermal resource development.

Keywords: Geothermal reinjection; Seepage heat transfer; Tracer test; Numerical simulation; Thermal breakthrough

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Introduction

The application of low-temperature geothermal water reinjection technology in the field of geothermal energy has emerged as a cornerstone of sustainable development strategies. This technology not only helps reduce the adverse impacts of geothermal development activities, such as curtailing water pollution and sustaining reservoir pressure and geothermal water level (Liu, 2003; Wang et al. 2020a), but also aligns with the global shift towards clean, renewable energy sources amid pressing environmental concerns Nonetheless, challenges inherent in the geothermal development process, such as declining reservoir pressure, reduced production capacity, and potential environmental issues, pose serious tests to the sustainability of geothermal energy development (Kamila et al. 2021).

*Corresponding author: Guo-qiang Zhou, Yan-guang Liu, *E-mail address*: 707978346@qq.com, gaoyuanzhixing@163.com

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Since its pioneering implementation at the Geysers geothermal field in the United States during the 1970s (Einarsson et al. 1975; Stefansson, 1997), low-temperature tailwater reinjection technology has been widely adopted worldwide. By reintroducing low-temperature tailwater generated during extraction back into underground thermal reservoir, the problems of groundwater level reduction and surface subsidence caused by geothermal fluid extraction are effectively alleviated, demonstrating the potential for sustainable geothermal energy development (Allen and Milenic, 2003). So far, reinjection technology has been implemented in more than half of the global geothermal fields, with some areas achieving reinjection rate of up to 100% (Kamila et al. 2021; Diaz et al. 2016), underscoring the important value of low-temperature tailwater reinjection technology in sustainable geothermal energy utilization. However, prolonged low-temperature tailwater reinjection may trigger adverse effects on the thermal reservoirs, such as temperature field reduction and even thermal breakthrough events. These consequences not only diminish geothermal well productivity but can also necessitate geothermal well shutdowns, resulting in significant economic losses (Cao et al. 2021). Therefore, studying the influence of low-temperature tailwater reinjection on thermal reservoir temperature field evolution is crucial for optimizing reinjection strategies, preventing thermal breakthrough, and improving mining efficiency and economic viability.

To address this challenge, scientists and engineers have employed a variety of research methods, including laboratory experiments, field tests and numerical simulation, to delve into the mechanism of the influence of low-temperature tailwater reinjection on thermal reservoir temperature evolution (Huang et al. 2021; Zeng et al. 2008; Zayed et al. 2023). Through these methods, researchers can unveilseepage and heat transfer characteristics of thermal reservoirs and propose optimal reinjection strategies based on experimental data and simulation results, thereby effectively controlling the change of temperature field and extending the economic life cycle of geothermal fields. However, the complexity of deep heat storage, particularly the heterogeneity of thermal reservoirs under high-temperature, high-stress environment and the complex geological structure, poses new challenges. These challenges manifest in, highly permeable pilot channels in thermal reservoirs, facilitating pilot flow in geothermal reinjection and resulting in significant heat storage and recovery efficiency reductions (Liu et al. 2023). These factors increase the difficulty in studying the evolution mechanism of thermal storage temperature field. Moreover, current research methods have some limitations in simulating real geological conditions, predicting temperature changes within hot reservoirs and addressing complex fracture networks.

This paper aims to review and analyze research progress regarding the temperature field evolution of thermal reservoirs under low-temperature tailwater reinjection conditions. It includes comparative analysis of temperature field evolution in different heterogeneous thermal reservoirs and explores key factors affecting temperature field evolution. In addition, this paper evaluates the advantages and limitations of current research methods and discusses future research needs and directions. This endeavor seeks to offer valuable insights for further research on deep thermal reservoir temperature field evolution, promote the scientific and efficient development of geothermal energy, and establish a solid theoretical and practical foundation for its sustainable utilization. Through comprehensive analyses and discussions, we hope to establish a more comprehensive understanding framework, provide effective management and technical strategies for geothermal energy development, and ensure that geothermal energy, as an important renewable energy source, plays a key role in the global energy transition.

1 Thermal reservoir temperature field evolution

Understanding the evolution mechanism of temperature field in a geothermal reservoir is paramount for optimizing geothermal extraction and management. The evolution of temperature field in low-temperature tailwater reinjection hot reservoirs refers to the disturbance of the reservoir's original thermal equilibrium caused by the reinjection of geothermal water after heat extraction. This process involves thermal conduction, convection, diffusion, and changes in the physicochemical properties of rocks, leading to continuous changes in the distribution of temperature within the reservoir. The time span of temperature field evolution in reinjection projects can span years, decades, or even centuries (Du et al. 2021; Wang et al. 2022b; Wang et al. 2021; Shi et al. 2023; Zayed et al. 2023).

The evolution of geothermal reservoir temperature field under the action of low-temperature tailwater reinjection can be divided into several stages.

(1) Initial phase: Prior to exploitation, the geothermal reservoir resides in a quasi-stable thermal equilibrium. Heat transfer within the deep reservoir is slow, primarily governed by the geothermal gradient and geological structures, in the absence of anthropogenic extraction.

(2) Production and reinjection phase: Geothermal fluid extraction for power generation or heating purposes leads to a drop in reservoir pressure. The utilized geothermal water, now at a reduced temperature, is reinjected into the reservoir.

(3) Early reinjection phase: Cold water absorbs heat from the reservoir rocks through thermal conduction and convection, causing temperature decline. A distinct cold zone emerges around the reinjection well, delineated by a sharp temperature gradient known as a cold front, while the temperature of the producing well remains unaffected.

(4) Temperature field evolution phase: Continuous injection of cold brine enhances thermal convection within the reservoir, expanding the cold zone around the reinjection well and advancing the cold front outward. The induced convective flow under the influence of extraction pumping accelerates thermal energy transfer, causing the cold front to bulge towards the production well.

(5) Long-term impact phase: Prolonged reinjection of cold brine causes the bulging cold front to eventually pass the production well, impacting its temperature. Consequently, the average temperature of the reservoir declines, diminishing the effective lifespan of the reservoir and the efficiency of energy recovery.

