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Original article

Analysis of core temperature variation and its influencing factors in deep rock *in-situ* temperature-preserved coring

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Abstract:
Deep rock *in-situ* temperature-preserved coring is important for the exploration and development of deep resources. In addition, understanding the temperature variation laws of the core during coring is fundamental to achieving temperature-preserved coring. In this study, under the coexistence of the core and strata water inside the coring tool, we explore the factors sensitive to the temperature variation of the core during coring and propose suggestions to reduce the unevenness of core temperature. The findings indicate that at a strata temperature of 150 °C and a core lifting speed of 2.5 m/s, during process of lifting the passively insulated core to the ground, natural convection occurs within the coring tool due to buoyancy, circulating in a counterclockwise direction. The temperature difference of the core in the axial and radial directions is 21 and 7.7 °C, respectively, with temperature variation rates of 21 and 308 °C/m per unit length, respectively. The greatest decrease in temperature is observed at the outer edge of the core bottom. The natural convection of strata water results in significant temperature differences along the axis of the core, exacerbating the unevenness of core temperature. To ensure uniform core temperature, efforts should be made to minimize the space between the core and the inner tube. In addition, the use of water-blocking mechanisms should be facilitated to reduce the ingress of strata water into the coring device. During the coring process, the frequency of active thermal insulation gradually increases as the ambient temperature decreases, thereby reducing the temperature difference between the inner and outer sides of the coring device to suppress the occurrence of natural convection. These research findings have practical implications for achieving deep rock *in-situ* temperature-preserved coring, providing theoretical and technical guidance for the development of deep resources such as coal, geothermal energy, and oil and gas.

1. Introduction

As the global energy demand continues to expand, shallow resource reserves are gradually diminishing and the development of resource extraction is necessary toward the deep part of the Earth (Xie et al., 2015). For example, coal mining depths have now exceeded 1,500 meters, geothermal exploitation depths have surpassed 5,000 meters, and oil and gas extraction depths have reached 8,800 meters, indicating that deep-seated resource extraction has become commonplace (Xie et

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al., 2024). However, deep underground resource extraction often faces high ground stress and temperature environments, leading to numerous engineering hazards during the process of deep underground resource exploitation. Compared to shallow rock strata, the physical and mechanical properties of deep rock strata undergo significant changes (He et al., 2021; Feng et al., 2022; Yang et al., 2023; Zhao et al., 2024b). Among these, temperature is one of the primary factors leading to alterations in the physical and mechanical properties of rocks (Yin et al., 2013; Qiu et al., 2024). Many scholars have conducted extensive research on this topic. In terms of gas-containing coal and rock strata, regarding the mechanical properties, scholars have combined studies on microscopic mechanisms with macroscopic mechanical experiments and found that high temperatures can reduce the strength of coal and rock via thermal shock, thermal expansion and other mechanisms (Wang et al., 2013; Liu et al., 2020; Su et al., 2022; Zhang et al., 2022; Zheng et al., 2022; Jia et al., 2023; Wang et al., 2023). In studies concerning the absorption/desorption behavior of gases such as methane, researchers have pointed out that temperature elevation is a primary factor inducing a significant desorption of adsorbed gas (Sakurovs et al., 2008; Guan et al., 2018; Li et al., 2023). Regarding gas permeability, research findings indicate that the relationship between the permeability of different types of gas-bearing coal and rock strata and temperature under various stress conditions is complex. Relevant research in this field is still inconclusive, with ongoing efforts in this area (Yin et al., 2013; Zou et al., 2020; Xie et al., 2022). In terms of oil and gas resources, scholars have found that temperature change significantly affects rock permeability and seepage pattern (Liu et al., 2024a). The accurate assessment of underground oil and gas resources is closely related to the porosity and permeability of reservoir rocks (Zhou et al., 2010). The analysis of samples from the Daqing and Yan'an oil shales revealed that porosity significantly increases within the range of 100-200 °C (Zhao et al., 2012). Observations via computed tomography of oil shales under high temperatures indicated that high temperatures lead to the connectivity of pores and fractures (Saif et al., 2017) and that the connectivity of rock pores and fractures is closely related to rock permeability (Rabbani et al., 2017). The above research results highlight that temperature is a key factor influencing the *in-situ* properties of deep rock strata. Therefore, there is an urgent need to obtain rocks that maintain their *in-situ* temperature for parameter measurement and modeling, thereby guiding deep engineering activities.

