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Research Paper

Progress and prospect of mid-deep geothermal reinjection technology

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Abstract: Mid-deep geothermal reinjection technology is crucial for the sustainable development of geothermal resources, which has garnered significant attention and rapid growth in recent years. Currently, various geothermal reinjection technologies lag behind, lacking effective integration to address issues like low reinjection rates and thermal breakthrough. This paper reviews the basic principles and development history of mid-deep geothermal reinjection technology, focusing on various technical methods used in the process and analyzing their applicability, advantages, and disadvantages under different geological conditions. It highlights the unique challenges posed by deep geothermal resources, including high temperature, high pressure, high stress, chemical corrosion, and complex geological structures. Additionally, it addresses challenges in equipment selection and durability, system stability and operation safety, environmental impact, and sustainable development. Finally, the paper explores future directions for mid-deep geothermal reinjection technology, highlighting key areas for further research and potential pathways for technological innovation. This comprehensive analysis aims to accelerate the advancement of geothermal reinjection technology, offering essential guidance for the efficient reinjection and sustainable development of geothermal resources.

Keywords: Middle and deep geothermal; Geothermal reinjection; Sustainable development; Technological progress; Research path

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Introduction

With the continuous growth in global energy demand and increased awareness of environmental protection, developing and utilizing renewable energy has become a crucial topic in the energy field. Geothermal energy, as a renewable energy source, has gained significant attention in recent years due to its vast development potential and environmental friendliness (Diaz et al. 2016; Kamila et al. 2021). Specifically, mid-deep geothermal resources have become a key focus in geothermal development given their abundant reserves and stable heat energy (Ma, 2023; Zhang et al. 2024a). To achieve the sustainable development of geothermal resources, mid-deep geothermal reinjection technology has emerged as a critical method to enhance energy utilization efficiency, extend the lifespan of geothermal wells, and reduce environmental impacts (Wang and Lu, 2023).

The development of mid-deep geothermal reinjection technology has evolved from the exploitation of shallow geothermal resource to the utilization of mid-deep geothermal resources (Allen and Milenic, 2003; Kaya et al. 2011). Throughout this evolution, the integration of advanced monitoring

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techniques, numerical simulation technologies, and intelligent control systems has significantly enhanced reinjection efficiency and reliability (Jin et al. 2022; Yu et al. 2024, Rodriguez-Gomez et al. 2023). For instance, continuous improvements in drilling and completion techniques for geothermal reinjection wells, optimization of reinjection processes under varied geological conditions, and the maturation of control technologies during reinjection have been particularly noteworthy (Božiček et al. 2017). These advancements in technology have provided robust support for the effective implementation of geothermal reinjection.

Mid-deep geothermal reinjection technology offers unique advantages in energy utilization and environmental protection, yet it also faces numerous technical challenges. These challenges primarily arise from the specific characteristics of geothermal reservoirs, including high temperature, high pressure, high stress, chemical corrosion, uneven formations and complex fault fractures. Despite advancements in deep geothermal exploration, development and utilization, there remains a significant lag in various types of medium and deep geothermal reinjection technologies. Issues such as equipment selection and tolerance, system temperature management, operation safety, environmental impact and sustainable development are inadequately addressed. There is a lack of effective and targeted reinjection technology combinations. Consequently, problems like low reinjection rates in sandstone and other low permeability thermal reservoirs, as well as issues like thermal breakthrough in geothermal reinjection projects, have not been resolved for a long time. These challenges significantly hinder the efficient and sustainable development of geothermal.

This paper reviews the basic principles and development history of mid-deep geothermal reinjection technology, focusing on the various technical methods used in the process and analyzing their applicability along with their pros and cons under different geological conditions. It then highlights the unique challenges posed by deep geothermal resources, including high temperature, high pressure, high stress, chemical corrosion, and complex geological structures. The paper also addresses the challenges faced by reinjection technology in terms of equipment research and development, system temperature stability and operational safety, environmental impact, and sustainable development. Finally, it outlines future development directions for deep geothermal reinjection technology, proposing key research areas and potential paths for technological innovation. Overcoming the challenges in geothermal reinjection engineering and technology is crucial for promoting the efficient and sustainable development of mid-deep geothermal reinjection.

1 The basic principle and development history of mid-deep geothermal reinjection technology

1.1 Basic principle of mid-deep geothermal reinjection technology

Mid-deep geothermal resources refer to geothermal resources located deeper underground, typically at depths of 1,500 to 3,000 meters or even deeper. Compared to shallow geothermal resources, mid-deep geothermal resources are characterized by high temperatures, high pressure, and abundant heat, making them suitable for high energy consumption applications such as power generation and heating. The extraction and utilization of mid-deep geothermal resources hold significant potential but also face many engineering problems and technical challenges, with reinjection posing a particular difficulty (He et al. 2023; Fu et al. 2024).

The mid-deep geothermal reinjection technology is designed to address the unique characteristics of mid-deep geothermal reservoirs by reinjecting used geothermal fluids underground. This process helps maintain reservoir pressure, prevent subsidence, and depletion of geothermal water, thereby enhancing the sustainable utilization of geothermal resources. This technology is based on several key principles, as illustrated in Fig. 1: (1) Pressure maintenance: By reinjecting cooled geothermal fluids into the reservoir, pressure is replenished to prevent rapid pressure decline, thereby sustaining well productivity. (2) Reservoir rejuvenation: The reinjected cool fluid undergoes heat exchange within the reservoir, creating a cyclic system that efficiently utilizes geothermal resources and extends the lifespan of the wells. (3) Subsidence prevention: Reinjection prevents subsidence and surface collapse caused by the - compaction of the reservoir due to fluid extraction (Diaz et al. 2016).