Thermal reservoirs with disparate pore structures manifest divergent heterogeneity distribution traits. The plethora of pore structures within sandstone thermal reservoirs endows them with marked heterogeneity, whilst the presence of intricate fracture networks confers a robust heterogeneity upon both carbonate and granite thermal reservoirs. The degree of heterogeneity within these thermal reservoirs is not only influences the geothermal fluid percolation but also significantly affectsreservoir thermal field progression and thermal front configuration (Liu et al. 2020b; Yao et al. 2022; Zheng et al. 2022; Liu et al. 2019a).

The temperature field evolution processes in thermal reservoirs with different degrees of heterogeneity distribution are shown in Fig. 1 and Fig. 2, respectively (Wang et al. 2023; Wang et al. 2021). Fig. 1 illustrates the evolution process of temperature field in a sandstone thermal storage reservoir dominated by pore structure, with reinjection

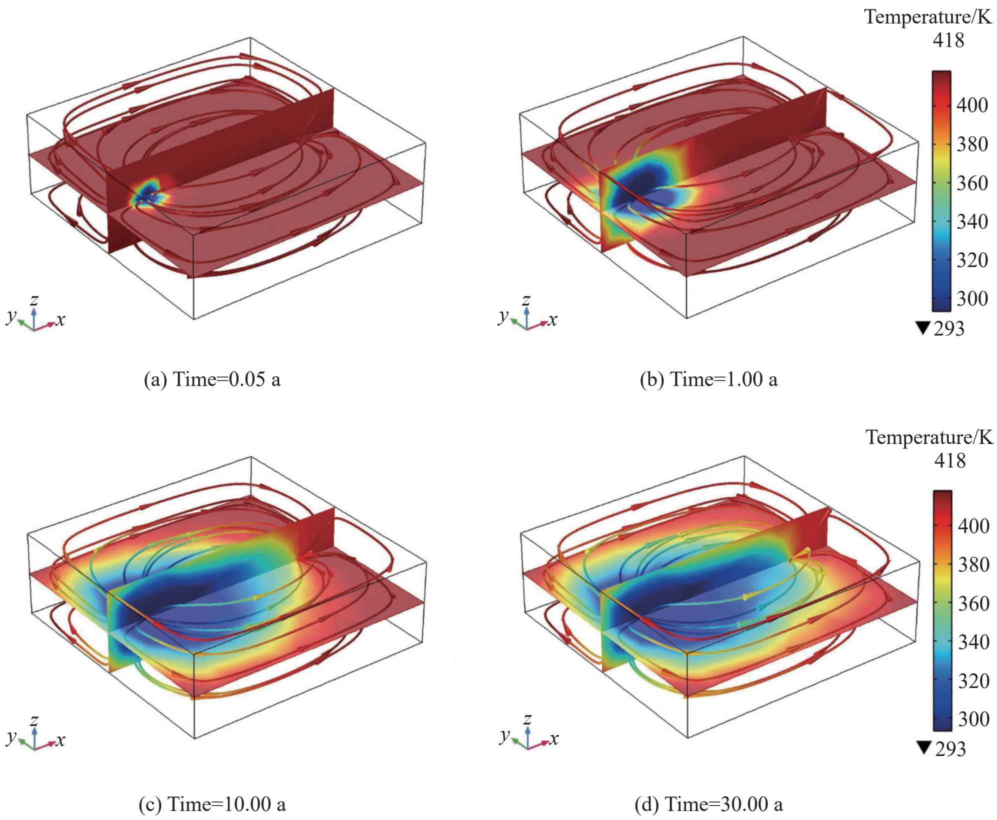

Fig. 1 Temperature field distribution of thermal reservoir in pore sandstone at different time (a) t=0.05a, (b) t=1a, (c) t=10a, (d) t=30a (Wang et al. 2023)

temperature at 293 K, thermal storage temperature at 417 K, and a well distance of 400 m. In contrast, Fig. 2 shows the reservoir temperature field distribution in a carbonate rock thermal reservoir or granite thermal reservoir dominated by fracture structure, with a well distance of 270 m, reinjection tailwater temperature of 30ºC and reservoir temperature of 92ºC for 20 years of simulated operation.

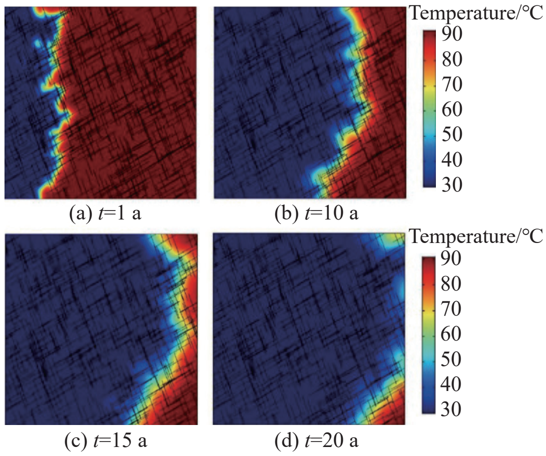

Fig. 2 Temperature field distribution of fractured carbonate thermal reservoir at different time (a) t=1a, (b) t=10a, (c) t=15a, (d) t=20a (Wang et al. 2021)

Comparison of the temperature field evolution processes in two different types of non-homogeneous heat reservoirs reveals consistent overall trends but in the extension speed of the low-temperature zone, the morphology of the cold front, and temperature drop. These differences depend on factors such as internal pore structure, physical properties of different types of reservoirs, as well as the design of reinjection scheme, influencing the heat reservoir temperature field. The heat transfer in porous reservoir is relatively uniform, with a round and smooth cold peak surface in the initial reinjection stage. With long-term operation, the cold front expands evenly, transitioning from round to conical. However, in fissure-structured reservoirs, partially connected fissures accelerate the tailwater flow and the local cold front migration, resulting in a jagge cold front shape during migration and expansion (Jin et al. 2022).

2 Influencing factors of temperature field evolution in thermal reservoir

Understanding the impact mechanism of low-temperature tailwater reinjection on the thermal reservoir temperature field evolution is crucial for the development and utilization of geothermal energy. The reinjecting process involves multiple complex physical and chemical mechanisms, including thermal conduction, thermal convection, heat diffusion, and water-rock interactions. There are numerous factors affecting these processes, among which the properties of the thermal reservoir and the reinjection scheme are two categories that have a significant impact on the evolution of the thermal reservoir's temperature field.

