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Research Progress and Prospects of Closed-Loop Heat Extraction Technology for Hot Dry Rock

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Abstract: *Hot dry rock (HDR) represents a key clean energy resource essential for achieving the "dual carbon" goals. Conventional Enhanced Geothermal Systems (EGS) face challenges including induced seismicity and fluid loss, positioning closed-loop heat extraction technology as a vital alternative. This paper systematically reviews the research progress and engineering practices of three closed-loop heat extraction technologies: coaxial borehole heat exchangers, U-shaped wells, and super-long gravity heat pipes. The latest achievements in numerical simulation, field testing, and engineering application are critically assessed, and the distinctive characteristics of different configurations in terms of heat extraction performance and operational modes are summarized. Future development directions, including configuration diversification, working fluid multiplicity, and intelligent operation and control, are also discussed. This review aims to provide a reference for the green and efficient development of hot dry rock resources.*
Keywords: *hot dry rock; closed-loop heat extraction; coaxial borehole heat exchanger; U-shaped well; super-long gravity heat pipe*

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I. Introduction

The global energy system is accelerating its low-carbon transition, and geothermal energy—clean, stable, and abundant—is regarded as a strategic resource for achieving the "dual carbon" goals. As the principal carrier of deep geothermal energy, hot dry rock (HDR) holds remarkable potential. Lin (Lin et al., 2013) estimated, using the volumetric method based on heat flow and geothermal gradient data, that total HDR resources at 3.0–10.0 km depth in mainland China amount to 2.52×10^{25} J, equivalent to 8.6×10^{6} billion tons of standard coal—about 2.6×10^{5} times China's 2010 energy consumption. Even at a conservative 2% recoverability, the recoverable portion is 168 times conventional hydrothermal resources and 4,400 times the 2010 national consumption. These figures confirm China's exceptional HDR endowment and its vast potential as a future strategic energy alternative. However, HDR reservoirs are marked by extreme "high temperature, high hardness, high in-situ stress, and low permeability" conditions, and conventional EGS face bottlenecks such as induced seismicity, fluid loss, and limited economic viability. Recently, closed-loop heat extraction—"extracting heat without extracting water"—has emerged as a promising alternative, though wellbore–formation heat transfer mechanisms and key parameter optimization require further study. Wang (Wang et al., 2012) recommended near-term focus on HDR resources at 4–7 km depth with target temperatures of 150–250°C, pointing to southern Tibet, western Yunnan, the southeastern coast, North China, and the Songliao Basin as favorable targets. Focusing on the safe, efficient operation of closed-loop systems, this paper systematically reviews three representative technologies—coaxial borehole heat exchangers, U-shaped wells, and super-long gravity heat pipes—to provide a theoretical reference for the green and economical development of HDR resources.

II. Current Status of Hot Dry Rock Resource Development and Utilization

Hot dry rock (HDR) refers to dense, high-temperature rock formations buried at depths of several kilometers with temperatures exceeding 180°C (National Energy Administration, 2018). The global HDR resource potential far exceeds that of total conventional fossil fuels (MIT, 2006). As a clean, stable, and carbon-free energy source, its development and utilization are of great significance for energy security and structural transformation (Li et al., 2026). The total HDR resources in mainland China at depths of 3–10 km are estimated to be approximately 2.52×10^{25} J, equivalent to 856 trillion tons of standard coal, with recoverable resources amounting to roughly 3,200 times the national energy consumption in 2021 (Lin et al., 2012, 2021). As shown in Fig. 1, recent exploration breakthroughs have been remarkable. Wells such as GR1 in the Gonghe Basin of Qinghai (3,705 m, 236°C), M-1 in Matouying of eastern Hebei (4,000 m, 151.25°C), and Huadong 1R in northern Hainan (4,387 m, >185°C) have laid the foundation for experimental development (Lin et al., 2021).