1.2 Development history of mid-deep geothermal reinjection technology

The history of mid-deep geothermal reinjection

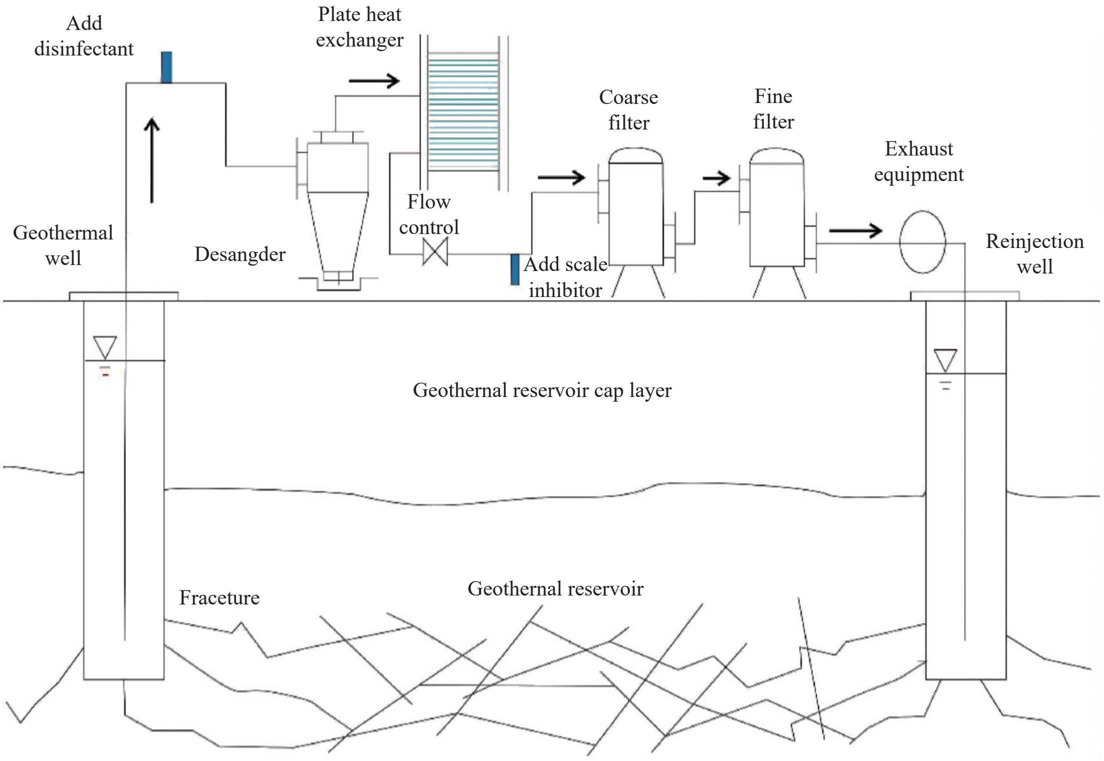


Fig. 1 Principle of geothermal reinjection and schematic diagram of water quality detection and filtration (Chitgar et al. 2023)

technology dates back to the early stage of geothermal resource utilization. As geothermal resources development progressed, reinjection technology has experienced several significant stages of advancement.

(1) Early exploration (before the mid-20th century) - natural reinjection:

In the early days of geothermal development, natural reinjection methods were employed to maintain geothermal water equilibrium through natural geological structures and water circulation systems. During this period, no systematic artificial reinjection techniques were in place (Kaya et al. 2011).

(2) Initial stage (1950s–1970s) -- Initial attempts:

In the 1950s, with advancements in geothermal power generation technology, there was a surge in the consumption of geothermal water resources, highlighting the critical need for reinjection. A pioneering effort occurred in 1958 at the Wairakei geothermal field in New Zealand, which implemented artificial reinjection. However, the effectiveness of this early reinjection was limited due to the lack of advanced technology and expertise at the time (Allis, 1981; Allis et al. 1985).

(3) Development stage (1980s–1990s) -- Technological exploration and improvement:

During the 1980s, significant advancements were made in manual reinjection technology, accompanied by progress in drilling and reinjection techniques. The United States began implementing artificial reinjection technology on a large scale, notably at the Geysers geothermal field in California and various geothermal projects in Nevada (Einarsson et al. 1975; Stefansson, 1997). Furthermore, Iceland, with its extensive experience in geothermal resource utilization, also began adopting reinjection technology in projects such as the Reykjanes geothermal field (Eysteinsson, 2000).

(4) Mature application stage (from the beginning of the 21st century to now) - technology maturity and wide application:

In the 21st century, as geothermal resources development has expanded and environmental protection awareness has increased, mid-deep geothermal reinjection technology has gradually matured and become widely adopted. Advanced geological exploration techniques and porous media fluid models have optimized the design and layout of reinjection wells, improving reinjection efficiency. Various water treatment technologies, such as reverse osmosis, ion exchange, and precipitation treatment, have been developed to address issues with minerals and solid particles in reinjection water. Successful applications of advanced reinjection technology include addressing formation settlement and resource depletion at the Salton Sea geothermal field in California, United States (Brodsky and Lajoie, 2013; Kaspereit et al. 2016). In Japan's Matsukawa Geothermal Field, sustainable development of geothermal resources has been achieved through advanced drilling and reinjection technology (Hanano, 2003; Aoyama et al. 2022). In China, large-aperture gravel filling, perforation technology, and scale removal techniques have significant improved reinjection rates in complex strata, with some sites maintaining 100% reinjection for many years. Recent advancements have also enabled deep well geothermal reinjection to 4000 m in Xiongan, China (Yue et al. 2021; Wang et al. 2021b). Modern technology has further enhanced the field with the integration of intelligence and automation, utilizing sensors and data analysis to monitor reinjection process in real time, optimize parameters, and improve outcomes. Furthermore, the application of high-performance materials, such as those resistant to high temperatures and corrosion, has increased the durability and reliability of reinjection wells. Despite these advancements, ongoing innovation and development are essential to address the engineering and technical challenges associated with mid-deep geothermal exploration, exploitation and utilization.

The development of mid-deep geothermal reinjection technology has progressed from initial exploration to full maturity. As technology continues to advance and practical experience grows, medium and deep geothermal reinjection technology is expected to become increasingly efficient, cost-effective, and environmentally friendly. This advancement will provide a strong technical foundation for the sustainable development of geothermal resources in the future.

2 Advantages and disadvantages of mid-deep geothermal reinjection technology and its applicability

Geothermal reinjection is a complex and systematic engineering process that involves drilling and completion techniques, reinjection procedures, and optimization control technologies. Its effectiveness and applicability can vary significantly depending on geological and development conditions. When selecting and optimizing reinjection technologies, several factors must be considered, including geological characteristics, formation pressure, permeability, temperature conditions, and development objectives.

2.1 Drilling and completion technology of geothermal reinjection wells

(1) Drilling technology of geothermal reinjection wells

Geothermal production wells and geothermal reinjection wells share many similarities in infrastructure and processes. However, due to their differing functions and operational requirements, there are notable differences in well design, drilling depth, wellhead treatment, and maintenance. Both types of wells require similar geological exploration processes and drilling technologies, as well as precise drilling equipment, to penetrate various geological layers and reach predetermined depths. Comprehensive geological exploration and evaluation are necessary before drilling to determine the optimal drilling location and path.

Drilling equipment and tools such as drill rigs, drill bits, casing, and mud systems are used for both production and reinjection wells (Agoun, 2000). However, the design of geothermal reinjection wells focuses on ensuring the smooth injection of water into the geothermal reservoir while preventing wellbore blockage and damage. This often necessitates special filters and injection devices. Additionally, geothermal reinjection wells generally have smaller drilling depths and diameters compared to production wells, with a focus on optimizing the injection volume.

