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Design and Heat-Transfer Performance of a Hybrid Insulated Inner-Pipe String for Deep Geothermal Coaxial Heat Exchangers

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Abstract

Deep geothermal coaxial heat exchangers are constrained by the lack of thermally insulated inner pipes suitable for high-temperature deep-well operation, the excessive weight of conventional steel pipe strings, and the limited temperature resistance of polymer pipes. To address these challenges, this study proposes a hybrid insulated inner-pipe string consisting of an upper steel section and a lower aluminum-alloy section. A transient coupled seepage-heat-transfer model of the deep coaxial heat exchanger and surrounding formation was developed using COMSOL Multiphysics to quantify the effects of key parameters, including inner-pipe thermal conductivity and insulation length, on heat extraction performance. Based on a comparative evaluation of candidate materials, 7075-T6511 aluminum alloy was selected for the lightweight inner-pipe section, and a composite insulation structure combining a vacuum layer with silica aerogel felt was developed together with a spiral-fin structure for enhanced heat transfer. Laboratory tests showed that the mass per unit length of the aluminum-alloy insulated inner pipe was only 36.9% of that of a steel pipe with the same dimensions, while its thermal conductivity was as low as 0.008 W/(m·K) and its yield strength remained 381 MPa at 150 °C. A field-scale test conducted in a 4050-m-deep geothermal well demonstrated that the hybrid inner-pipe string, comprising a steel section from 0 to 3685 m and an aluminum-alloy section from 3685 to 4001 m, reduced the total string weight by 5.7% relative to an all-steel configuration. The system achieved a heating coefficient of performance (COP) of 6.80 and a heat extraction rate per unit well depth of 352 W/m, corresponding to an estimated annual saving of 770.73 t of standard coal equivalent. These results demonstrate that the proposed hybrid insulated inner-pipe string provides a viable system-level solution for deep geothermal coaxial heat extraction.

by integrating lightweight design, thermal insulation, high-temperature mechanical reliability, and heat-transfer performance.

Keywords: deep geothermal energy, coaxial heat exchanger, hybrid insulated inner-pipe string, thermally insulated inner pipe, numerical simulation, enhanced heat transfer

1 Introduction

Geothermal energy is characterized by abundant reserves, broad geographical availability, stable operation, and relatively low sensitivity to climatic conditions[1,2], making it an important option for low-carbon energy supply and the large-scale utilization of renewable energy[3]. As geothermal development extends to greater depths, deep geothermal resources are attracting increasing attention because of their higher reservoir temperatures and greater recoverable thermal potential, particularly for building heating and district energy systems[4-6]. Compared with conventional geothermal systems that rely on groundwater extraction, closed-loop downhole heat extraction enables thermal energy to be recovered without directly producing formation water[7], thereby reducing problems associated with reinjection, scaling, and disturbance of the subsurface water environment[8]. Owing to their relatively simple wellbore configuration, strong adaptability to existing wells, and stable operating performance[9], coaxial heat exchangers have become an important technical route for deep geothermal development based on the concept of “heat extraction without groundwater production”[10].

During coaxial heat extraction, the low-temperature circulating fluid flows downward through the annulus between the inner and outer pipes while continuously absorbing heat from the surrounding formation, and subsequently returns to the surface through the central inner pipe[11,12]. Because a substantial temperature difference persists between the upward-flowing hot fluid and the downward-flowing cold fluid[13], radial heat transfer across the inner pipe can cause pronounced thermal short-circuiting within the wellbore[14]. Consequently, the thermal insulation performance of the inner pipe directly affects the outlet temperature and the effective heat extraction capacity of the system[15]. Previous field and numerical studies have shown that reducing the thermal conductivity of the inner pipe can effectively suppress parasitic heat transfer between the hot and cold flow streams and improve overall heat extraction performance[16]. Other operating and structural parameters, including inner-pipe diameter, insulation length, circulation rate, and inlet temperature, also influence the thermal behavior of coaxial heat exchangers[17]. Field investigations by Kohl et al. demonstrated the significant effect of inner-pipe heat loss on coaxial heat-exchanger performance, while Beier et al. developed analytical heat-transfer models for predicting wellbore and formation temperature responses[18,19]. Subsequent numerical studies further examined the effects of inner-pipe thermal conductivity, pipe diameter, and insulated-section length on outlet temperature and heat extraction power[20]. These studies consistently indicate that reducing the thermal conductivity

of the inner pipe generally improves heat extraction capacity, while strong coupling exists between thermal insulation parameters and operating conditions in deep-well applications[21,22].

Current approaches for reducing wellbore heat loss mainly focus on low-thermal-conductivity materials and composite insulation structures[23]. Polymer pipes such as PE-RT II offer the advantages of low density, low thermal conductivity, and convenient installation, and multilayer composite configurations and aerogel-based insulation schemes have been progressively developed[24]. However, their limited long-term temperature resistance restricts their application in high-temperature deep geothermal wells. An alternative approach employs double-wall steel pipes with an evacuated annular space to form vacuum-insulated structures. Such designs provide superior mechanical strength and high-temperature resistance and have already been applied in geothermal and oil and gas wells. Additional measures, including aerogel wrapping, low-emissivity coatings, getters, and surface treatments, have also been introduced to improve the long-term thermal insulation performance of steel pipes. In parallel, convective heat transfer can be enhanced by introducing helical blades, fins, or other flow-disturbance structures into the heat-transfer passage. However, such enhancement is generally accompanied by additional hydraulic resistance, making it necessary to balance thermal gains against increased flow losses.

Despite substantial advances in heat-transfer modeling, insulation materials, and structural design for coaxial heat exchangers, an important engineering trade-off remains unresolved in deep geothermal wells[25]. Polymer inner pipes can simultaneously achieve low mass and low thermal conductivity, but their long-term temperature resistance is limited[26]. Steel vacuum-insulated pipes, by contrast, provide reliable thermal insulation and load-bearing capacity but impose a substantial weight penalty[27]. As well depth increases to several kilometers, the accumulated self-weight of an all-steel insulated inner-pipe string places increasingly stringent demands on wellhead load capacity, pipe connections, and deployment operations. For the $\Phi 114 \times 80$ mm P110 steel insulated pipe considered in this study, the mass per unit length reaches 29.78 kg/m, whereas the long-term operating temperature of PE-RT II pipe under its design-life conditions is only approximately 95 °C. Therefore, simply pursuing a lower thermal conductivity or replacing one material with another cannot simultaneously satisfy the combined requirements of thermal insulation, high-temperature mechanical performance, and lightweight design in deep geothermal wells.

The design of inner pipes for deep coaxial heat exchangers therefore needs to move beyond the conventional optimization of individual pipe properties toward functional configuration of the entire pipe string along the well depth[27]. Because different depth intervals do not necessarily perform identical thermal and structural functions, high thermal insulation performance and low structural weight do not need to be achieved using a single material throughout the entire well[28]. Based on this concept, this study proposes a segmented hybrid insulated inner-pipe string that combines steel and lightweight aluminum-alloy insulated inner pipes along the well depth. This configuration enables the different materials to exploit their respective advantages in thermal insulation, load-

bearing capacity, and weight reduction, thereby reconciling heat-transfer performance and structural loading at the pipe-string scale. Unlike conventional approaches that mainly optimize the thermal conductivity of a single material, the structure of an individual pipe, or local heat-transfer enhancement parameters, the proposed concept integrates material selection, insulation design, axial pipe-string segmentation, and heat-transfer performance within a unified engineering framework[29].