Continental scientific drilling is an indispensable means of addressing challenges related to resources, disasters and the environment. For instance, China's first 10,000-meter scientific exploration well, Deep Earth Taco Well I, has reached a drilling depth of 10,000 meters (Sun et al., 2024). The rock cores obtained from this well can facilitate the development of fundamental theoretical understanding regarding the strata of deep-seated oil and gas reservoirs at this depth range. However, traditional continental drilling techniques cannot conduct temperature-preserved coring (Liu et al., 2024b; Zhao et al., 2024a). Temperature distortion can lead to the incomplete scientific acquisition of resource reserves and gas phase information (Zhou et al., 2010), making it challenging to accurately assess deep-seated resource reserves.

At present, only combustible ice coring involves thermal insulation, but it relies solely on passive maintenance of the vacuum insulation principle at low temperatures, resulting in losses during coring and retrieval. However, deep-seated rock cores are in a high-temperature state, the preservation of which is the exact purpose of temperature-preserved coring, which is contrary to the research direction of temperature-preserved combustible ice coring. Therefore, the existing thermal insulation techniques cannot be applied to the thermal insulation coring of deep rock. It is necessary to develop an *in-situ* temperature-preserved coring (ITP-coring) device for deep rocks to maintain the *in-situ* temperature of the core environment, providing a sound basis for subsequent tests.

On the basis of the concept proposed by Xie et al. (2020), the idea of deep rock ITP-coring combines active and passive thermal insulation. The temperature-preserved coring device ensures that the temperature of deep, high-temperature rock cores remains constant during coring, thereby accurately obtaining *in-situ* temperature information of deep rock strata. The temperature variation laws of the rock core during the coring process can provide a reference for optimizing active thermal insulation design, serving as the foundation for achieving thermal preservation coring. Additionally, numerical simulations can be used during the design phase to verify the effectiveness of the insulation plan, thereby effectively shortening the design feedback cycle and improving the design efficiency. Successful implementations include the multiple autoclave corer and the dynamic autoclave piston corer designed by the German Ministry of Education and Research, and the pressure temperature core sampler and the high pressure temperature corer designed by research institutions in Japan (Abegg et al., 2008; Zhu et al., 2011). From the aforementioned research, it is evident that the design of insulation devices for extreme environments relies on numerical simulation methods. The high-temperature and high-pressure environment in deep continental areas differs significantly from the low-temperature and high-pressure environment of the deep sea. Moreover, due to the complexity of the deep Earth environment, the cost of directly verifying the thermal insulation effectiveness of a designed coring device through experimental means is prohibitively high. Therefore, this paper focuses on exploring the temperature variation laws of the core during coring only under passive thermal insulation. It analyzes the sensitivity factors of core temperature variation under the coexistence of core and strata water in the coring device and proposes recommendations to reduce the unevenness of core temperature, providing a useful reference for the precise control of core temperature in active thermal insulation approaches. The overarching aim is to establish a theoretical basis for the design of deep rock *in-situ* insulation coring devices and the optimization of coring processes.

2. Overview of the deep rock ITP-coring process

Deep-sea temperature-preserved coring faces a low-temperature environment with minimal temperature variation.

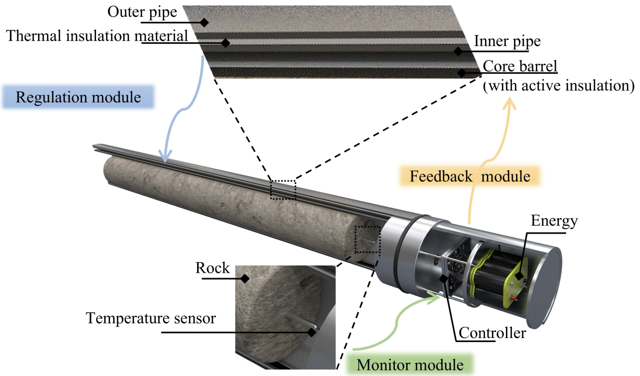

Fig. 1. Schematic of deep rock ITP-coring technology.