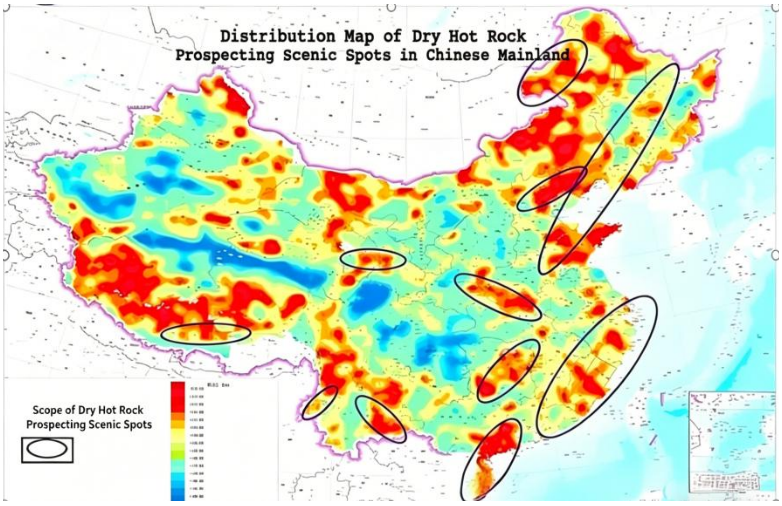

Fig. 1 Global status of geothermal energy development

At present, hot dry rock development relies primarily on Enhanced Geothermal Systems (EGS), which use hydraulic fracturing to create artificial reservoirs for heat extraction and power generation (Xu et al., 2024). Over 60 global demonstration projects exist (Wang et al., 2025). The U.S. Fenton Hill project first verified feasibility, France's Soultz achieved 1.5 MW and Australia's Habanero reported 91% recovery. Major investments continue: the U.S. FORGE program (>$200 million) has completed highly deviated horizontal wells and multi-stage fracturing, while the EU Horizon 2020 funded 11 projects (€134 million). Drilling efficiency has improved, with Cape Station single-well cycles reduced to 20–35 days and costs to $4.8 million (Li et al., 2026).

China's Gonghe Basin project has completed five wells exceeding 4,000 m, tripling drilling speed, and achieved first grid-connected experimental power in 2021 (Zhang et al., 2022; Wang et al., 2025). However, EGS commercialization remains constrained by uncontrollable fractures, high drilling costs (granite penetration <1.2 m/h in China vs. 21 m/h abroad), induced seismicity, and environmental risks (Xu et al., 2024; Li et al., 2026; Guo et al., 2020).

Overall, while China's HDR theoretical research is internationally competitive, practical aspects such as reservoir construction, drilling equipment, and long-term circulation testing lag behind. Consequently, closed-loop heat extraction—requiring no reservoir stimulation and minimal environmental disturbance—has emerged as a key complementary pathway for green HDR development.

III. Current Status of Closed-Loop Heat Extraction Technology for Hot Dry Rock

Enhanced Geothermal Systems (EGS) currently represent one of the mainstream technologies for hot dry rock development. However, EGS relies on hydraulic fracturing to create artificial reservoirs and thus faces inherent bottlenecks such as fluid loss, induced seismicity, and rapid thermal decline (Xu et al., 2024). In this context, Closed-Loop Geothermal Systems (CLGS), which adhere to the principle of "extracting heat without extracting water," have emerged as an important alternative approach due to their elimination of the need for reservoir stimulation and their minimal environmental disturbance. In a closed-loop system, heat is extracted from the surrounding rock via heat conduction through a sealed wellbore heat exchanger, and the circulating working fluid undergoes no mass exchange with the formation, thereby fundamentally avoiding the core risks associated with EGS. The current CLGS technology spectrum primarily comprises three major categories: coaxial closed-loop geothermal systems (CCLGS), U-shaped closed-loop geothermal systems (UCLGS), and super-long gravity heat pipes (SLGHP). Their configurations are also progressively evolving from single-well designs toward multi-branch architectures and from simple to more complex geometries.

3.1 Coaxial Closed-Loop Geothermal System (CCLGS)

A coaxial closed-loop geothermal well comprises surrounding rock and soil, cement, a coaxial borehole heat exchanger, and a circulating working fluid. The fluid flows down the annulus between inner and outer pipes, absorbs formation heat through the outer wall, and is pumped back via the insulated inner pipe. This simple, single-well design is the most widely deployed CLGS technology. Wang (Wang et al., 2025) developed a 3D model incorporating geothermal gradient, geological stratification, and groundwater seepage, showing that at 2000 m depth with seepage velocity > 1×10^{-5} m/s, the heat transfer mechanism shifts from conduction to convection, raising local annular heat transfer by 56.7%. Liu (Liu et al., 2023) examined heat extraction loss and the role of inner pipe insulation in performance and equipment selection. Liu (Liu et al., 2025) applied orthogonal experiments for multi-factor sensitivity analysis, identifying key parameters governing heat transfer efficiency. Field measurements by the Hebei Academy of Sciences (2024) report a heat extraction rate of 118 W/m, indicating high output and low operating costs. The technology is now deployed at scale in China, for instance, Li (Li et al., 2023)modeled a coaxial heat exchanger for the Fengheyuan project in Xi'an, simulating flow and temperature fields to support engineering application.