Current drilling technologies include positive circulation drilling, gas lift reverse circulation drilling, and directional drilling techniques (Song et al. 2023). Each of these technique has specific advantages, disadvantages, and applications. Positive circulation drilling and gas lift reverse circulation drilling are suitable for vertical well production (Fig. 2a), while directional drilling techniques can be used for deviated wells (Fig. 2b), horizontal wells, and other trajectory-changing wells (Zhang and Zhang, 2014). A detailed comparison of the advantages, disadvantages, and applicability of commonly used drilling technologies is provided in Table 1.

Given the high temperature and pressure characteristics of mid-deep geothermal reservoirs, cooling systems are installed during drilling to reduce the temperature inside the well, protecting drilling tools and wellbore equipment. Furthermore, the use of corrosion-resistant coatings and materials is crucial to extend the lifespan of the wellbore and equipment (Finger and Blankenship, 2012).

(2) Completion technology of geothermal reinjection wells

The completion process of geothermal wells is a

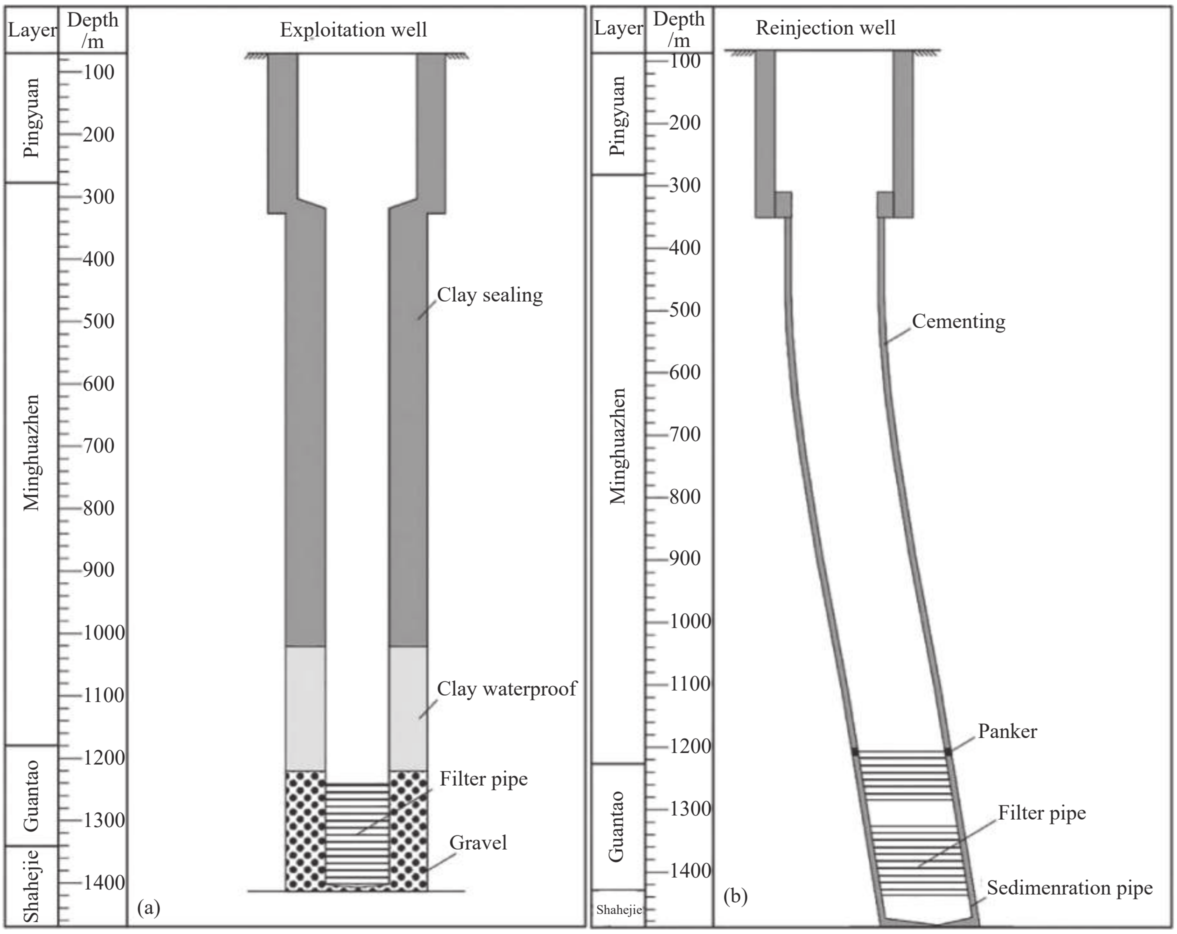


Fig. 2 (a) geothermal vertical well and (b) geothermal inclined well (Zhao et al. 2024)

Table 1 Advantages, disadvantages and applicability of commonly used drilling techniques (Ma et al. 2014; Zhang and Zhang, 2014)

Drilling processes		Applicability	Advantages	Disadvantages
Positive circulation drilling technique	Drilling fluid	Most geological conditions	Stable borehole, simplicity for the operator, matured technology	Easily polluted reservoirs, high lost circulation costs
	Clean water	Geological conditions with stable formation and low pressure	Fast drilling speed, effective well washing, low reservoir pollution, and low costs	Borehole instability, poor cutting carrying ability
	Clean water filling air	Drilling projects with stable formation, low pressure, and high environmental requirements	Protect reservoirs, reduce lost circulation, increases drilling speed, prevents differential pressure sticking	High technical requirements
Air lift reverse circulation technique		Drilling in loose and collapsible formations	High efficiency, long bit life, good well quality, reliable, continuous core drilling, time-saving	High technical requirements
Directional drilling technique		Drilling in complex formations, deep wells, and multiple target zones	Achieves accurate positioning of the target layer, reduces impact of ground facilities and the environment	High cost, high technical requirements

critical step in well construction, involving several key procedures such as mud replacement, casing installation (including filters), gravel packing, and cementing. The goal is to establish a reliable channel between the heat reservoir and the wellbore, ensuring stable production and reinjection (Zhao, 2014). Conventional geothermal completion techniques have evolved over time and now include methods such as wire-wrapped screen casing completion, large-diameter wire-wrapped screen gravel packing completion, and bare-hole completion. The advantages, disadvantages, and applicability of these techniques are detailed in Table 2.