2.1 Effect of thermal reservoir properties on thermal reservoir temperature field

Thermal reservoir permeability is an intrinsic property of the reservoir. The effects of thermal reservoirs permeability on the temperature field vary greatly (Liu et al. 2020b; Qu et al. 2017). Low permeability thermal reservoirs are not easily conducive to injection water in thermal reservoirs and heat exchange with rock masses, leading to the water accumulated at the injection well. Consequently, heat conduction dominates in the reservoirs layer, with weak heat convection effect, resulting in slow heating of the injected water and the formation of a low-temperature zone. A thermal reservoir with higher permeability enables reinjection water to have exchange heat over a larger range, facilitating more efficient heat extraction and a faster migration of the cold front in the temperature field, leading to a greater temperature field drop. However, excessively high permeability can cause rapid fluid velocity, resulting in poor heat exchange and thermal breakthrough.

The properties of fracture structure significantly influence the permeability of fractured geothermal reservoirs. These properties, including aperture, dip angle, and width, play a critical role in shaping the evolution of the temperature field within the reservoir (Li et al. 2019; Yao et al. 2022; Sun et al. 2023). Larger fracture apertures facilitate stronger flow mobility and velocity of injected waters, intensifying the convection effect. This leads to a more rapid decline in local reservoir temperature and a faster movement of the temperature field's cold front and a greater temperature decrease at production well. The relationship between different fracture apertures and the average reservoir temperature is shown in Fig. 3 (Li et al. 2019). Fracture dip angle affects the flow direction and velocity of the hot fluid in the fractures. Fractures with different dip angles promote the flow of injected water in the geothermal reservoir, leading to a faster local temperature decrease, uneven heat exchange, and a saw-tooth-shaped cold front in the temperature field. Fracture width directly affects reservoir permeability. Wider fractures enhance the injected flow mobility and heat exchange capacity. However, excessively wide fractures accelerate flow velocity, reducing contact time with rock, and hastening temperature changes within the reservoir, thus affecting temperature field evolution.

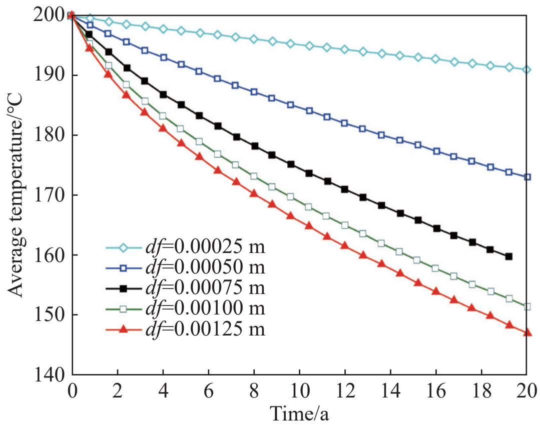

Fig. 3 Relationship between different fracture openings and average reservoir temperature (Li et al. 2019)

2.2 Influence of reinjection scheme on thermal reservoir temperature field

The reinjection scheme encompasses various factors, including production well spacing and distribution pattern, injection temperature and pressure, and others, which directly affect the distribution and evolution of thermal reservoir temperature field. Properly designed reinjection scheme can result in premature thermal breakthrough in geothermal wells, and, in severe cases, lead to well shutdown.

Proper production and injection well spacing and distribution patterns are determined based on the characteristics of the thermal reservoir. Optimal well spacing should not only maintain thermal reservoir, but also mitigate the risk of thermal breakthrough caused by the formation of preferential flow channels between production and injection wells (Zhou et al. 2022; Du et al. 2019; Tang and Qiu, 2023; Wang et al. 2021; Fan et al. 2023). The spacing between injection and production wells determines the seepage path and duration of heat exchange for reinjected water. When the distance is too short, reinjected water may affect production well temperature. Increasing spacing allows reinjected water sufficient time and distance to absorb heat from the geothermal reservoir, delaying the arrival of cold front at production wells. Fig. 4 illustrates the relationship between different injection-production spacings and geothermal reservoir temperature of the on the production side (Wang et al. 2021). In addition to well spacing, the layout of injection wells also influences seepage path and duration of reinjected water. When the line connecting the injection wells aligns with the main direction of fractures, a dominant pathway is formed. This dominant pathway accelerates the injected water flow, enhancing geothermal recovery efficiency. However, it also speeds up the movement of thermal front, resulting in a greater decrease in temperature (Zheng et al. 2022). Currently, numerical simulation methods are employed to quantitatively assess well spacing and location selection. This involves adjusting the distribution of well spacing and locations, simulating reservoir flow and temperature fields, and analyzing temperature changes at production wells.

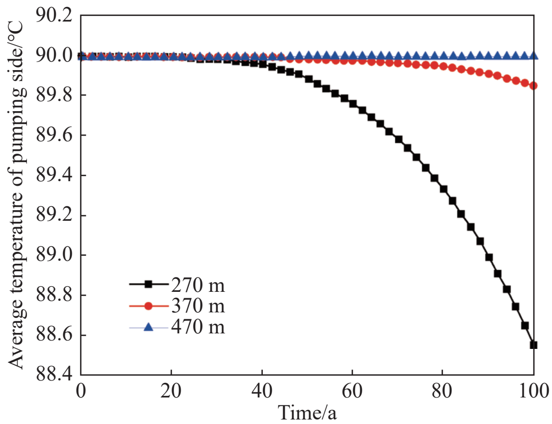

Fig. 4 Average temperature of thermal reservoir on the mining side with different irrigation and irrigation spacing (Wang et al. 2021)

The magnitude of reinjection pressure directly affects the flow rate and velocity of reinjected water. The greater the reinjection pressure, the greater the flow rate, resulting in a larger amount of low-temperature water injected per unit of time. As reinjection water mixes with the hot fluid in the geothermal reservoir, localized temperature drops occur. At the same time, higher reinjection pressure enhances fluid mobility within the reservoir and the heat convection process, promoting thermal transfer and accelerating the movement of the thermal front. As shown in Fig. 5, higher reinjection pressures result in an initial temperature drop at the extraction well, with a greater rate and extent of the temperature decrease (Zhou et al. 2022; Bett and Yasuhiro, 2023; Cheng et al. 2023).