3.2 U-Shaped Closed-Loop Geothermal System (UCLGS)

The U-shaped closed-loop system connects two or more vertical wells via a horizontal or multi-branch section, forming a U-shaped circulation channel that substantially increases heat exchange area and thermal output. Field tests by Hebei University of Engineering demonstrate that large-diameter, long-horizontal-reach U-shaped wells achieve high heat extraction and stable operation, overcoming the limited output and rapid thermal decline of single-well coaxial systems.

In numerical simulation, Chen (Chen et al., 2026) used a three-dimensional THM coupled finite element model to evaluate spiral wellbores for HDR heat extraction, finding that spiral configurations increase production temperature by 12.67%, heat extraction per meter by 23.73%, and power generation by 27.07% compared with cylindrical wellbores. Li (Li et al., 2024) proposed a clustered multi-branch U-shaped well method and developed a field-scale reservoir–wellbore coupled model for the Gonghe Basin, revealing that high injection rates cause rapid thermal breakthrough and steep decline in early-stage heat extraction.

Regarding working fluids, Sun (Sun et al., 2025) modeled a supercritical power generation system for U-shaped HDR wells and assessed seven refrigerants, systematically examining the effects of flow rate, vertical depth, horizontal length, geothermal gradient, and rock thermal conductivity on system performance. Xu (Xu et al., 2023) conducted a sensitivity analysis of U-shaped well heat extraction parameters using orthogonal experiments and variance analysis, refining the theory of efficient HDR heat extraction. A schematic of the U-shaped closed-loop system is shown in Figure 2.

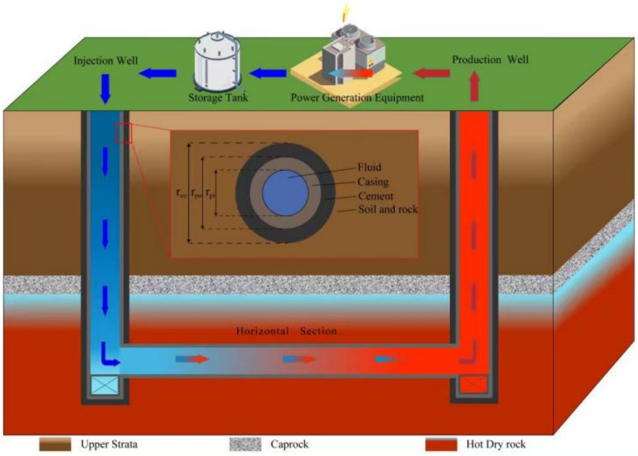

Fig. 2 Development of hot dry rock using U-shaped wells

3.3 Super-Long Gravity Heat Pipe Technology (SLGHP)

Super-long gravity heat pipe technology utilizes the boiling–condensation phase-change cycle of the working fluid within the pipe to achieve long-distance, self-driven heat transfer from the bottom of the well to the surface without the need for external pumping. It represents an innovative direction in closed-loop heat extraction technology. In October 2025, the journal Energy reported field test results combining a modular thermoelectric generator (TEG) with a gravity heat pipe exceeding 3,000 m in length. At the Gonghe Basin geothermal field in China, the TEG achieved a peak power output of 1,253.2 W under a temperature difference of 80.0°C, with a thermoelectric conversion efficiency of 2.2% (equivalent to 90% of the theoretical maximum), thereby validating the feasibility of direct thermoelectric power generation from hot dry rock (Long et al., 2025). To address the limitation imposed by the thermal conductivity of the surrounding rock in a single well, Li (Li et al., 2025) proposed an enhanced heat transfer scheme employing forced convection induced by a downhole pump. Numerical simulations indicated that the optimal reservoir thickness is approximately 1,000 m, the optimal pump power is about 81 kW, and the best performance is achieved when the pump is positioned at the midpoint of the reservoir. In terms of standardization, the Geological Society of China issued the group standard T/GSC 012–2025, Technical Specification for Geothermal Energy Development Using Super-Long Gravity Heat Pipes, in December 2025, signifying that the technology has entered a phase of standardized development (Geological Society of China, 2025).