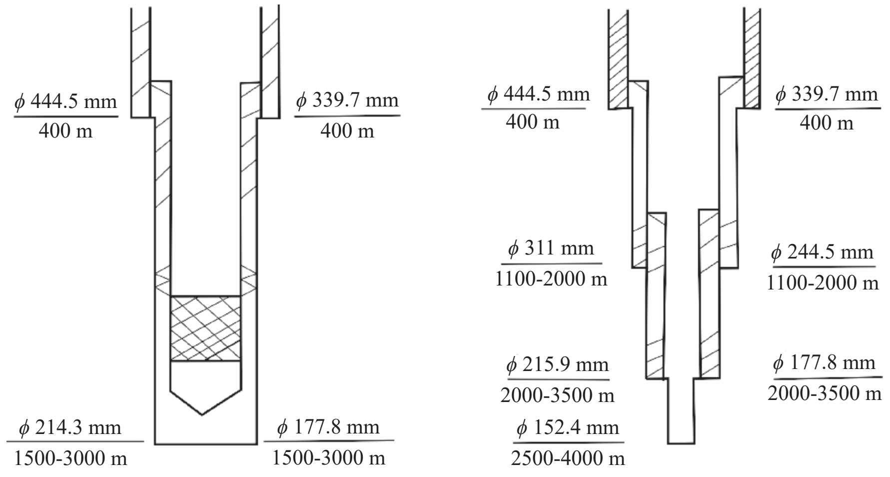
Low-permeability heat reservoirs, which are common in mid-deep layers, often require specialized technologies to meet reinjection requirements. For these low-permeability geothermal reservoirs, multi-stage completion techniques are employed. These may include staged fracturing or acidization to enhance permeability and fluid pathways in low-permeability reservoirs. Additionally, high-strength casing and cement sealing are utilized to prevent wellbore collapse and leakage, ensuring the long-term stability. In high-temperature and high-pressure mid-deep heat reservoirs, materials resistant to extreme conditions, such as special alloy casings and cement slurries, are used during the completion process to prevent deformation or damage to the wellbore caused by high temperature and pressure.

Different wellbore structures and completion methods are employed for geothermal injection wells based on the geological structure and lithology characteristics of the geothermal reservoir. These methods are designed to ensure stable production and wellbore integrity post-injection. For porous heat reservoirs, such as those with loose and semi-cemented sandstone and conglomerate rocks, a wellbore structure as shown in Fig. 3 (a) is typically used. This design includes a filter-equipped casing at the bottom of the well to prevent sand intrusion.

In contrast, for fractured rock geothermal reservoirs, such as hard carbonate and granite formations, as shown in Fig. 3 (b), a multi-casing structure is employed. This structure reinforces the

Table 2 Advantages, disadvantages and applicability of commonly used completion techniques (Zhao, 2014; Ma et al. 2008; Jiang et al. 2011; Jia et al. 2015)

Well formation technology	Advantages	Disadvantages	Problem	Applicability
Mesh wrapped wire filter pipe into a well	Small diameter, high efficiency, easy to control, well wall stability during drilling	Not suitable for sandstone reservoirs with poor cement and fine grain size.	Can block pores in the filter layer, increasing water resistance and affecting the water output, the reinjection effect is not ideal.	This technology is suitable for geothermal well with better sand consolidation and coarse +particles.
Large diameter wire filter pipe filled with gravel into the well	Effectively increases the diversion area, reduces water resistance, ensures good water output, excellent sand control	Large drilling workload, high cost, deeper drilling depth, higher well completion risk.	Difficult to maintain the stability of the hole wall, high construction risk, challenging to deliver gravel material in deep wells	This technology is often used in shallow geothermal well construction.
Perforating a well	Allows reactivation of target layers that would otherwise remain non-productive.	Underground operations are difficult and costly	Complex and changeable formation environment makes it hard to obtain accurate formation parameters	More suitable for sand-producing reservoirs, fractured reservoir and waterflooding reservoir development.



(a) (b)

Fig. 3 (a) pore type thermal reservoir well structure, (b) bedrock fracture type thermal reservoir well structure (Ma et al. 2008) wellbore incrementally with depth to withstand varying formation pressures and temperatures. Upper unstable formations are sealed off with casing, and initial completion for heat injection often uses open-hole techniques. Configurations like three- or four-branch wells tailored to the complexity of drilling formations (Ma et al. 2008).

2.2 Reinjection process

(1) Pressure reinjection

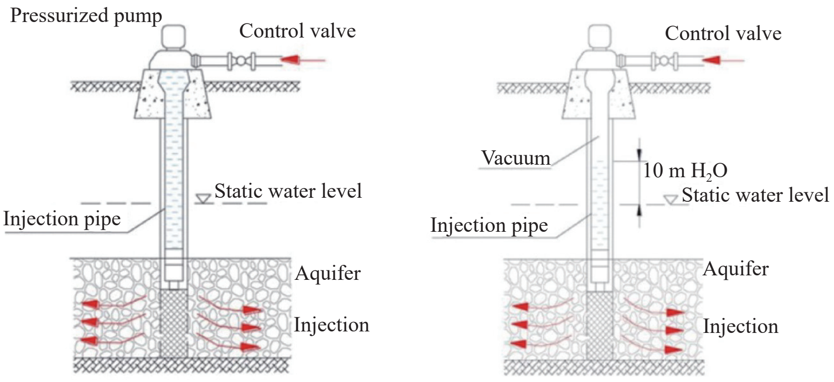
Pressure reinjection technology in geothermal energy involves using artificial pressure, often with the assistance of booster pumps, to increase the pressure of wellhead water for geothermal tailwater reinjection or to enhance the reinjection rate (Fig. 4a). This technology aims to achieve both environmental protection and sustainable geothermal energy utilization. The effectiveness of pressure reinjection depends on several key factors. Firstly, suitable geothermal reservoirs should have high permeability and porosity, allowing for the efficient entrance of reinjection fluids into the reservoir. Secondly, the reservoir temperature must be sufficiently high to enable reheating of the reinjected fluid for effective heat exchange. Additionally, the reservoir must possess adequate pressure-holding capacity to accommodate the reinjected fluid without triggering significant geological changes or seismic activity. Challenges associated with pressure reinjection include the pressure differential between the hot reservoir and the wellhead, the extent of fracture development, and occasionally, the smooth flow of hot groundwater (Xue et al. 2023). Generally, sandstone and other porous type reservoirs have a slightly stronger capacity at the beginning of reinjection, allowing for the use of natural reinjection and pressure reinjection during the initial stage, with pressure reinjection being used in the later stage (Song et al. 2020).

In recent decades, pressure reinjection technology has witnessed significant developments, with notable improvements in several areas. Modern pressure reinjection technology has made substantial advancements in injection modes, fluid management, and monitoring technology. One key advancement is the application of stratified injection technology, which allows for more effective utilization of temperature and pressure conditions at different reservoir depths. Additionally, the utilization of computer simulation has enhanced the accuracy of predicting the impact of reinjection on geothermal reservoirs, facilitating the optimization of reinjection schemes and reducing uncertainties.

Studies have shown that appropriate pressure reinjection can help minimize the negative impacts of geothermal development on surface and groundwater resources, as well as mitigate geological issues such as land subsidence. Furthermore, pressure reinjection technology has been successfully implementation in various geothermal fields globally. Notable examples include the Helcher geothermal field in Iceland, the Radlow Geothermal field in Italy, and the Geiser geothermal field in California, United States. The experiences and data gathered from these cases provide valuable insights for the advancing pressure reinjection technology in geothermal applications (Diaz et al. 2016; Kamila et al. 2021).