To implement this concept, a transient coupled heat-transfer model incorporating the coaxial heat exchanger, cement sheath, and surrounding formation was established under representative deep geothermal geological conditions and validated against field heat-extraction data. The model was then used to evaluate the effects of circulation conditions, inner-pipe thermal conductivity, pipe diameter, and insulation length on system heat extraction performance. Considering the high-temperature and load-bearing requirements of deep wells, several engineering polymers and aluminum alloys were comparatively evaluated, and 7075-T6511 aluminum alloy was selected as the base material for the lightweight lower inner-pipe section. A composite thermal insulation structure combining a vacuum cavity with silica aerogel felt was developed, while a spiral-fin configuration was introduced to enhance local convective heat transfer. The engineering applicability of the lightweight insulated inner pipe was subsequently assessed through density measurements, high-temperature tensile testing, and thermal-conductivity testing, followed by a field-scale industrial test of the hybrid pipe string in a 4050 m deep geothermal well. The overall research framework thus integrates numerical analysis, material selection, structural design, performance testing, and field validation.

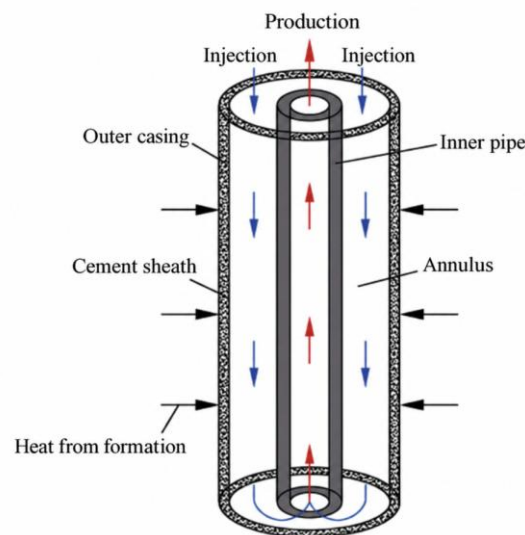


Fig.1 Schematic diagram of coaxial heat exchanger

The main contributions of this study are threefold. First, the effects of inner-pipe insulation performance and insulated-section configuration on heat extraction efficiency are quantitatively evaluated from the perspective of the overall thermal behavior of the deep coaxial heat exchanger,

providing a thermal basis for segmented pipe-string design. Second, a segmented steel–aluminum hybrid insulated inner-pipe string is proposed, integrating lightweight aluminum alloy, vacuum–aerogel thermal insulation, and enhanced heat-transfer structures to jointly address the requirements of insulation, temperature resistance, mechanical strength, and weight reduction. Third, multiscale validation is achieved through laboratory performance testing and a deep-well field trial, extending the evaluation from material and pipe-level properties to full-well heat-transfer performance and thereby providing experimental and field evidence for the engineering application of hybrid insulated inner-pipe strings in deep geothermal coaxial heat-extraction systems.

2 Numerical investigation of the effects of insulated inner-pipe parameters on the heat extraction performance of a coaxial heat exchanger

2.1 Model development

Based on the geothermal geological conditions of the Xi'an Depression in the Guanzhong Basin, a transient coupled groundwater-flow and heat-transfer model was developed using COMSOL Multiphysics to characterize the thermal behavior of a deep coaxial heat exchanger and the surrounding formation[30]. The computational domain consisted of three components: the coaxial heat exchanger, the cement sheath, and a $200\text{ m} \times 200\text{ m}$ surrounding formation domain, as illustrated in Fig. 2. The annular space between the high-thermal-conductivity outer pipe and the borehole wall was filled with cement. During operation, the circulating fluid flowed downward through the annulus between the inner and outer pipes, entered the inner pipe at the bottom of the well, and subsequently returned to the surface through the inner pipe.

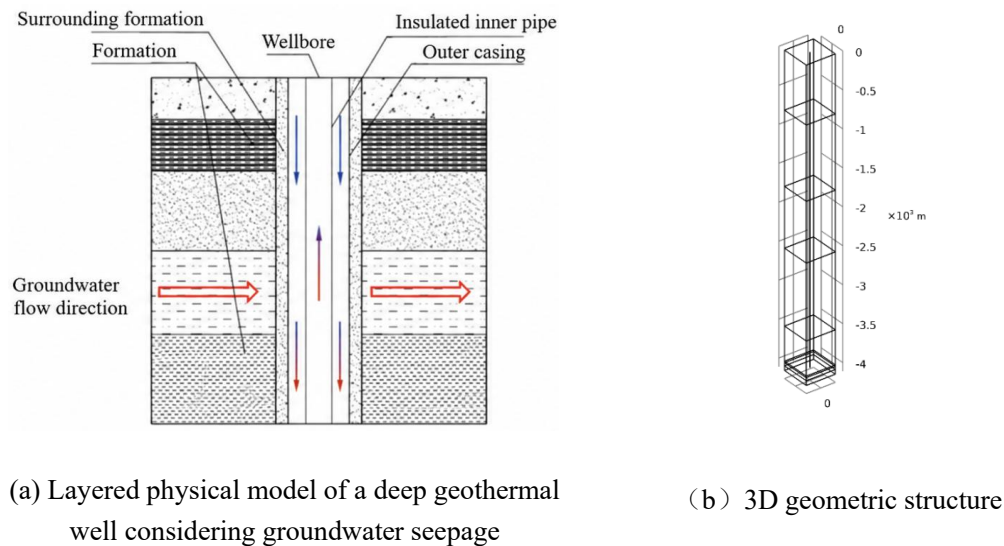


Fig.2 3D geometric model and mesh generation of coaxial heat exchanger

The governing equations accounted for heat transfer in porous media, heat conduction in the solid domains, convective heat transfer of the circulating fluid within the wellbore, and groundwater flow.

Heat transfer within the porous formation was described under the assumption of local thermal equilibrium between the reservoir rock and geothermal fluid. Turbulent flow and convective heat transfer within the wellbore were modeled using the k - ϵ turbulence model, whereas groundwater flow through the porous formation was described by Darcy's law.

The initial temperature field was prescribed according to fiber-optic temperature measurements. The average geothermal gradient was 29.3 °C/km, and the mean ground-surface temperature was set to 15 °C. At locations sufficiently far from the borehole axis, a constant-temperature condition was imposed to represent the far-field thermal boundary, while the inlet temperature at the top of the outer-pipe annulus was specified according to the corresponding operating condition.

2.2 Model validation

To evaluate the reliability of the numerical model, simulated results were compared with field measurements obtained from a 4050 m deep geothermal well located in Lianhu District, Xi'an. The field test was conducted over a total period of 192 h, consisting of eight repeated operating cycles, each including 10 h of continuous circulation followed by 14 h of shutdown. The inlet temperature and volumetric flow rate were maintained at 10.23 °C and 29.94 m³/h, respectively.