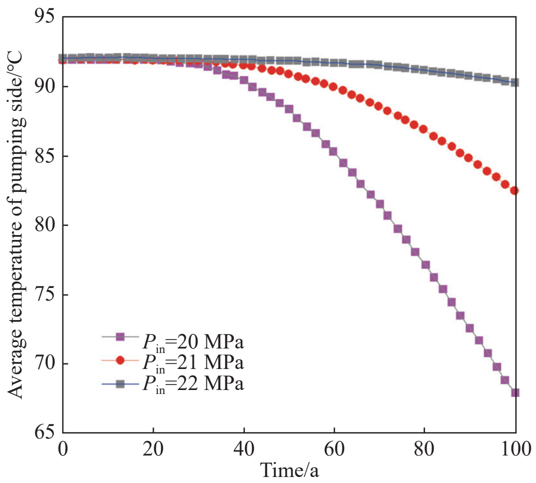

Fig. 5 Mining side temperature at different reinjection pressure (Wang et al. 2021)

Comparing research across different geothermal fields reveals a fundamental similarity in the impact mechanism of reinjection temperature on thermal reservoir temperature fields. Lower reinjection temperatures result in greater temperature difference between reservoir rock and reinjected fluid, which enhances convective heat transfer within the thermal reservoir and increases heat exchange efficiency with reservoir rock. Consequently, the cold front in the thermal reservoir temperature field forms prematurely, with amplified rates and extents of temperature decrease. Trends in temperature changes at production wells with different reinjection temperatures are illustrated in Fig. 6 (Wang et al. 2022a; Cheng et al. 2011; Xiao et al. 2021; Cui et al. 2018a), which displays the variations in production well temperatures under current reinjection temperature of 30°C and the simulated reinjection temperatures of 40°C

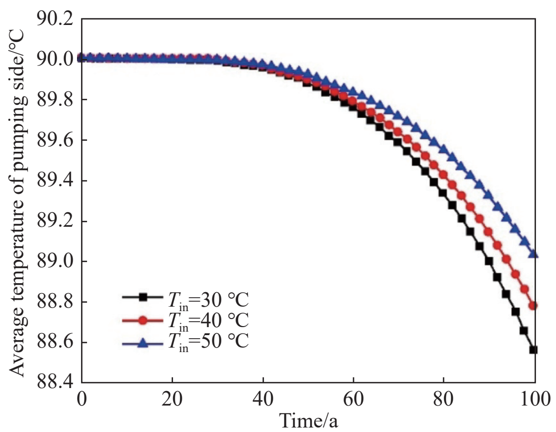

Fig. 6 Mining side temperature at different reinjection temperature (Wang et al. 2021)

and 50°C. It can be seen that the migration of the cold front is closely related to the tailwater temperature. The lower tailwater temperature, the greater temperature difference occurs between the thermal reservoir rock and the fluid, leading to earlier cold front formation. This relationship is also influenced by reinjection pressure, reinjection fluid velocity, thermal reservoir structure and characteristics.

3 Research method of temperature field evolution in thermal reservoir under low temperature tailwater reinjection

The primary methods employed in studying the evolution thermal reservoir temperature field under the conditions of low-temperature tailwater reinjection include laboratory experiments, field tests, and numerical simulations. Laboratory experiments on heat transfer in rock seepage not only provide important parameters for accurately calculating thermal reservoir temperature field but also serve as an excellent approach to investigate percolation heat transfer theory. Although field reinjection tests are costly, they offer significant practical value and serve as an important validation of indoor experiments. Numerical simulation provides enhanced capability for predicting and assessing of the thermal storage temperature field. By integrating these various methods, complementing each other, and verifying results, research into the mechanism of thermal reservoir temperature field evolution can be refined.

3.1 Laboratory experiments

Laboratory experiments on the evolution of temperature field in hot reservoir typically focus on single fracture rock to study heat transfer properties of rock fracture seepage. Percolation heat transfer experiments aim to analyze the process of heat exchange between the rock surface and fluid in the thermal reservoir, a process closely related to seepage. Early studies on fluid flow and heat transfer in rock fractures primarily focused on smooth or horizontal fractures. Researchers used the parallel plate model to simulate actual rough fracture to investigate the effects of rock sample temperature, crack opening, fluid flow rate and other factors on the heat transfer within the fractures under different temperature and pressure conditions (Zhao and Brown, 1992; Zhao and Tso, 1993). However, subsequent research discovered that the parallel plate simplification method introduced inaccuracies to experimental results. To better fit the actual thermal reservoir scenario, most studies utilized artificially split granite with rough fracture surfaces to investigate the impact of roughness on experiments. Fractal dimension and profile waviness were introduced to characterize the roughness of granite and sandstone samples. Experiments were carried out to analyze the seepage characteristics of smooth cracks and rough cracks, and to study the effect of lithology and roughness on the seepage heat transfer characteristics of rock fractures (Ma et al. 2019b; Ma et al. 2019a; He et al. 2016; Zhang et al. 2021).

In order to obtain systematic conclusions due to the significant variation in fracture structure among natural rock samples, it is essential to employ a method for controlling roughness and aperture ensure repeatability in rock samples. Therefore, Huang et al. (2021) utilized Joint Roughness Coefficient (JRC) model and 3D printing technology to artificially create rock samples with varying surface roughness. Subsequently, they conducted seepage heat transfer tests to analyze the seepage heat transfer characteristics at different temperatures and flow rates (Huang et al. 2021). In recent years, Du et al. (2021) and Liu et al. (2023) have performed small-scale experiments using dye tracing techniques to address the challenge of insufficient visibility of fluid percolation and heat transfer processes in experiments. By visualizing the microscopic etched model structure, they were able to observe in detail the seepage behavior of reinjection water at different fracture angles and flow rates. On the basis of these observations, they integrated a physical model of cementation to further investigate the fluid flow dynamics relative to the temperature field (Du et al. 2019; Liu et al. 2020a).