The average surface temperature of the three major oceans is 17.6 °C, and the temperature below 3,000 meters to the seabed ranges from 0 to 2 °C, indicating that the maximum temperature gradient in the ocean is -0.67 °C/100 m. In contrast, the deep terrestrial environment is characterized by a complex "three-high" condition (Xie et al., 2015), with high ground temperature being one of the main challenges faced by deep rock temperature-preserved coring. The average temperature gradient in deep terrestrial regions is approximately 4 °C/100 m. This is significantly higher than that in the deep sea and results in more drastic temperature variations and high-temperature conditions. If only passive thermal insulation measures are taken, the temperature of the obtained core will be lower than the *in-situ* temperature, leading to a distortion of physical and mechanical information of the core. On the other hand, relying solely on active thermal insulation would require high energy consumption. Furthermore, the extremely limited space for deep rock coring restricts the total amount of electrical energy supply, making it difficult to maintain the core inside the coring tool at the *in-situ* temperature throughout the entire coring process. Therefore, in response to the project requirements for deep rock ITP-coring with strata temperatures of 150 °C, our research team proposed a scheme combining active with passive thermal insulation (see Fig. 1) (He et al., 2020, 2022; Xie et al., 2020). The passive thermal insulation scheme aims to reduce the temperature fluctuations in the core due to changes in external environmental temperature, thereby minimizing the energy consumption required for active thermal insulation, while the active thermal insulation technology works in conjunction with three modules - temperature monitoring, feedback and regulation - to fulfill the requirement of maintaining the original *in-situ* temperature throughout the coring process in the confined space of deep rock ITP-coring.

According to the temperature-preserved coring approach described above, the foundation of achieving temperature-preserved coring is to understand the temperature variation in the core during the coring process. Considering the current coring tool design, establishing a numerical heat transfer model that accounts for natural convection of strata water can aid in investigating the temperature variation of the core with only passive thermal insulation, providing support for the further design and optimization of solutions combining active and passive thermal insulation.

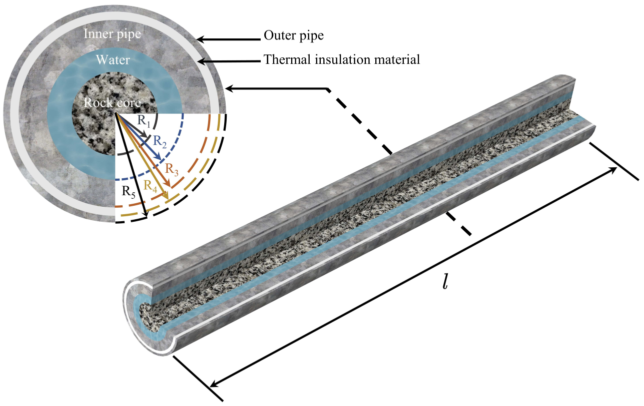

Fig. 2. Simplified model of the core sampler with passive thermal insulation only.

Table 1. Dimensional parameters of the simplified core chamber model.

R_1 (mm)	R_2 (mm)	R_3 (mm)	R_4 (mm)	R_5 (mm)	l (m)
25.0	39.5	56.0	61.0	65.0	1.0

Notes: R_1 is the inner radius of rock core, R_2 and R_3 are the inner and outer radius of the inner pipe respectively, R_4 and R_5 are the inner and outer radius of the outer pipe respectively, l is the length of core sampler.

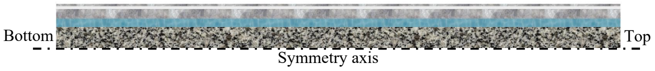

Fig. 3. Geometric model used in numerical simulation.

3. Physical heat transfer model based on ITP-coring

This study considers a coring tool within the length range of the rock core. During the coring drilling process, the *in-situ* rock core and *in-situ* strata water enter the coring tool, which employs only passive thermal insulation and can be simplified into the following components (see Fig. 2).

The generalized model dimensions of the coring tool are shown in Table 1.

4. Numerical simulation of heat transfer for ITP-coring

According to the heat transfer physical model of ITP-coring established in Section 3, the aspect ratio of the model is relatively large and the heat dissipation at both ends of the coring tool can be neglected. Therefore, the ends of the coring tool are set as adiabatic. The simplified model of the coring tool is cylindrical and heat transfer occurs radially outward from the center. A two-dimensional geometric model is employed for analysis, considering half of the cylinder to exploit symmetry, with the axis of symmetry set as adiabatic. The geometric model is shown in Fig. 3, where the core lifting direction is from the bottom end to the top, and the direction of gravity acceleration is from the top to the bottom. The physi-

Table 2. Physical property parameter of the corer chamber.