As the heat-extraction test progressed, the outlet temperature exhibited an overall decreasing trend, although the rate of decline gradually diminished, eventually stabilizing at approximately 48 °C. This behavior can be attributed to the progressive disturbance of the thermal field surrounding the wellbore. During the initial stage of operation, the formation adjacent to the well retained a relatively undisturbed temperature distribution and therefore supplied heat to the circulating fluid more effectively. With continued operation, the temperature of the near-well formation gradually decreased, whereas heat from the deeper and more distant formation could not be replenished rapidly enough through conduction. Consequently, the outlet temperature declined progressively before approaching a quasi-stable state.

The simulated outlet temperatures showed good agreement with the measured values, as shown in Fig. 3. The overall calculation error was 6.6%, indicating that the model reproduced the measured thermal response with acceptable accuracy and was therefore suitable for the subsequent parametric analyses.

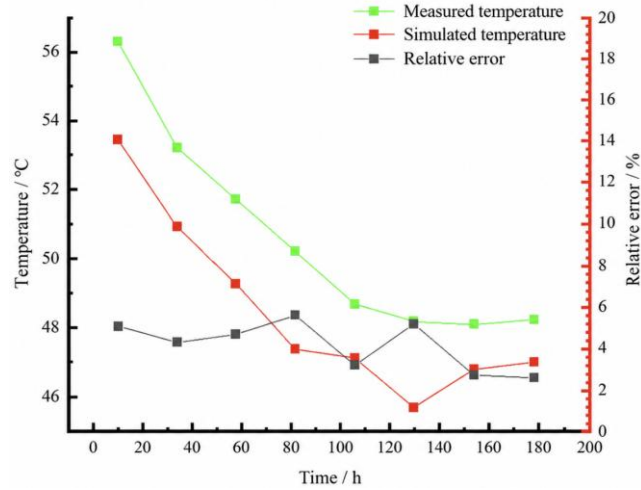


Fig. 3 Comparison between simulated and measured outlet temperatures

2.3 Effects of operating conditions on heat extraction performance

(1) Effect of inlet flow rate

With all other parameters held constant, the inlet flow rate was varied from 20 to 40 m³/h. The simulation results showed that increasing the flow rate caused the outlet temperature to decrease from approximately 55 °C to 37 °C, corresponding to a reduction of about 18 °C. In contrast, the heat extraction power increased from approximately 1020 to 1280 kW, representing an increase of more than 25%, while the performance coefficient increased from 0.955 to 0.995.

The decrease in outlet temperature with increasing flow rate is mainly attributable to the shorter residence time of the circulating fluid within the heat exchanger, which reduces the amount of heat absorbed per unit volume of fluid. However, the greater fluid throughput increases the total amount of heat transported per unit time, resulting in a higher overall heat extraction rate. These results indicate that increasing the inlet flow rate within an appropriate range can enhance the heat extraction power and overall thermal performance of the system, although the associated pumping energy consumption must also be considered.

(2) Effect of inlet temperature

As the inlet temperature increased from 5 to 25 °C, the outlet temperature increased from approximately 41.5 to 51.8 °C. In contrast, the heat extraction power decreased from 1080 to 770 kW, corresponding to a reduction of approximately 29%, while the performance coefficient decreased slightly from 0.977 to 0.975.

The increase in inlet temperature reduced the temperature difference between the circulating fluid and the surrounding formation, thereby weakening the thermodynamic driving force for heat transfer and decreasing the amount of heat extracted from the formation per unit time. A lower inlet

temperature therefore provides a larger temperature difference between the fluid and the formation and is more favorable for enhancing heat extraction under the simulated operating conditions.

2.4 Effects of insulated inner-pipe parameters on heat extraction performance

(1) Effect of thermal conductivity

As the thermal conductivity of the inner pipe increased from 0.006 to 0.4 W/(m·K), the heat extraction power of the coaxial heat exchanger decreased from 1211 to 1043 kW, corresponding to a reduction of more than 14%. Meanwhile, the performance coefficient decreased from 0.99 to 0.86.

A higher thermal conductivity enhances radial heat transfer between the upward-flowing hot fluid in the inner pipe and the downward-flowing colder fluid in the annulus, thereby intensifying the thermal short-circuiting effect within the wellbore. Consequently, part of the extracted heat is transferred internally before reaching the surface, reducing the amount of useful thermal energy delivered by the system. These results indicate that a lower inner-pipe thermal conductivity, and hence improved thermal insulation, is beneficial for suppressing thermal short-circuiting and enhancing heat extraction performance, as shown in Fig. 4.

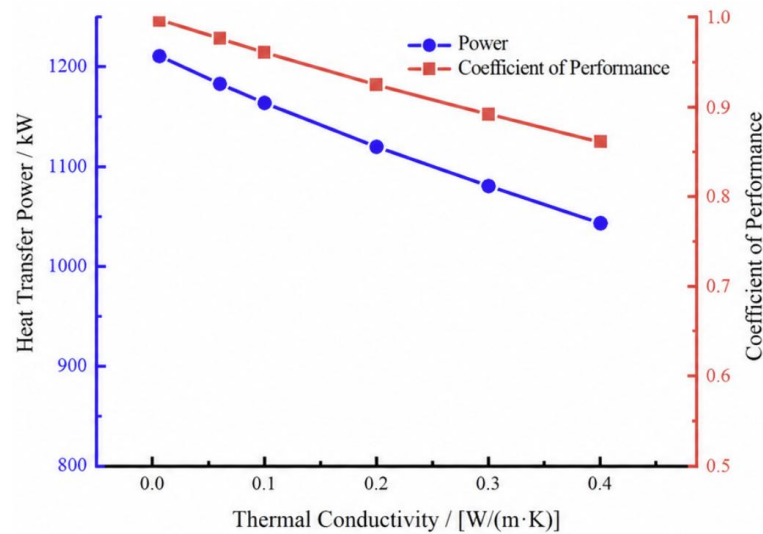


Fig. 4 Effect of inner-pipe thermal conductivity on heat extraction performance

(2) Effect of inner-pipe diameter

When the inner diameter of the inner pipe increased from 25 to 45 mm, the outlet temperature decreased from 44.4 to 43.8 °C, while the heat extraction power decreased from 1200 to 1179.4 kW, corresponding to a reduction of 1.75%. The performance coefficient also decreased from 0.984 to 0.974.

According to the numerical results, increasing the inner-pipe diameter altered the flow characteristics within the heat exchanger and reduced the residence time of the circulating fluid, thereby slightly weakening the overall heat-transfer process. Nevertheless, compared with the

effects of thermal conductivity and insulation length, the influence of inner-pipe diameter on the overall heat extraction performance was relatively limited.

(3) Effect of insulated-section length

As the insulated-section length increased from 2000 to 3500 m, the outlet temperature increased from 31 to 43.2 °C, representing an increase of more than 12 °C. Over the same range, the heat extraction power increased from approximately 720 to 1160 kW, corresponding to an increase of more than 60%.