The current system used in laboratory experiments can simulate the seepage and heat transfer of thermal reservoir under in-situ environment during production and injection. The experimental device usually consists of six parts: Water injection, sandwich, confining pressure, heating, temperature measurement, data acquisition and recording system, as shown in Fig. 7 (Huang et al. 2021; Huang et al. 2019). Through core gripper, confining pressure and heating system, the hot reservoir with high temperature and pressure is simulated, while the water injection system is used to inject distilled water at room temperature or about 20°C into the core at a constant flow rate and pressure. During the experiment, the inlet and outlet temperature, sample surface temperature and flow rate were monitored by the temperature measurement, data acquisition and recording system (Ma et al. 2019b; Ma et al. 2019a; Zhang et al. 2021; Ma et al. 2023).

The heat transfer characteristics of rock seepage in laboratory experiments are usually evaluated through convection heat transfer coefficient, a crucial parameter describing the heat transfer characteristics of fluid across the crack surface. Previous studies have analyzed the effect of seepage heat transfer on different rock samples and proposed calculation formula for the convective heat transfer coefficient, as outlined in Table 1.

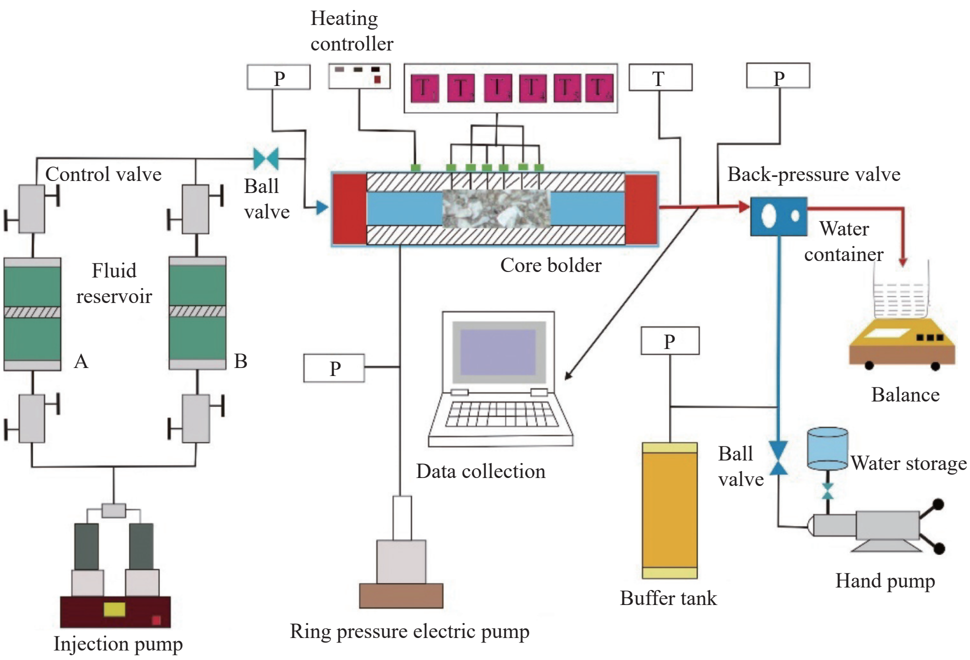

Fig. 7 Experimental apparatus for seepage and heat transfer (Huang et al. 2021)

Table 1 Formula for convective heat transfer coefficient of rocks

Author	Types of thermal storage rocks	Convective heat transfer formula
Zhao (2014)	Granite	$h=\dfrac{-\ln\dfrac{T_2-T_c}{T_1-T_c}\rho_w c_{p,w} u\delta\dfrac{K_r}{2}}{\ln\dfrac{T_2-T_c}{T_1-T_c}\rho_w c_{p,w} u\delta\dfrac{d}{4}+K_r L}$
Zhang (2014)	Granite	$h=\dfrac{21.16c_p\lambda\rho u\delta(T_2-T_1)}{42.32\lambda LT_0-2\pi c_p r_0\rho u\delta(T_2-T_1)-21.16\lambda L(T_1+T_2)}$
Bai et al. (2016)	Granite	$h=\dfrac{c_{p,w}\rho_w u\delta(T_2-T_1)}{2L\left(T_c-\dfrac{c_{p,w}\rho_w u\delta(T_2-T_1)}{42.32K_r L}-\dfrac{T_1+T_2}{2}\right)}$
Li et al. (2017)	Granite	$h=\dfrac{c_{\rho,w}m(T_2-T_1)}{S(T_s-T_f)}$
Luo et al. (2019)	Granite	$h=\dfrac{c_{p,w}\rho_w q_v(T_2-T_1)}{dL\left(T_c-\dfrac{T_1+T_2}{2}\right)}$
Zhan (2021)	Carbonate rock	$h=\dfrac{c_w\rho_w q_w(T_{w2}-T_{w1})}{2LR\left[\dfrac{1}{2}(T_{i1}+T_{i2})+T_c-(T_{w1}+T_{w2})\right]}$

However, significant disparities persist in the calculation of the convective heat transfer coefficient under similar rock conditions. This difference can be attributed to the influence of the internal structure of rock samples and fluid injection conditions on the heat transfer process. Fracture roughness, fracture distribution, injection flow rate, injection velocity and rock sample temperature are key factors that determine the convective heat transfer coefficient.

In the table, h is the convective heat transfer coefficient (W/(m^{-2}·K)); $c_{p,w}$ is the specific heat capacity of water (J/(kg·K)); ρ_w is the density of water (kg/m^3); u is the flow rate of water (m/s); δ is the crack opening (mm); T_1 is the inlet temperature (°C or K); T_2 is the outlet temperature (°C or K); L is the characteristic length of rock sample (mm); T_c is the outer surface temperature of the rock sample (°C or K); L_e is half of the characteristic length of the rock sample (mm). K_r is the thermal conductivity of the rock (W/(m·K)); d is the diameter of rock sample (mm); S is the fracture surface area of the rock sample (mm^2); m is the mass of rock sample (kg); T_f is the average temperature of the inner surface of the rock sample (°C or K); q_w is the volume flow of water (m^3/s).