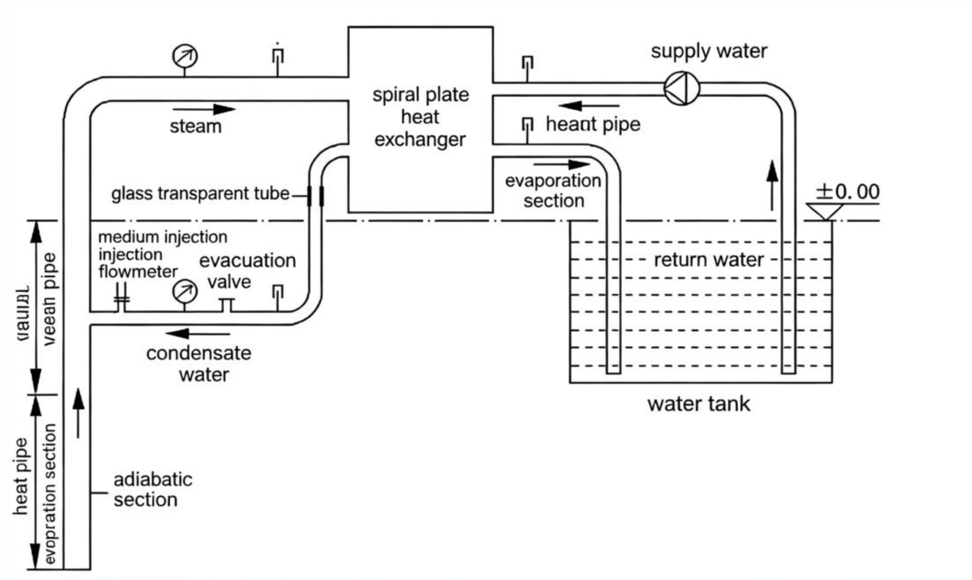

Fig. 3 Heat extraction process of the super-long gravity heat pipe

IV. Future Development Prospects

Closed-loop heat extraction technology, with its advantages of no hydraulic fracturing, no fluid loss, and low environmental risk, is transitioning from an EGS supplement to a mainstream approach for hot dry rock development. Future progress will follow three main directions: diversified configurations, multiple working fluid options, and intelligent operation. System configurations will center on U-shaped wells, coaxial heat exchangers, multi-branch horizontal wells, and spiral wellbores, with optimized wellbore structures extending system life beyond 50 years (Chen et al., 2024). Working fluids will diversify beyond water-based options. Supercritical CO_2 is promising due to its low viscosity, high expansivity, and carbon sequestration co-benefits (Chen et al., 2025). Ammonia–water and organic mixtures can enhance low-temperature heat transfer, and low-boiling-point media such as ammonia or pentane enable phase-change self-circulation in gravity heat pipes. Fluid selection will be tailored to reservoir temperature, well architecture, and energy demand. In operations, the integration of big data, artificial intelligence, and digital twins will enable subsurface-to-cloud collaborative optimization, allowing real-time prediction and mitigation of thermal decline. In the long term, closed-loop heat extraction has the potential to become China's third energy pillar alongside solar and wind power, contributing substantially to energy security and carbon neutrality.

V. Conclusion

(1) Hot dry rock is a strategic resource for China's energy transition. Conventional Enhanced Geothermal Systems (EGS) face inherent risks such as induced seismicity and fluid loss. Closed-loop heat extraction, based on "extracting heat without extracting water," avoids these issues and offers a viable alternative for green development, positioning it as a mainstream direction.
(2) Three closed-loop technologies—coaxial, U-shaped, and super-long gravity heat pipes—now form a complementary matrix. Coaxial systems are mature and widely used for heating. U-shaped wells increase heat output via horizontal sections. Gravity heat pipes enable pumpless, self-driven heat extraction. This technology suite has moved from concept validation to practical engineering.
(3) Future development will focus on diversified well configurations, optimized working fluids (e.g., supercritical CO_2), and intelligent, AI-driven operation. Combined with standards, domestic manufacturing, and policy support, closed-loop extraction has the potential to become China's third major energy pillar after solar and wind power, contributing significantly to energy security and carbon neutrality.

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