Increasing the insulated-section length effectively suppressed thermal short-circuiting between the counter-flowing streams, allowing a greater proportion of the heat absorbed from the formation to be retained in the circulating fluid and transported to the surface. Improved insulation of the inner pipe also reduced the temperature of the downward-flowing fluid in the annulus, thereby increasing the temperature difference between the annular fluid and the surrounding formation and further promoting heat extraction from the formation. However, the incremental improvement gradually diminished as the insulated-section length increased. This trend indicates that thermal insulation in the upper portion of the well plays a particularly important role, providing a thermal basis for the segmented design of the hybrid inner-pipe string, in which the upper section should preferentially employ an inner pipe with superior insulation performance, as shown in Fig. 5.

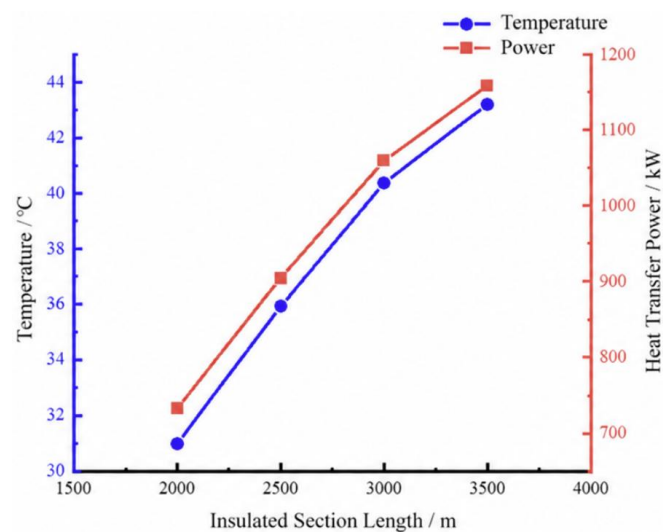


Fig. 5 Effect of insulated-section length on heat extraction performance

3 Development of a lightweight aluminum-alloy insulated inner pipe

3.1 Material selection

The insulated inner pipe is a key functional component of a coaxial heat exchanger. In deep geothermal wells with depths of approximately 4000 m, the bottom-hole temperature can reach 120–130 °C, imposing stringent requirements on both the high-temperature resistance and structural

reliability of the inner-pipe material. To identify a material suitable for lightweight deep-well applications, two major categories of candidate materials were evaluated: high-performance engineering polymers, including polyphenylene sulfide (PPS), polyether ether ketone (PEEK), and polyetherimide (PEI), and lightweight aluminum alloys that have demonstrated favorable strength-to-weight characteristics in deep drilling and related engineering applications.

Engineering polymers offer several advantages, including low density, good corrosion resistance, and relatively high temperature resistance. However, their high stiffness and limited flexibility make continuous coiling difficult, which constrains deployment and installation in deep wells. In addition, the manufacture of large-diameter, long-length polymer pipes remains relatively inefficient and costly. Considering these limitations, aluminum alloys were further evaluated as an alternative lightweight structural material. A comparison between 2024 and 7075 aluminum alloys led to the selection of 7075-T6511 aluminum alloy as the base material for the lightweight insulated inner pipe.

The T6511 temper combines solution heat treatment and artificial aging with an additional stress-relief treatment, resulting in a relatively uniform distribution of fine strengthening precipitates. Consequently, 7075-T6511 aluminum alloy exhibits high yield and tensile strengths, with a room-temperature tensile strength of approximately 570–640 MPa, while retaining favorable fracture toughness and fatigue resistance. These properties provide a suitable balance between lightweight design and mechanical reliability under the high-temperature and high-pressure conditions encountered in deep geothermal wells.

3.2 Structural design of the insulated inner pipe

As shown in Fig. 6, the main body of the aluminum-alloy insulated inner pipe consists of an insulated-coupling outer sleeve (1), coupling aerogel felt (2), insulated-coupling inner sleeve (3), End-A T-shaped ring (4), outer pipe (5), pipe-body aerogel felt (6), inner pipe (7), and End-B T-shaped ring (8). The outer pipe has an outside diameter of 114.3 mm and an inside diameter of 100.3 mm, whereas the inner pipe has an inside diameter of 79 mm and an outside diameter of 90 mm. Both ends of the outer pipe are externally upset and machined into a three-step cylindrical profile. Because the outside diameter of the inner pipe is smaller than the inside diameter of the outer pipe, an annular cavity is formed between the two components after assembly. The inner and outer pipes are precisely aligned by the T-shaped rings at both ends and subsequently joined by welding to form an integrated composite pipe body. The annular cavity is wrapped with SiO₂ aerogel felt and evacuated to a high-vacuum condition, thereby reducing heat transfer by both conduction and convection.

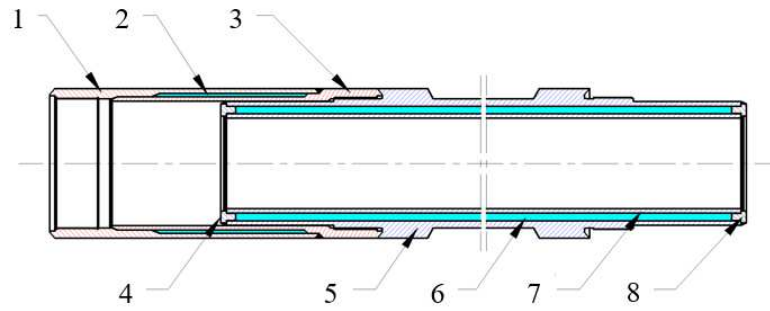


Fig. 6 Schematic of the insulated inner-pipe structure

As shown in Fig. 7, the insulated coupling consists of an insulated-coupling outer sleeve (1), coupling aerogel felt (2), insulated-coupling inner sleeve (3), coupling welds (4 and 7), pitch-diameter mating surface (5), and major-diameter mating surface (6). After the inner sleeve is inserted into the outer sleeve, an annular cavity is formed between the two components and filled with aerogel felt. The circumferential joints between the inner and outer sleeves are then welded and sealed under vacuum conditions to maintain the insulation cavity. Internal threads are machined at both ends of the coupling for connection with the insulated pipe bodies, while the mating surfaces provide positional constraint and sealing between the coupling and the pipe body. Multiple aluminum-alloy insulated pipe sections are connected end-to-end through threaded joints to form a complete insulated inner-pipe string, thereby combining thermal insulation, pressure-bearing capacity, structural strength, and weight reduction.