3.2 Field test

Field tests are conducted following the completion of geothermal drilling, in order to assess the hydraulic connection between production and injection wells and the feasibility of reinjection schemes. These tests can also provide valuable information for reinjection scheme optimization and the establishment of numerical models. Typically, field tests include pumping test and tracer test. Pumping test can be used predict the quantity of injection water and reservoir production. While pumping tests offer a straightforward flow and intuitive insight into site characteristics, they only reflect the macro-level characteristics of the heat reservoir and cannot accurately obtain internal changes (Luo, 2018). In contrast, tracer tests determine concentration the tracer concentration peak time from the concentration response curve. This allows for the analysis of seepage characteristics, heat transfer areas, temperature changes of low-temperature tailwater in the thermal reservoir, and prediction of heat migration breakthrough time. Tracer tests are more accurate and comprehensive than pumping tests in evaluating the connectivity between production and injection wells, predicting the heat transfer areas and temperature changes, and are widely used in most reinjection projects (Wang and Lu, 2023; Kuo et al. 2018).

The application of tracer tests in geothermal fields has evolved over time. Initially, natural tracers such as isotopes and inert gases were used, enabling the identification of water sources and the study of water migration in hot reservoirs. These tests proved valuable in monitoring dynamic changes in geothermal fields during exploitation, as well as determining optimal well locations and spacing (Ellis, 1977; Mazor and Truesdell, 1984). Subsequently, stable tracers such as artificially manufactured halides, fluorescein, and radioisotopes were used in tracer tests, such as chlorides in the Palinpinon-I geothermal field in the Philippines (Sullera and Horne, 2001). Fluorescein tracing experiments were conducted in the Olkaria geothermal field in Kenya (Wang'ombe et al. 2014), the Soultz-sous-Forets geothermal field in France (Radilla et al. 2012; Aquilina et al. 2004), and the Niutuzhen geothermal field (Wang et al. 2013; Qiao et al. 2023). Using sodium naphthalene sulfonate, a tracer test for well injection was carried out in Xianxian geothermal field (Li et al. 2020; Liu et al. 2019b; Liu et al. 2022). Radioisotope tracer tests were conducted in the Wairakei geothermal field in New Zealand (Bullivant and O'sullivan, 1989) and the Wanglanzhuang geothermal field (Zeng et al. 2008). These tests have demonstrated well inter-well connectivity and water transport time, but stabale tracers alone are insufficient to assess heat transfer area and temperature changes.

In recent years, tracer tests have advanced with the introduction of reactive and intelligent tracers. The use of these tracers can obtain the heat transfer area and temperature variation of hot reservoir and expand the study range of tracer tests. Reactive tracers are generally divided into two categories: Adsorption tracers and temperature-responsive tracers. The heat exchange area between the fracture and the rock matrix can be determined by adsorbing the adsorbed tracer on the rock surface during migration. Temperature-responsive tracers undergo a thermal decay reaction in the thermal reservoir system, allowing for the assessment of temperature changes based on the reaction rate (Cao et al. 2018; Cao et al. 2020). Previous studies have confirmed that amino G, saffranine T and Rhodamine W undergo adsorption reactions at high temperatures, while some experiments use the adsorption of cations, such as lithium and cesium ions (Reimus et al. 2020; Hawkins et al. 2018). In the Lightning Dock geothermal field, adsorption and temperature-responsive tracers were combined to study the effective heat transfer area and temperature decline of thermal storage, and the uncertainty of using multiple tracers was also discussed (Reimus et al. 2020). Smart tracers are designed in combination with nanotechnology, and their diffusion, thermal degradation and adsorption can be achieved by adjusting the size, shape, shell and surface ligand of the nanoparticles. Tracer test applications can be designed as conservative tracers or reactive tracers according to requirements (Alaskar et al. 2015; Liao and Cirpka, 2011). Many laboratory studies have been conducted, but smart tracers have not yet been used in field tracer tests (Bottacin-Busolin et al. 2021).

Selecting appropriate tracer is crucial for achieving satisfactory tracer test results. As there are many types of tracers with different functions and properties (Table 2), the selection of tracers is influenced by different thermal reservoir lithology (Liu, 2019; Ren et al. 2023; Pollack et al. 2021). For example, tracers with acidic aqueous solution should be avoided for carbonate thermal reservoir, while granite thermal reservoirs are prone to reacting with alkaline tracer due to their higher SiO_2 content. In field test, the environmental conditions of thermal reservoir and the physical and chemical properties of the tracer should be fully considered to minimize the influence on the test results.

3.3 Numerical simulation

Analytical methods and numerical simulation methods play a pivotal role in analyzing data from laboratory experiments and field tests, contributing significantly to our understanding of geother-

Table 2 Classification of common tracers

Category	Common tracers	Advantage	Shortage
Natural tracer	Hydrogen and oxygen isotopes, noble gases, ^{222}Rn	—	—
Inert tracers	NaCl, KCl, NaBr, KBr, Ki. el. halide	Good low temperature stability and easy to detect	The background value in storage is high, adsorption, and the reaction occurs at high temperature.
	Fluorescein, sodium naphthalenesulfonate, rhodamine, saffron	Economical and relatively non-toxic, low value in thermal reservoir, easy to detect	Sensitive to pH, salinity and high chloride concentration, photochemical and chemical decay, susceptible to sediment adsorption, decomposition at high temperatures and loss of fluorescence properties.
Radioactive tracers	^{3}H,^{35}S,^{82}Br,^{131}I	High sensitivity, strong anti-interference ability, easy to detect	The test requirements are high and easy to pollute the environment.
Reaction tracer	Esters, amides, carbamates	The heat exchange area and temperature drop rate can be determined	Data analysis requires experimental correction factors, which increases the workload.
Smart tracer	Nanoparticles, quantum dots	Economical, environmentally friendly, stable, easy to detect, designed as a conservative or reaction tracer as needed	—

mal utilization. While analytical methods provide accurate solutions by assuming the geometric shape or physical property parameters of the analysis domain, their applicability limited to simple thermal reservoir structures with well-defined problems. In contrast, geothermal utilization involves the complex interactions among various physical fields and dynamic changes in physical property parameters, posing challenges for analysis solely through analytical methods. To address these limitations, numerical simulation methods have gained prominence in geothermal development. These methods allow for modeling reservoirs based on their physical and chemical states, compensating for the high costs associated with drilling in laboratory experiments and field tests. Furthermore, numerical simulation method effectively addresses the complexity of multi-parameter and multi-physical field interactions, which cannot be adequately handled by analytical methods. Currently, numerical simulation accurately describes the heterogeneity of thermal reservoir and the evolution of multi-field coupling reinjection processes, making it the primary approach for evaluating thermal reservoir performance, optimizing production and injection schemes, and predicting thermal breakthroughs in geothermal engineering (O'Sullivan et al. 2001; Luo, 2018; Yu et al. 2023).