(2) Vacuum reinjection

Vacuum reinjection plays a crucial role in enhancing the efficiency of geothermal fluid reinjection and prolonging the lifespan of geothermal resources by reintroducing cooled geothermal fluid into the geothermal reservoir under vacuum conditions using specialized equipment (Fig. 4b) (Zhang et al. 2021a). This method effectively manages issues such as bubble plugging and microbial plugging.



(a) Pressure rejinction (b) Vacuum reinjection

Fig. 4 Reinjection process principal diagram (Song et al. 2020)

The operational principle behind vacuum reinjection is as follows: in a setup featuring a low groundwater level, raising water via the reinjection well, which is equipped with additional sealing devices, results in both the pump pipe and the water pipe filling with water. Upon shutting down the pump, closing the control and water valves, and allowing gravity to move the water, a vacuum is created between the pump water surface and the control valve. This results in a distinct water head difference of approximately 10 m between the interior and exterior of the pump. Opening the water source valve and control valve initiates a vacuum siphoning effect, allowing water to enter the pump, disrupt the existing pressure equilibrium, generate a hydraulic gradient around the well, and overcome aquifer resistance (Zhang et al. 2024b).

Advancements in vacuum pump technology and injection equipment for mid-deep geothermal systems have significantly enhanced the efficiency and stability of reinjection processes. Notably, progress in this technology has been validated through comprehensive studies encompassing computer simulations and on-site experiments investigating pressure dynamics and fluid behavior during vacuum reinjection. These analyses facilitate the development of optimized reinjection strategies. Notably, regions rich in geothermal resources, such as Iceland and the United States, have successfully integrated mid-deep geothermal vacuum reinjection practices, accumulating valuable practical insights.

Mid-deep geothermal reinjection technology is continually advancing through ongoing process research. Artificial reinjection, which includes pressure reinjection and vacuum reinjection, is a crucial technique for enhancing the utilization efficiency and environmental sustainability of geothermal resources. When choosing a specific injection method, it is important to consider its advantages, drawbacks, and suitability in conjunction with the unique circumstances. Table 3 presents a breakdown of the benefits, limitations, and applicability of typical reinjection processes.

2.3 Optimization and control technology of geothermal reinjection

(1) Tracer technology and numerical simulation technology

Optimization and control technologies are crucial for geothermal energy development, aiming to enhance reinjection efficiency and prolong the lifespan of geothermal resources. Key techniques include tracer technology, numerical simulation, and water quality optimization.

Tracer technology involves using tracers to track the flow path, velocity, and distribution of geothermal fluids within the reservoir, allowing for understanding of reservoir dynamics and reinjection effects (Wang and Lu, 2023; Kuo et al. 2018). Common tracers include dyes, radioactive isotopes, and chemical substances. The selection of suitable tracers requires consideration of their chemical stability, detection sensitivity, and environmental safety (Li et al. 2020; Liu et al. 2019b; Liu et al. 2022).

By injecting tracers into reinjection wells and monitoring their appearance time and concentration changes in production wells, valuable information on flow paths and velocities within the reservoir can be obtained. Analyzing tracer distribution and migration patterns enables the evaluation of the circulation efficiency of geothermal fluids and optimization of reinjection schemes.

Table 3 Advantages, disadvantages and applicability of common reinjection processes

Reinjection process	Applicability	Advantages	Disadvantages
Pressure reinjection	Suitable for most thermal reservoir conditions and large-scale geothermal reinjection projects	Easy to operate and can run quickly, improving efficiency; Reinjection flow rate can be precisely controlled by adjusting the pressure. Mature, reliable systems that are easy to maintain and manage; not limited by the composition of geothermal water and can be applied in different thermal reservoirs.	Requires high pressure pumps and related equipment, increasing energy consumption and safety risks; reauires stronger pipeline during reinjection. Continuous high pressure can cause formation rupture and bubble plugging.
Vacuum reinjection	Typically used in hot reservoirs with high water quality, high temperature and low permeability, or in geothermal fields requiring rapid pressure replenishment	Ensures pure water quality and prevents pollutants from entering the reinjection water. Reduces gas solubility and bubble formation, decreasing the risk of plugging geothermal reservoirs. Avoids pipe and equipment corrosion caused by oxidation during reinjection. Enhances permeability of the reinjection water, reducing injection pressure and resistance, thus improving reinjection efficiency.	Requires professional equipment and personnel leading to high cost. Establishing and maintaining a vacuum environment is time-consuming and energy-intensive, leading to lower production efficiency and higher energy consumption.

This method excels in accurately tracking geothermal fluid flow paths and acquiring detailed reservoir information, providing real-time monitoring of reinjection effects to support optimization efforts (Axelsson, 2013). However, tracer experiments entail certain costs involving tracer selection and the use of detection equipment. Careful consideration is necessary, as some tracers may have environmental impacts (Cao et al. 2020).

Numerical simulation technology involves using computer models to simulate and predict the physical and chemical processes in geothermal reservoirs in order to optimize geothermal reinjection schemes. Commonly used software includes TOUGH2, MODFLOW, and FEFLOW. Initially, a numerical model of the geothermal reservoir is established based on geological, geophysical, and hydrogeological data (Yu et al. 2023). Subsequently, model parameters are calibrated using historical data and on-site experimental results to enhance simulation accuracy. Different reinjection schemes are then simulated to evaluate their impacts on reservoir pressure, temperature, and flow rate, with the objective of selecting the optimal scheme.

An advantage of this approach is its ability to quickly predict the effects of various reinjection schemes, thus saving time and costs. Furthermore, it allows for the comprehensive consideration of multiple influencing factors, such as geological conditions and fluid properties, to provide a holistic optimization plan. However, a drawback of this method is that constructing precise numerical models requires a significant amount of data and expertise, leading to high model complexity. Therefore, the predictive results of the models may exhibit some level of uncertainty, necessitating validation and adjustment using actual data (Zhou et al. 2022).

(2) Optimize and regulate well layout and reinjection parameters

Optimizing the layout and reinjection parameters of control wells is crucial for enhancing the efficiency and sustainability of geothermal resource utilization. This process involves comprehensive surveys, experiments, tests, and numerical simulations (Zhou et al. 2022; Du et al. 2019; Tang and Qiu, 2023; Wang et al. 2021a; Fan et al. 2023). Well layout optimization involves strategically positions and determines the number of production and reinjection wells to maximize geothermal resource exploitation efficiency. By considering the geological conditions and fluid distribution within the geothermal reservoir, a rational well layout is designed to ensure fluid circulation between production and reinjection wells. The optimal spacing between production and reinjection wells is determined through numerical simulations and field experiments to prevent undue interference and resource wastage. Dynamic adjustments to the well network layout are made based on tracer tests and production data to enhance reinjection efficiency and reservoir utilization (Axelsson et al. 2015).