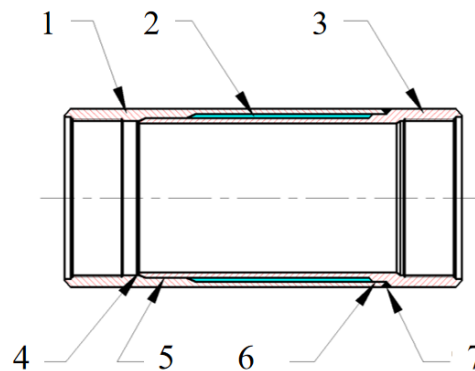


Fig. 7 Schematic of the insulated coupling structure

3.3 Structural integrity and galvanic corrosion protection

The structural integrity of the aluminum-alloy insulated inner pipe was evaluated according to SY/T 5724-2008, *Structural and Strength Design of Casing Strings*. At a well depth of approximately 4000 m, the inner and outer pipes are subjected to a hydrostatic pressure of about 40 MPa. The calculated collapse resistance of the outer pipe was 58.1 MPa, while its internal pressure resistance

reached 46.3 MPa. The tensile capacity of the threaded connection was reported as 21.7 MPa. These results indicate that the designed pipe body and threaded connection satisfy the load-bearing requirements for operation under the high-temperature and high-pressure conditions of a 4000 m deep geothermal well.

In addition to mechanical loading, the direct connection between steel and aluminum-alloy components introduces a potential risk of galvanic corrosion. To mitigate this problem, a thermally insulating and electrically isolating pup joint was designed, as shown in Fig. 8. The joint consists of a steel outer sleeve (1), thermal-insulation component (2), aluminum-alloy inner sleeve (3), End-A large-diameter section (4), spiral-groove section (5), intermediate small-diameter section (6), and End-B large-diameter section (7). A PEEK insulating liner is incorporated between the steel outer sleeve and the aluminum-alloy inner sleeve, while the stepped and spiral-groove geometry provides mechanical interlocking and electrical isolation between the dissimilar metallic components.

PEEK has a temperature resistance of approximately 260 °C, an electrical resistivity of at least $10^{12} \Omega \cdot m$, and a compressive strength of at least 120 MPa, enabling it to withstand the downhole thermal and mechanical environment. By preventing direct electrical contact between steel and aluminum, the insulating structure suppresses the formation of a galvanic couple and thereby reduces the risk of galvanic corrosion, improving the long-term service reliability of the aluminum-alloy insulated pipe string.

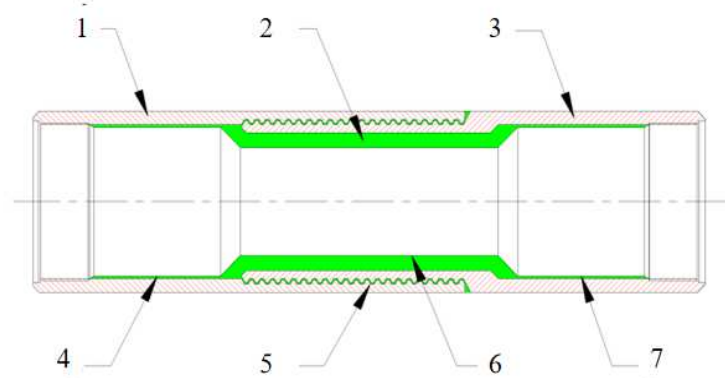


Fig. 8 Structure of the thermally insulating and electrically isolating pup joint

4 Optimization of the spiral-fin heat-transfer enhancement structure

4.1 Heat-transfer enhancement mechanism and performance evaluation

To further improve the heat-transfer performance of the deep geothermal coaxial heat exchanger, a **spiral-fin structure** was introduced on the outer surface of the aluminum-alloy insulated inner pipe, as shown in **Fig. 9**. The fins enhance convective heat transfer by increasing fluid disturbance and turbulence intensity and by reducing the thickness of the thermal boundary layer. Their influence

on the flow and heat-transfer process can be summarized in three aspects: an increase in the effective heat-transfer area, enhanced flow disturbance, and additional flow resistance. Therefore, the design of the spiral-fin structure requires an appropriate balance between heat-transfer enhancement and the associated increase in hydraulic losses.

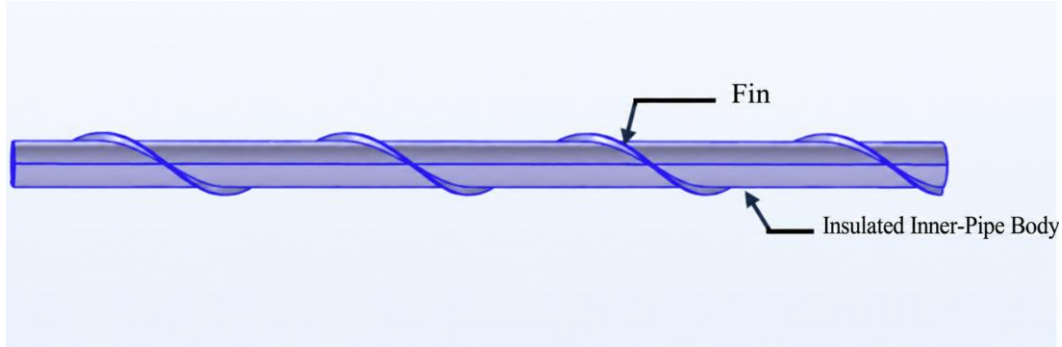


Fig. 9 Model of the spiral-fin heat-transfer enhancement structure

To quantitatively evaluate the overall thermal–hydraulic performance of the enhanced heat-transfer structure, the **performance evaluation criterion (PEC)** was adopted:

$$\text{PEC} = \frac{Nu_e/Nu_r}{(f_e/f_r)^{1/3}}$$

where Nu_e and Nu_r denote the Nusselt numbers of the finned pipe and the reference smooth pipe, respectively, and f_e and f_r denote the corresponding friction factors. The PEC therefore provides a combined measure of the enhancement in convective heat transfer relative to the accompanying increase in flow resistance.

4.2 Numerical modeling, validation, and parametric optimization

A three-dimensional numerical model of the coaxial heat exchanger equipped with spiral fins was developed using the turbulence and conjugate heat-transfer modules in COMSOL Multiphysics. The computational section had a length of 1000 mm. The outer pipe had an outside diameter of 244.3 mm and an inside diameter of 222.1 mm, while the inner pipe had an outside diameter of 114.3 mm and an inside diameter of 79 mm. A velocity inlet and pressure outlet were prescribed at the inlet and outlet boundaries, respectively, and the heat-transfer wall was maintained at a constant temperature of 100 °C. A mesh-independence analysis confirmed that the predicted results were insensitive to further mesh refinement, indicating that the adopted mesh resolution was sufficient for the subsequent simulations.

The numerical model was further validated using established empirical correlations. The friction factor and Nusselt number of the smooth and finned configurations were compared with predictions obtained from the Konakov correlation and the Gnielinski correlation, respectively. The mean absolute errors of the Nusselt number and friction factor for the enhanced heat-transfer configuration

were 6.19% and 6.56%, respectively, both below 10%. These deviations indicate that the numerical model reproduced the expected thermal–hydraulic behavior with acceptable accuracy and was therefore used for the subsequent parametric analysis.

The effects of the principal geometric parameters of the spiral fins were investigated using a controlled-variable approach. The fin height was varied as $H = 10, 15$, and 20 mm, the fin thickness as $T = 4, 6$, and 8 mm, and the fin spacing as $G = 216.89, 125.24$, and 54.42 mm. Their effects on the outlet temperature, Nusselt number, friction factor, and overall performance evaluation criterion were systematically evaluated.