Table 3 presents several commonly used multi-field coupled simulation programs and their functionalities in geothermal reinjection research (Luo, 2018; Liu et al. 2019a; Zhao et al. 2022). These software programs offer a wide range of reservoir modeling capabilities and finite element multi-field coupling analysis, equipped with extensive material databases and predefined fracture element modules. They have been widely utilized in research studies.

The application of numerical simulation method is based on the establishment of thermal reservoir model. Tailored to different types of thermal reservoirs such as pore type, karst-type and fissure-type reservoirs, ensuring alignment with actual pore structure. At present, the multi-field coupling models for thermal storage mainly include equivalent continuum model, dual or multiple media model, discrete fracture network model, random continuum model and mixed mode (Chen et al. 2014; Liu and Liu, 2014).

(1) Equivalent continuum model: Based on continuum theory, the equivalent continuum model assumes that complex geological formations behave as continuous media, averaging water flow within fractures across the entire thermal reservoir. Widely used, this model suggests stable permeability when the thermal reservoir range is larger than a certain scale, often represented by equivalent permeability. However, it is important to acknowledge that the pore volume of bedrock is significantly larger than the fissure, and therefore, the water storage capacity should not be ignored. In general, the equivalent continuum model is suitable in case of high fracture density (Wang et al. 1995). This model uses the mass conservation equation to describe the thermal reservoir seepage process (Wang et al. 2020b):

$$\frac{\partial}{\partial t}(\rho_{\mathrm{f}}\varphi)+\nabla\cdot(\rho_{\mathrm{f}}u_f)=Q_{\mathrm{m}} \tag{1}$$

Where: t is time (s), ρ_f is the fluid density (kg/m^3), Q_m is the fluid mass source (kg/(m^3·s)), Darcy velocity field, u_f is:

$$u_f=-\frac{\kappa_r}{\mu}\nabla p_{\mathrm{f}}+\rho_f g\nabla z \tag{2}$$

Where: μ is hydrodynamic viscosity (Pa·s), K_r is permeability (m^2), and p_f is fluid pressure (Pa), g is the acceleration of gravity (m/s^2) and z is the vertical coordinate (m).

The mathematical description of heat transfer process in thermal reservoir is usually based on the convection diffusion equation, which averages thermodynamic properties by volume to incorporate solid matrix and pore fluids (Cui et al. 2018b):

$$(\rho C_p)_{\mathrm{eff}}\frac{\partial T}{\partial t}+\rho_{\mathrm{f}}C_{\mathrm{p,f}}u_f\cdot\nabla T-\nabla\cdot(k_{\mathrm{eff}}\nabla T)=q_f \tag{3}$$

Where: $C_{p,f}$ is the specific heat capacity of the fluid under constant pressure (J/kg/K), T is the temperature (K), q_f is the heat source (W/m^3), and $(\rho Cp)_{eff}$ is the equivalent volumetric heat capacity of the reservoir rock mass (Pandey et al. 2018):

Table 3 Common numerical simulation software and functions

Software name	Algorithm	Multi-field coupling capability
COMSOL	Finite elements	THMC
OPENGEOSYS	Finite elements	THMC
FLUENT	Limited volume	THM
TOUGH-FLAC	Finite difference	THM
FRACMAN	Finite elements	THM

$$(\rho C_{\mathrm{p}})_{\mathrm{eff}} = (1-\varphi)\rho_s C_{p,s} + \varphi \rho_f C_{p,f} \tag{4}$$

Where: k_{eff} is the effective thermal conductivity of reservoir rock mass (W/m/K), calculated as the weighted average value of reservoir rock mass thermal conductivity k_r and fluid thermal conductivity k_f (Liu et al. 2019a);

$$k_{eff} = (1-\varphi_r)k_r + \varphi_r k_f \tag{5}$$

(2) Dual media or multiple media models: Dual or multiple media models are often used to solve the fluid-thermal coupling problem in fractured or porous media. These models treat the model domain as two overlapping media: Fractured media conducting water and matrix rock storing water, taking into account the energy exchange between them. However, the assumption of regular crack distribution and quasi-static assumption of dual media models cannot reflect the reality (Zhang, 2017). When the phenomenon of water storage is considered in such models, the following relationship is expressed:

$$\frac{\partial}{\partial t}(\varphi_r \rho_f) = \rho_f S_r \frac{\partial p}{\partial t} \tag{6}$$

According to the elastic theory of porous media, the water storage coefficient Sr can be represented by porosity φ, Biot coefficient α_B, fluid bulk modulus K_f, and mass bulk modulus K_d.

$$S_r = \frac{\varphi}{K_{\mathrm{f}}} + (\alpha_{\mathrm{B}} - \varphi)\frac{1-\alpha_{\mathrm{B}}}{K_{\mathrm{d}}} \tag{7}$$

The equation for thermal reservoir seepage flow in the synchronous equations (1), (2), (6), and (7) is;

$$\rho_f S_r \frac{\partial p}{\partial t} + \nabla \cdot \rho_f \left(-\frac{\kappa_r}{\mu}\nabla p\right) = Q_m \tag{8}$$

(3) Discrete fracture network model: With the development of computing technology, the discrete fracture network model is widely used to simulate the multi-field coupling effect of fractured rock mass. This model can depict the local behavior of a single fracture and the macro behavior of a complex fracture network more realistically compared to the equivalent continuum model. It also overcomes the challenge faced by the equivalent continuum model in determining the size and equivalent parameters of the representative unit. However, due to the complexity of fracture geometry, and physical and mechanical parameters, the calculation workload is substantial (Wolfsberg, 1997). The tangential formula of Darcy's law is used in the governing equation of the model to demonstrate seepage and heat transfer in the fracture unit (Al-Khoury et al. 2005; Al Khoury and Bonnier, 2006).

$$b_{fr}\frac{\partial}{\partial t}(\varphi_{fr}\rho_f) + \nabla_T \cdot (\rho_f q_{fr}) = b_{fr} Q_m \tag{9}$$

$$q_{fr} = b_{fr} u_{fr} = -\frac{\kappa_{fr}}{\mu} b_{fr} \nabla_T p \tag{10}$$

Where: φ_{fr} is the fracture porosity; ∇_T is the gradient operator confined to the slit plane; q_{fr} is the volume flow rate per unit length in the fracture (m^3/s). κ_{fr} is the fracture permeability (m^2); u_{fr} is Darcy velocity in the fracture (m/s)