The advantage of a rational well layout is the maximization of geothermal resource utilization while reducing waste. Optimizing well spacing prevents excessive interference of reinjection fluid with production wells, ensuring stable production. However, the complexity of considering multiple factors in well layout design increases design intricacies. Additionally, dynamic adjustments based on actual production conditions add to management challenges.

Initially, well layout optimizations followed Diaz et al.'s concept of inner and outer field reinjection, wherein reinjection wells were empirically placed at the boundaries of the production area to balance reservoir pressure and avoid rapid impacts on production well temperatures (Diaz et al. 2016). Geothermal fields in China, mainly in Hebei, Tianjin, and Shandong, significantly improved geothermal exploitation efficiency by adopting the inner field injection mode (Kong et al. 2020; Bing, 2021; Cheng et al. 2011). With increasing production demands and varying reservoir conditions, the traditional "one extraction, one injection" geothermal well system has become insufficient. The Paris Basin geothermal field in France implemented a three-well layout model of "one extraction, two injections" combining inner and outer field reinjection (Lopez et al. 2010).

The current trend in geothermal field development involves optimizing multi-well or cluster well layouts through numerical simulations (Zhang et al. 2021b). Various well layout methods, such as "checkerboard," "track," and "concentrated injection," are considered to establish numerical models for calculating temperature field variations in the geothermal reservoir for each layout (Fig. 5). By comparing the heat extraction efficiency of each layout, the optimal well layout method is selected. This optimization approach has been successfully applied in Xianxian County and Xiong'an New Area in Hebei Province, China, among other regions (Zhao et al. 2017; Liu et al. 2020; Liu et al. 2019a; Wang et al. 2022).

Parameter optimization refers to improving reinjection efficiency and geothermal energy utilization by adjusting key parameters of the reinjection

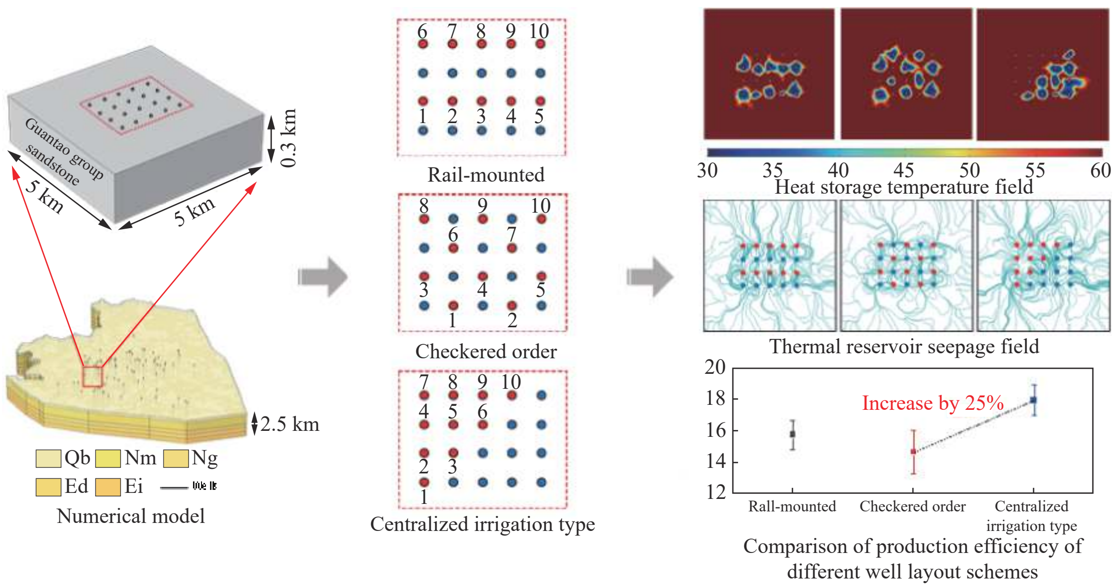


Fig. 5 Optimized well distribution mode of deep geothermal centralized production and reinjection (Liu et al. 2020)

system, such as reinjection flow rate, reinjection pressure, reinjection temperature, chemical composition of reinjection fluid, etc. This process involves determining the optimal reinjection flow rate based on reservoir characteristics and production requirements. By monitoring and adjusting reinjection pressure, reservoir pressure can be maintained at an optimal level to prevent it from being too high or too low, thereby maintaining reservoir stability. Additionally, optimizing the temperature and chemical composition of the injected fluid based on the temperature and lithology distribution of the geothermal reservoir helps reduce chemical damage to the reservoir rock and improves heat exchange efficiency.

The advantage of parameter optimization is that it can improve reinjection efficiency and reduce costs. Reinjection parameters can be flexibly adjusted according to actual production conditions, ensuring stable production. However, the disadvantage is that parameter optimization requires real-time monitoring and data analysis, which demands high technical support. The optimization and control of multiple parameters also increase the complexity of the system, requiring professional management and operation. (Liu et al. 2022) successfully simulated the relationship between different reinjection flow rates and thermal reservoir temperature field evolution under well reinjection in the Xian County geothermal field in China (Fig. 6). Successful cases in geothermal fields, such as the Haelsche geothermal field in Iceland, the Geysers geothermal field in California, USA, and the Xian County geothermal field in China indicate that scientific parameter optimization and technical application can significantly enhance the sustainability and economic efficiency of geothermal energy development (Zhou et al. 2022; Bett and Yasuhiro, 2023; Cheng et al. 2023; Li et al. 2023).

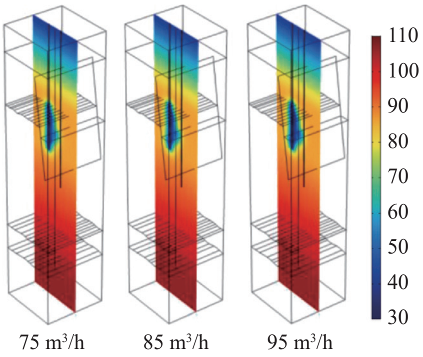


Fig. 6 Influence of reinjection flow optimization on temperature field change of reservoir (Liu et al. 2022)

Currently, the vast majority of geothermal fields use water as the working fluid for geothermal reinjection systems. Optimizing the physical and chemical properties of the reinjection fluid can extend the service life of geothermal wells and reduce energy loss, thereby achieving sustainable utilization of geothermal resources. Firstly, suspended solids, organic matter, and dissolved substances in the reinjection water are removed using techniques such as filtration, precipitation, and chemical treatment to avoid clogging in the wellbore or thermal reservoir (Xia et al. 2023). Secondly, the water quality of the reinjection water is regularly tested and monitored to ensure it meets reinjection standards and avoids contaminating the groundwater. The physical properties of the reinjection water can change under high-temperature conditions, such as changes in density and viscosity. The density of the reinjection fluid decreases with increasing temperature; therefore, adjusting the temperature of the reinjection fluid to increase its density can enhance natural reinjection effects and reduce pumping energy consumption. The change in viscosity is used to control the seepage velocity of the reinjection water in the thermal reservoir, thereby affecting the heat transfer process in the thermal reservoir to achieve the goal of extending the service life of the geothermal reinjection system (Shi et al. 2023; Chitgar et al. 2023).