As the Reynolds number increased from 5000 to 25,000, the outlet temperature decreased under all simulated conditions. Nevertheless, the finned configurations consistently produced higher outlet temperatures than the corresponding smooth-pipe configuration, demonstrating the beneficial effect of the spiral fins on convective heat transfer. Among the three geometric parameters, fin height exerted the strongest influence. Increasing the fin height from 10 to 20 mm led to marked increases in both outlet temperature and Nusselt number, whereas the effect of fin thickness was comparatively modest. By contrast, reducing the fin spacing, corresponding to a denser fin arrangement, resulted in a lower Nusselt number. This trend suggests that excessively dense fins may restrict the flow passage and induce a less favorable velocity distribution, thereby weakening the overall heat-transfer enhancement.

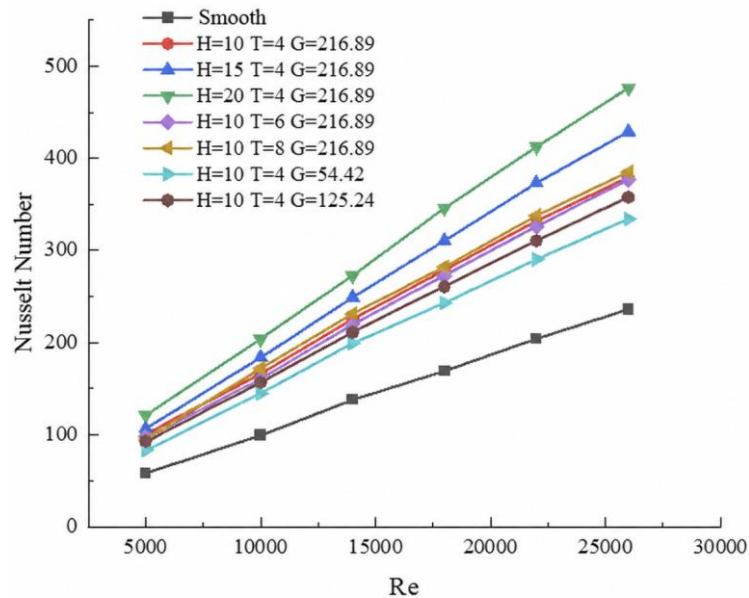


Fig. 10 Effect of spiral-fin geometric parameters on the Nusselt number

The introduction of spiral fins also increased the flow resistance relative to that of the smooth pipe. The friction factor increased substantially as the fin height increased from 10 to 20 mm, and it also increased as the fin spacing decreased, whereas fin thickness had a comparatively limited effect.

Therefore, the improvement in heat-transfer performance must be evaluated together with the corresponding hydraulic penalty.

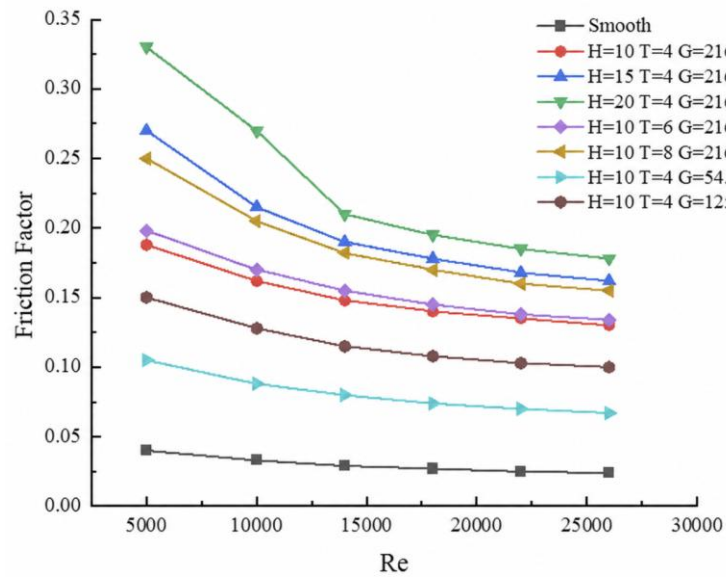


Fig. 11 Effect of spiral-fin geometric parameters on the friction factor

The PEC results showed that the configuration with a fin height of 20 mm achieved the highest overall thermal-hydraulic performance, indicating that the additional heat-transfer enhancement associated with increasing fin height outweighed the corresponding increase in flow resistance. In contrast, increasing the fin thickness and decreasing the fin spacing both reduced the PEC. Considering both heat-transfer enhancement and hydraulic resistance, the optimum geometric configuration was determined to be a fin height of 20 mm, fin thickness of 4 mm, and fin spacing of 216.89 mm. This configuration exhibited the best overall performance over a Reynolds-number range of approximately 4000–26,000.

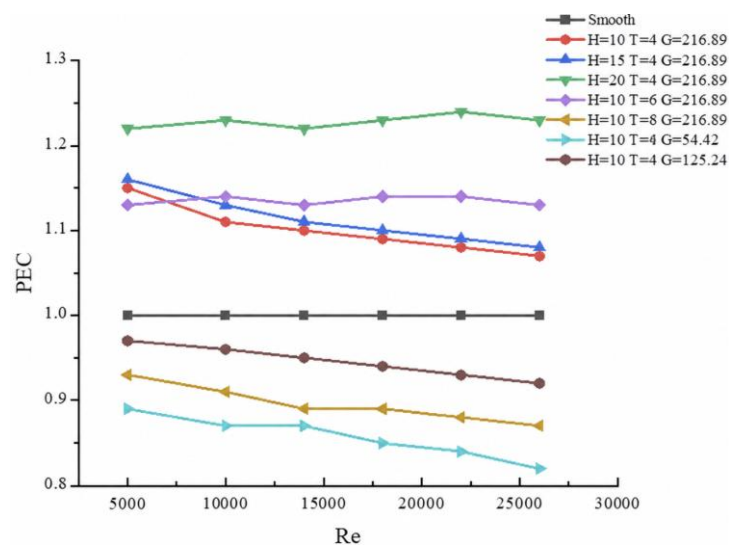


Fig. 12 Effect of spiral-fin geometric parameters on the performance evaluation criterion (PEC)

5 Field-scale testing and performance evaluation

5.1 Field site, geothermal conditions, and hybrid inner-pipe configuration

The field-scale test was conducted in a 4050 m deep geothermal well constructed in the Xi'an Depression of the Guanzhong Basin. The Xi'an Depression is a typical Cenozoic half-graben basin characterized by thick sandstone–mudstone interbedded sequences, providing favorable geological conditions for the occurrence and development of deep geothermal resources. The test well was constructed under projects supported by Tiandi Science & Technology Co., Ltd. and Xi'an Coal Science Geothermal Energy Development Co., Ltd.