The heat transfer equation for the fractures can be expressed as follows:

$$b_{fr}(\rho C_p)_{eff}\frac{\partial T}{\partial t} + b_{fr}\rho_f C_{p,f} u_f \cdot \nabla_T T - \nabla_T \cdot (b_{fr} k_{eff} \nabla_T T) = b_{fr} \cdot q_f \tag{11}$$

$b_{fr} \cdot q_f$ considers the flow and heat transfer between fractures and rocks:

$$b_{fr} \cdot q_f = \left(u_{rz}\rho_f C_{p,f} T - k_{eff}\frac{\partial T}{\partial z}\right)_{z=-b_{fr}/2} - \left(u_{rz}\rho_f C_{p,f} T - k_{eff}\frac{\partial T}{\partial z}\right)_{z=b_{fr}/2} \tag{12}$$

(4) Stochastic continuous model: This model is utilized to determine the permeability distribution of fractured rock mass by determining permeability ranges and grades based on field tests and other methods. The application of stochastic continuous model is more direct and convenient, with broad application prospects (Neuman and Depner, 1988).

(5) Hybrid model: This model combines characteristics from various models. For instance, the discrete fracture model is combined with the random continuous model to obtain the equivalent permeability of the model. This is achieved by randomly generating a discrete fracture network within the model (Jackson et al. 2000; Botros et al. 2008). Another example is the combination of discrete fracture model with equivalent continuum model, where different models are used to address fractures of different scales (Wang et al. 1995). Moreover, the discrete fracture network can be fused with dual medium model, treating the fracture as a single medium. In this case, parameters such as porosity and permeability are assigned, and seepage and energy exchange between the bedrock and fracture are taken into consideration (Sun et al. 2016).

4 Current research issues

As geothermal development expands in breadth and depth of, deep thermal reservoirs are often characterized by high temperature, large stress, strong heterogeneity, and complex pore geometry. These characteristics pose new challenges for understanding the heat transfer process of rock seepage and the evolution of thermal reservoir temperature field under the conditions of injection and production. Over the years, reinjection engineering has accumulated valuable experience.

(1) Imperfect theory of convective heat transfer coefficient for large-scale and complex fracture morphologies

Convective heat transfer coefficient is crucial for evaluating the heat transfer characteristics of rock fracture seepage. While numerous experimental studies have been conducted on seepage and heat transfer in rocks with single fissures, conducting experiments on large rock samples and complex multi-fissure samples remain challenging due to the complexity of cracks in thermal reservoir and limitation in experimental equipment sample size. Therefore, there is a lack of convective heat transfer coefficient theory applicable to large size and complex fracture morphology, hindering the analysis of temperature evolution in the heat transfer process of rock fractures.

(2) Limited accuracy of single tracer test

In terms of tracer tests conducted at geothermal fields, conservative tracers are mostly used, and the tracers are relatively singular. This limits the ability to qualitatively assess the connectivity of thermal reservoir, leading to multiple interpretations of preferential channels in thermal reservoir. Additionally, using reactive tracers for quantitative evaluation of heat transfer surface area and temperature drop rate in thermal reservoir introduces uncertainties. As a result, the accuracy of thermal reservoir information is compromised, making it difficult to analyze the temperature drop rate and predict the thermal breakthrough time during the evolution of the temperature field in thermal reservoir.

(3) Limited computational power of heterogeneous thermal reservoir model under group injection

When establishing thermal reservoir models under reinjection conditions using numerical simulation, it is common to employ double well model to analyze the evolution process of the thermal reservoir temperature field. However, as geothermal fields adopt large-scale exploitation mode involving multiple wells or groups of wells, there is growing need to establish larger reservoir geothermal models that incorporate multi-fracture considerations. The computational resources of numerical simulation software are often inadequate to efficiently handle the extensive scale and numerous parameters involved in multi-well or group well models, leading to lengthy calculation times and compromised accuracy.

5 Summary and prospect

This study provides a comprehensive review of the evolution of temperature field in thermal reservoirs with low-temperature tailwater reinjection. It highlights the consistent trend and difference in temperature field evolution in different heterogeneous thermal reservoirs. The general trend of temperature field evolution across different heterogeneous thermal reservoirs is consistent. However, significant differences arise due to variations in pore structure, physicochemical properties and reinjection parameters such as reinjection pressure and temperature. These differences manifest in the morphology, migration velocity and temperature drop of the cold front, particularly in porous sandstone and fractured carbonate or granite hot reservoirs, emphasizing the influence of heterogeneity on temperature field evolution.

Geothermal reinjection engineering requires careful selection of reinjection well layout, reinjection pressure and temperature based on specific geological conditions and heat storage properties to develop geothermal resources scientifically, efficiently and sustainably. In order to deepen the understanding of temperature field evolution in deep heat storage and improve the sustainable development capability of deep geothermal resources, the following future research directions are proposed:

(1) Scaling up experimental research: Conduct larger-scale experiments of rock seepage heat transfer to improve the calculation method of convective heat transfer coefficient in large-scale and complex fracture morphologies. This will enable accurately evaluation of the seepage heat transfer characteristics of heat storage and provide a solid foundation for studying temperature field evolution.

(2) On-Site observation of heat transfer: Observe the actual heat transfer area and temperature drop of thermal reservoir on-site by combining a variety of tracers. Comprehensive analysis of tracer test results will deepen the understanding of the evolutionary mechanism of heat storage temperature field in injection-production system.

(3) Complex fracture and group well modeling: Establish complex fracture and group well models covering the scale of geothermal fields to study the

distribution characteristics of thermal reservoir temperature field under group well reinjection conditions and their influence on the evolution process of temperature fields. Optimize the model calculation method to adapt to large-scale fracture model solving and improve computational efficiency and processing power.

(4) Integration of artificial intelligence: With the development of artificial intelligence technology and the accumulation of geothermal reinjection research data, leverage methods such as deep learning to improve research efficiency and uncover deeper temperature field evolution laws in future development of the geothermal energy field.

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