3 Engineering problems and technical challenges of mid-deep geothermal reinjection technology

Mid-deep geothermal reinjection technology offers distinctive benefits in energy utilization and environmental protection. Nevertheless, it encounters numerous issues and hurdles in geothermal reinjection engineering. One persistent challenge is the inadequate reinjection rate of sandstone and low-permeability geothermal reservoir, alongside unresolved thermal breakthrough concerns in geothermal reinjection projects. Furthermore, the deep geothermal reservoir becomes increasingly intricate as geothermal exploration and exploitation reach greater depths. This complexity is characterized by high temperature, high-pressure, high - stress, chemical corrosion, uneven formation, and complex fault fracture. Consequently, these new characteristics pose significant challenges to geothermal reinjection engineering and technology. The engineering issues and challenges arising can be categorized into four key aspects.

3.1 Equipment selection and durability

The selection of equipment and its durability are critical for the long-term success of mid-deep geothermal reinjection technology, particularly during drilling, completion, and logging stages. In the drilling phase, it is essential to choose equipment that can withstand high-temperature and high-pressure conditions to ensure stable operation in deep underground environments. Additionally, the effects of thermal expansion and contraction must be considered to prevent equipment damage, which could affect drilling efficiency and safety. For instance, in high-temperature and high-pressure geothermal reservoirs, drilling guidance technology faces technical challenges related to material tolerance, sealing performance, thermal expansion and contraction effects, and the performance of electronic devices and data transmission at elevated temperatures. These factors can lead to equipment damage, failure, and disruptions in the drilling process.

In the completion process, selecting and designing equipment materials becomes crucial because the equipment will be exposed to high-temperature and high-pressure underground environments for extended period. It is essential to choose materials that are resistant to corrosion and aging, and to implement effective sealing designs. This ensures the long-term stability and efficiency of the geothermal reinjection system. Failure to do so can lead to equipment damage and accelerated wear, which in turn can impact the stability and performance of the system.

In high-temperature and high-pressure environments, logging technologies such as density, ultrasonic imaging, and acoustic logging encounter challenges such as poor stability, lack of durability, and high costs. These technologies may become unstable due to materials unable to withstand extreme conditions, resulting in equipment damage and inaccurate data. Consequently, the accuracy and efficiency of the logging process are compromised. Addressing the effects of thermal expansion and contraction in high-temperature environments is crucial to prevent equipment failure and data transmission interruptions, which exacerbate the challenges in the logging process.

In summary, the specific application stages of drilling, completion, and logging play critical roles in mid-deep geothermal reinjection technology. However, insufficient consideration and resolution of equipment selection and durability issues hinder the development of geothermal reinjection technology and impede the stable, efficient, and environmentally friendly operation of the system.

3.2 System stability and operation safety

The stability and operational safety of geothermal reinjection systems are crucial for the energy utilization efficiency and environmental protection of geothermal systems. The chemical characteristics and geological conditions of mid-deep geothermal water are highly complex, leading to potential fluctuations or risks during system operation. For example, corrosive substances in groundwater can damage pipes or equipment, increasing the system failure rate. Changes in geological structures can also cause system instability, particularly in earthquake-prone areas, where geothermal reinjection systems face safety risks during geological disasters.

Existing drilling technology can cause issues such as fracturing the borehole wall and expanding the borehole during geothermal drilling, with falling rocks easily causing stuck drilling. Once the geothermal reinjection well is operational, the surrounding rock of the borehole can undergo rheological deformation, leading to phenomena such as squeezing and crushing the casing. Severe wear on the outer diameter of the drill bit can produce a small borehole, which can also cause stuck drilling. Geothermal extraction and reinjection often require a well-developed underground fracture system, but complex strata with developed fractures can lead to serious well leakage problems. For instance, in the ZK201 well in Yangbajing, Tibet, continuous drilling fluid leakage occurred from a depth of several dozen meters to the bottom of the well due to highly developed fractures and numerous faults in the strata (Xi et al. 2011).

The occurrence and handling of these problems often significantly increase the cost of reinjection, hindering the development process of geothermal reinjection. According to a report by the U.S. Department of Energy, the time and materials cost for plugging leaks due to well leakage accounts for about 15% of the total well cost (Finger and Blankenship, 2012; Song et al. 2023).

3.3 Environmental impact and sustainable development

The application of mid-deep geothermal reinjection technology can significantly impact on the surrounding environment, including groundwater resources, geological structure, and surface environment, necessitating in-depth analysis and comprehensive assessment. Many challenges hinder this process:

(1) Insufficient data and poor accuracy. The geological, hydrological, and environmental data for mid-deep geothermal reinjection are often insufficient, especially in remote areas or undeveloped geothermal areas. This data deficiency compromises the comprehensiveness and accuracy of environmental impact assessments. The complexity of the underground environment may introduce errors in the collected data. For example, the flow direction and velocity of groundwater and the detailed characteristics of geological structures are difficult to measure accurately, which can affect the assessment results.

(2) Complex geological conditions. The heterogeneity and unevenness of geological layers complicate assessments. Geological conditions vary greatly across regions, making standardized assessment methods challenging to apply and necessitating personalized analysis based on specific situations. During geothermal reinjection, geological structures may change, such as through compression, expansion, or fracturing of rock layers. These changes are difficult to predict and control, and current methods for continuous monitoring and dynamic adjustment of assessments are still imperfect.

(3) Diversity and long-term nature of environmental impacts. The environmental impacts of geothermal reinjection are multidimensional, affecting groundwater resources, geological structures, and surface environment. These impacts are intertwined and difficult to assess individually, requiring a comprehensive consideration of various factors. Additionally, the impacts are long-term and latent, and short-term assessments cannot fully capture their extent. Long-term monitoring and tracking are essential for accurately evaluating their effects over time.

(4) Reinjection blockage. This is the primary reason for the low reinjection rate in mid-deep geothermal reinjection and a significant barrier to their sustainable development. Various reasons contribute to reinjection blockage, as detailed in Table 4 (Cao et al. 2021; Li et al. 2021). While technology to address reinjection blockage is continually advancing, most studies focus on techniques targeting blockage caused by single factors. Research on blockage resulting from the combined action of multiple factors remains insufficient, particularly for blockage caused by the porosity-

Table 4 Statistics of causes of plugging of geothermal reinjection (Cao et al. 2021)

Clogging cause	Percentage /%
Suspended matter	50
microorganisms	15
chemical precipitation	10
Bubble plugging	10
Clay expansion	5
Particle recombination	5
Other	5

geostatic type thermal storage reinjection process. Sandstone thermal storage reinjection blockage continues to be a global challenge.