After drilling and well completion, a series of downhole logging operations were conducted, including natural gamma, temperature, spontaneous potential, caliper, acoustic transit-time, and continuous deviation measurements. From shallow to deep, the penetrated stratigraphic succession comprised the Quaternary (0–770 m), Neogene Zhangjiapo Formation (770–1748 m), Lantian–Bahe Formation (1748–2540 m), Gaoling Group (2540–3540 m), Paleogene Bailuyuan Formation (3540–3990 m), and Honghe Formation (3990–4050 m). Temperature logging indicated a geothermal gradient of approximately 2.93 °C/100 m, and the bottom-hole temperature reached 130.18 °C at the final well depth, confirming favorable thermal conditions for deep geothermal heat extraction.

The test well adopted a two-section wellbore configuration. The first section was drilled with a 444.5 mm bit to a depth of 814 m, followed by installation of 339.7 mm surface casing. The second section was drilled with a 311.15 mm bit to the final depth of 4050 m, with 244.5 mm casing subsequently installed. Based on the thermal and structural requirements identified in the preceding analyses, a segmented steel–aluminum hybrid insulated inner-pipe string was deployed in the well. The interval from 0 to 3685 m consisted of P110 steel insulated inner pipe, with a thermal-conductivity grade of E, a mass per unit length of 29.08 kg/m, a collapse resistance of 69 MPa, and an internal pressure resistance of 62 MPa. The interval from 3685 to 4001 m employed the developed 7075 aluminum-alloy insulated inner pipe, with a thermal-conductivity grade of D, a mass per unit length of 10.96 kg/m, a collapse resistance of 58.1 MPa, and an internal pressure resistance of 46.3 MPa, as illustrated in Fig. 13.

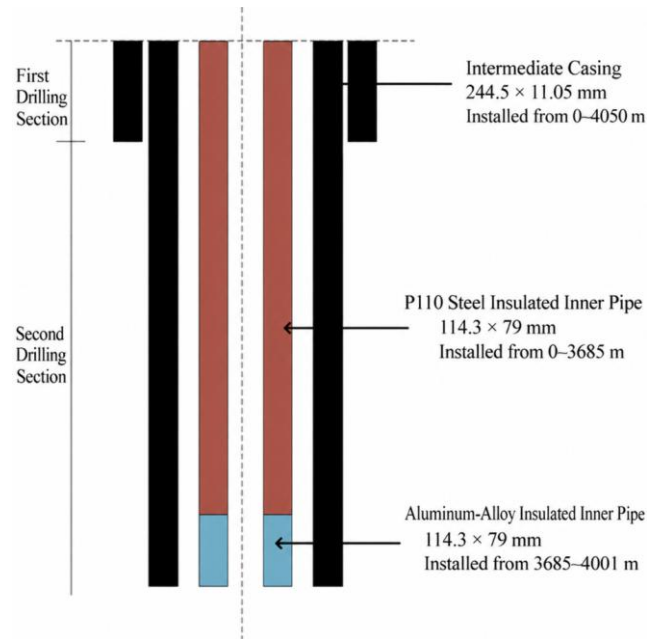


Fig. 13 Schematic of the segmented steel–aluminum hybrid insulated inner-pipe string

Through this segmented configuration, the total mass of the hybrid insulated inner-pipe string was reduced to 105,940 kg, corresponding to a 5.7% reduction relative to an all-steel insulated inner-pipe configuration. The lightweight aluminum-alloy section therefore reduced the accumulated self-weight of the deep-well pipe string while maintaining the required pressure-bearing capacity. In addition, spiral fins were welded onto the outer surface of the aluminum-alloy insulated inner pipe to form an enhanced heat-transfer structure, thereby promoting heat exchange between the high-temperature deep formation and the circulating working fluid.

5.2 Distributed temperature sensing and thermal insulation performance

A distributed temperature sensing (DTS) system was employed to continuously monitor the temperature of the circulating fluid inside the inner-pipe string. The DTS system measures the temperature continuously along the entire optical fiber based on the Raman scattering effect, enabling kilometer-scale distributed temperature measurements using a single fiber. This technique is well suited to complex downhole environments involving high temperatures, high pressures, and strong electromagnetic interference.

The DTS temperature profiles showed an approximately linear decrease in fluid temperature along the steel insulated inner-pipe section, whereas a larger temperature decrease was observed over the aluminum-alloy insulated section. Analysis of the DTS profiles obtained during nine stable operating periods showed that the circulating fluid experienced a temperature drop of 0.93–1.11 °C while flowing upward through the 316.57 m-long aluminum-alloy insulated inner-pipe section, corresponding to a weighted average temperature drop of only 1.03 °C. After entering the steel insulated inner-pipe section, the fluid flowed upward over a distance of 3679.47 m to a position

approximately 6 m below the wellhead assembly, during which the temperature decreased by 3.54–10.32 °C, with a weighted average decrease of 6.58 °C. Over the entire inner-pipe string, the total temperature drop ranged from 4.61 to 11.29 °C, with a weighted average of 7.61 °C.

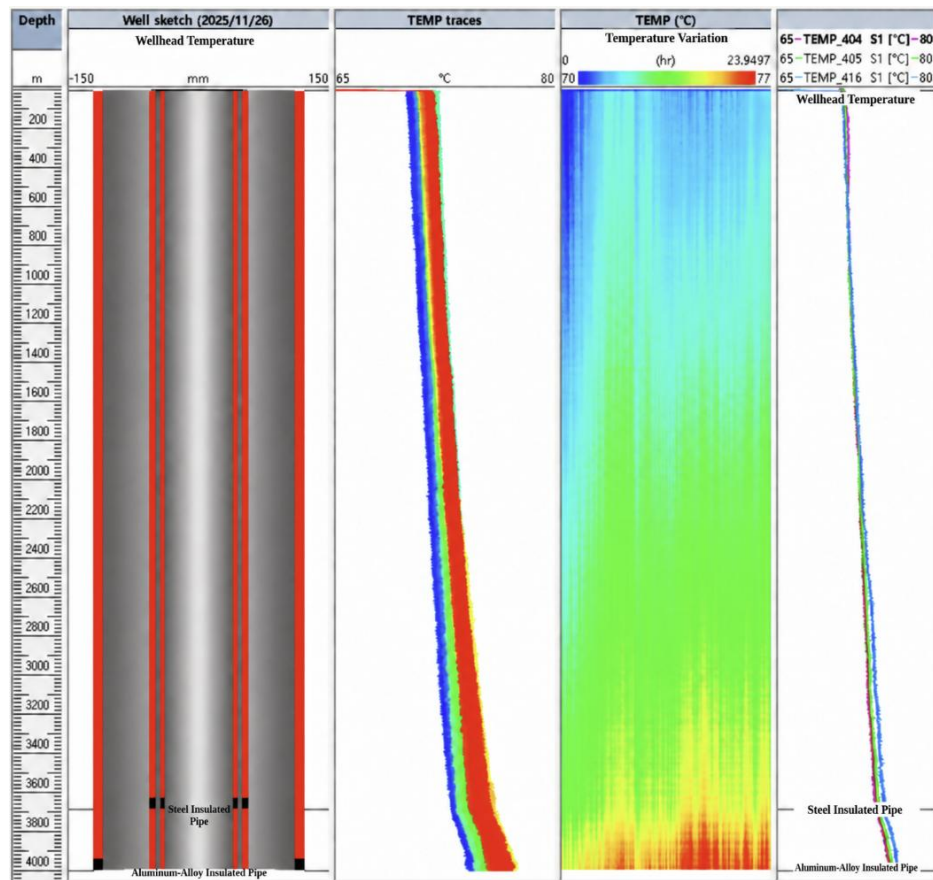


Fig. 14 DTS temperature-drop profile along the hybrid insulated inner-pipe string

These measurements indicate that the developed aluminum-alloy insulated inner pipe maintained effective thermal insulation under deep-well operating conditions and met the intended design requirements.

5.3 Heat extraction performance and comprehensive benefit assessment

The heat-extraction test was conducted continuously for 6 days. The maximum outlet temperature reached 71.43 °C, while the maximum temperature difference between the inlet and outlet was 52.78 °C. Across nine operating cycles, the average inlet–outlet temperature difference was 46.41 °C, and the mean circulation flow rate was 31.81 m³/h. Based on the distributed temperature sensing data, the average heat extraction power was calculated to be 1716.58 kW. Over the 6-day test period, the heat extraction power decreased by 12.3%, with the rate of decline gradually slowing as operation continued.

Long-term performance was further evaluated using measured operating data collected over a three-month heating season from December 2025 to February 2026. As the continuous operating time

increased, the heat extraction power exhibited a progressive decline. During the initial stage, corresponding to the first 17 days, the heat extraction power decreased from approximately 1600 to 1500 kW. Between days 17 and 30, it declined more rapidly to approximately 1420 kW. Thereafter, from day 30 to day 90, the decline became more gradual, with the heat extraction power reaching approximately 1300 kW by the end of the monitoring period. The average heat extraction rate per unit well depth reached 352 W/m, indicating favorable long-term heat extraction performance of the deep geothermal system and effective thermal insulation of the hybrid inner-pipe string.

From the perspective of energy-saving and environmental performance, the system was estimated to save 770.73 t of standard coal equivalent per year, corresponding to a reduction of approximately 2019.31 t of CO₂ emissions, together with substantial reductions in SO₂ and nitrogen oxide emissions. The heating system achieved a coefficient of performance (COP) of 6.80, while the operating cost was approximately 2.37 CNY/(m²·month). Compared with gas-boiler heating and municipal district heating, the annual operating costs were reduced by approximately CNY 919,000 and CNY 625,600, respectively. These results demonstrate that the proposed deep geothermal coaxial heat-extraction system provides favorable thermal, environmental, and economic performance under field operating conditions.

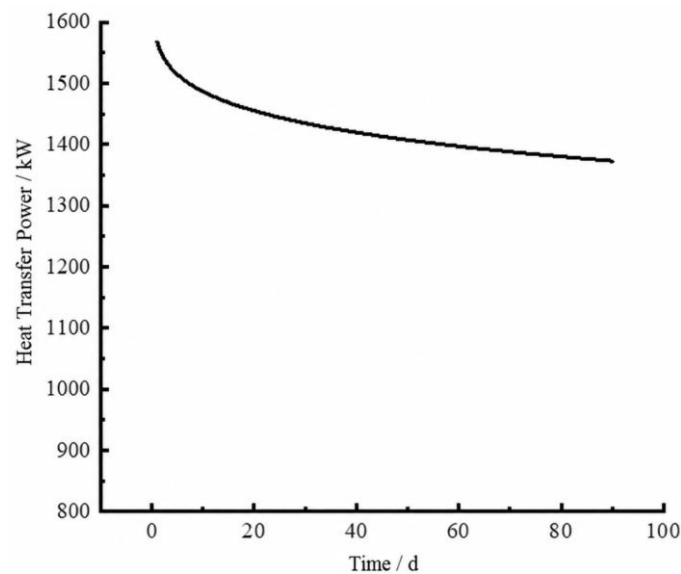


Fig. 15 Variation in heat extraction power during the heating season

6 Conclusions

This study developed and field-validated a segmented steel–aluminum hybrid insulated inner-pipe string for deep geothermal coaxial heat extraction. The main conclusions are as follows:

- (1) A transient coupled groundwater-flow and heat-transfer model for the deep geothermal coaxial heat exchanger was established and validated against field measurements, with an overall deviation of 6.6%. The simulations showed that increasing the inlet flow rate enhanced the heat extraction

power and overall thermal performance, whereas increasing the inlet temperature reduced both. Lower inner-pipe thermal conductivity, a smaller inner diameter, and a longer insulated section were generally favorable for heat extraction. However, the incremental benefit of increasing the insulation length gradually diminished, indicating that thermal insulation in the upper portion of the well is particularly important.

(2) 7075-T6511 aluminum alloy was selected as the structural material for the lightweight insulated inner pipe. A composite insulation structure combining an evacuated annular cavity with SiO₂ aerogel felt was developed together with a threaded connection system. Structural calculations yielded a collapse resistance of 58.1 MPa and an internal pressure resistance of 46.3 MPa, satisfying the mechanical requirements of the 4000 m deep-well application considered in this study. A PEEK-based thermally insulating and electrically isolating pup joint was further introduced to mitigate galvanic corrosion at the steel–aluminum interface.

(3) Optimization of the spiral-fin heat-transfer enhancement structure showed that fin height was the dominant geometric parameter governing the overall thermal–hydraulic performance. The optimum configuration consisted of a fin height of 20 mm, a fin thickness of 4 mm, and a fin spacing of 216.89 mm, providing the highest PEC over a Reynolds-number range of approximately 4000–26,000.

(4) Laboratory tests confirmed the lightweight and high-temperature performance of the developed aluminum-alloy insulated inner pipe. Its mass per unit length was only 36.9% of that of a steel pipe with the same dimensions, while its yield strength remained 381 MPa at 150 °C. The measured thermal conductivity was as low as 0.008 W/(m·K), meeting the reported Grade D requirement for vacuum-insulated tubing.

(5) Field testing in a 4050 m deep geothermal well demonstrated the engineering feasibility of the proposed hybrid configuration. The steel section extended from 0 to 3685 m, while the aluminum-alloy section extended from 3685 to 4001 m, resulting in a 5.7% reduction in total string weight relative to an all-steel configuration. DTS measurements showed a weighted average temperature drop of 7.61 °C over the full inner-pipe string. The system achieved a heating COP of 6.80 and an average heat extraction rate per unit well depth of 352 W/m, with an estimated annual saving of 770.73 t of standard coal equivalent. These results indicate that the proposed hybrid insulated inner-pipe string can simultaneously reduce structural weight, maintain thermal insulation and mechanical reliability, and support efficient heat extraction in deep geothermal coaxial systems.

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Date Availability

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Author Contributions Statement

Z.H. contributed to the conceptualization, methodology, numerical simulation, experimental investigation, data analysis, and preparation of the original manuscript. D.D. contributed to the conceptualization, methodology, supervision, and review and editing of the manuscript. H.G. contributed to field investigation, data acquisition, validation, and interpretation of the experimental and field-test results. W.L. contributed to experimental investigation, data curation, field testing, and validation. All authors reviewed and approved the final manuscript.