Long-term geothermal reinjection may alter the temperature and pressure fields of the geothermal reservoir, leading to heat loss and formation fracturing. As the reinjected water flows underground, it continuously absorbs heat from the thermal reservoir rock (Cao et al. 2021). This process results in a decrease in the geothermal reservoir temperature, reducing the thermal energy utilization efficiency of geothermal resources (Liu et al. 2020, Liu et al. 2019a). The injection of reinjected water causes an increase in pressure and a decrease in temperature around the reinjection well. The increase in pressure can lead to formation compaction or expansion, while temperature changes may cause thermal expansion or contraction of the rock layers. These factors may have various environmental impacts, potentially hindering the sustainable development of geothermal reinjection.

3.4 Monitoring techniques and forecasting methods

Reinjection has become an essential part of geothermal resource development and utilization. The dynamic monitoring and prediction technology of temperature and chemical fields in concentrated reinjection areas is a key technology in geothermal development and utilization. However, current monitoring technologies and equipment face technical bottlenecks in deep geothermal reinjection environments. These include insufficient pressure and temperature resistance of monitoring equipment, which limits the reliability and continuity of monitoring data. Models used to simulate and predict the impact of geothermal reinjection environments also have certain limitations. They need to be calibrated and validated based on extensive measured data, and their accuracy and reliability need to be improved in complex underground environments. Accurately depicting the complex fracture network inside the thermal reservoir is challenging, and the lack of continuous monitoring data for reinjection parameters hinders model correction. This results in a significant gap between the optimization results of numerical models and actual engineering conditions. The optimization process must consider various working conditions, increasing the workload and time required. If the actual geothermal reservoir structure is further aligned, it will also lead to a decrease in computational efficiency.

4 Future development direction of mid-deep geothermal reinjection technology

To promote the efficient, safe, and sustainable utilization of geothermal resources, the development of mid-deep geothermal reinjection technology will rely on the cross-integration and collaborative innovation of multiple disciplines. This technology will gradually evolve towards high temperature and high-pressure resistance, intelligent automation, and economic feasibility through upgrades, material innovation, and system optimization. Key areas for further research and potential paths for technological innovation are as follows:

4.1 High-temperature and high-pressure resistant materials and equipment

Future research should emphasize technical innovation and equipment research and development of high-temperature and high-pressure geothermal reinjection technology. This involves enhancing drilling technology to boost drilling efficiency and safety, advancing drilling guides, drilling fluids, and drilling robots capable of withstanding high temperatures and pressures. Additionally, enhancing well completion technology and creating novel materials resistant to high temperatures and corrosion are essential for ensuring the long-term stable operation of geothermal wells. Furthermore, the advancement of logging technology and equipment is also crucial, with a focus on developing 260–300°C high-temperature logging electronic components to accurately evaluate and monitor mid-deep geothermal resources. Future research should encourage collaborative efforts across disciplines such as geology, engineering, and materials science to address challenges in developing geothermal reinjection technology for high-temperature and high-pressure environments. By fostering collaboration among experts and researchers from diverse fields, technological innovation and equipment development can be accelerated, leading to reductions in the costs of high-temperature and high-pressure materials and technical equipment. Ultimately, verifying and applying these advancements in actual geological environments will confirm the feasibility and efficacy of the technology, laying the groundwork for its commercialization and widespread application.

4.2 Geothermal economic reinjection

To address the current challenges in reinjecting tailwater from mid-deep geothermal layers, we need to study technical measures to tackle scaling, corrosion, reduction in reservoir temperature, and premature thermal breakthrough in fractured bedrock reservoirs. These studies will lead to the formation of technical regulations. Additionally, addressing clogging in sandstone pore reservoirs during the reinjection process requires in-depth research and development of multi-level reinjection technologies. This includes developing and applying new materials, such as smart responsive materials and nanomaterials, to enhance anti-clogging effects and adaptability, resulting in corresponding technical regulations. Based on this work, we will establish reinjection research and demonstration bases for different types of geothermal reservoirs and formulate reinjection plans for mid-deep geothermal tailwater, promoting the green and sustainable development of geothermal resources.

4.3 Intelligence and automation

The development of advanced sensors and real-time monitoring technology enables the accurate monitoring of temperature, pressure, flow, and other parameters of geothermal Wells. By integrating Internet of Things (IoT) technology and Artificial Intelligence (AI), the utilization of big data analysis and prediction facilitates the optimization of the reinjection process, automatic adjustment of operating parameters, as well as intelligent monitoring and management of geothermal reinjection systems. This integration ultimately enhances efficiency and safety. Deploying a range of physical, chemical, biological, and intelligent tracers in combination with highly sensitive detection technologies allows for precise tracking of the flow path and mixing behavior of geothermal fluids in the reservoir. Through research and application of unattended and remote-control technology, labor costs and field operation risks are reduced, thereby enhancing the reliability of system operation. The future of geothermal reinjection systems will entail greater automation with minimal human intervention. Automatic injection equipment and systems will have the capability to automatically adjust reinjection parameters based on real-time data, thereby ensuring optimal reinjection effect.

4.4 Efficient numerical simulation technology

More accurate simulation of reservoir geological structure and fluid dynamics can be achieved using higher resolution numerical models and finer meshing. Combining advanced computational methods, such as parallel computing and machine learning algorithms, can enhance simulation speed and accuracy. Comprehensive consideration of the coupling effects among different physical fields, including heat, fluid mechanics, and chemical reactions, can offer a more detailed prediction and optimization scheme for reservoir behavior. Extensive analysis of tracer data and numerical simulation results can provide a thorough evaluation of reservoir behavior and reinjection effectiveness, enhancing the precision of reinjection system design and operation.

4.5 Environmentally friendly and sustainable development

Research and application of environmentally friendly reinjection fluid can reduce the impact on groundwater resources and ecological environment. Developing new fluid handling technologies can ensure water quality and environmental compatibility of reinjected fluids. Research on the complementary utilization of geothermal energy and other renewable energy sources (such as solar energy, wind energy, biomass energy, etc.) can lead to the design of a comprehensive energy system that improves energy utilization efficiency and system stability. Combined with the characteristics of geothermal energy, researching and applying energy storage technology (such as heat storage, cold storage, battery energy storage, etc.) can achieve efficient energy storage and scheduling. Through multi-energy complementarity and comprehensive utilization, combined with geothermal power generation, heating, agricultural and industrial applications, comprehensive utilization of geothermal resources can be achieved, optimizing the development and management of geothermal resources and promoting sustainable development.

In the future, deep geothermal reinjection technology is expected to play a greater role in improving the efficiency of geothermal resource utilization, extending the lifespan of geothermal wells, and reducing environmental impacts. It is hoped that through continuous research and technological innovation, existing technical bottlenecks can be overcome, achieving efficient and sustainable utilization of geothermal resources, and contributing to the global energy transition and low-carbon development.

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