λ_1, λ_2 (W/(m·K))	λ_3 (W/(m·K))	ρ (kg/m^3)	h_f (W/(m^2·K))	h_a (W/(m^2·K))	C_R (J/(kg·K))
16.27	0.26	2687.00	50.00	1,000.00	816.96

Notes: λ_1, λ_2 and λ_3 are the thermal conductivity of the inner metal cylinder, outer metal cylinder and insulation material respectively, ρ is the density of rock corer, h_f is the natural convection coefficient of *in-situ* strata water, h_a is the forced thermal conductivity between strata fluid and outer pipe, C_R is the specific heat capacity of rock core.

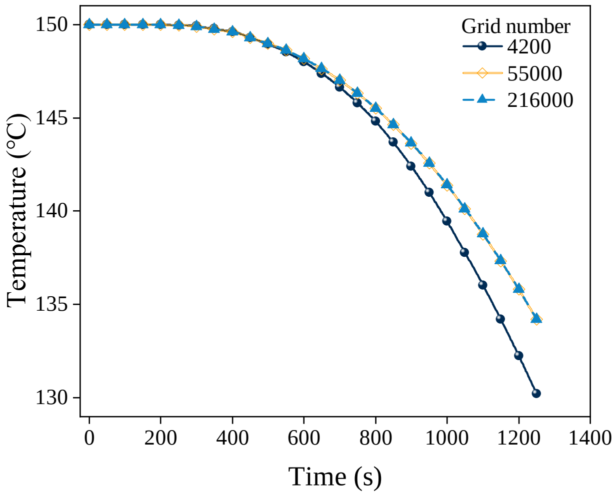

Fig. 4. Grid independence verification.

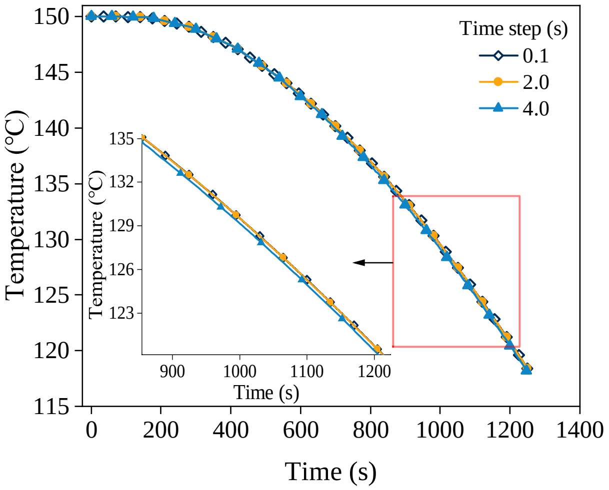

Fig. 5. Time step independence verification.

cal parameters used for modeling are shown in Table 2, with marble selected for the core and conventional water selected for the *in-situ* strata water.

Based on the project requirements for ITP-coring, assuming that the temperature of the strata is 150 °C, the ground temperature is set as 25 °C and the temperature gradient of the earth is set as 40 °C/km (Xie et al., 2015). Given a coring speed of 2.5 m/s (Wei et al., 2023), the total coring duration is 1,250 s. Further validation of the model is carried out for the grid and time step independence.

The model is divided into grids, with the *in-situ* strata water portion set as fluid elements and the rest set as solid elements. In addition, incompressible laminar flow is assumed for the *in-situ* strata water. Three different grid configurations are used, with total grid counts of 4,200, 55,000, and 216,000 respectively, to simulate the temperature distribution within the coring device during the coring process.

The temperature monitoring point at the bottom outer corner of the core is selected for assessing grid independence. As shown in Fig. 4, it can be observed that when the number of grids is not less than 55,000, the temperature at the monitoring point remains relatively constant with respect to the number of grids. Therefore, the total number of grids is set to 55,000 for subsequent simulations.

The total number of grids is set to 55,000, the coring speed is set to 2.5 m/s, and three time steps of 4.0, 2.0 and 0.1 s are set to simulate the temperature field distribution of the corer during the coring process, respectively. The temperature monitoring point at the bottom outer corner of the core was selected for assessing the independence of the time step. As shown in Fig. 5, it can be observed that the temperature of the monitoring point remains relatively unchanged when the time step is not greater than 2.0 s.

In summary, the total number of grids for numerical simulation is set to 55,000, and the time step is set to 2.0 s for subsequent analysis.

5. Results and discussion

5.1 Temperature variation law of the core during the coring process

Fig. 6 presents the temperature contour plots of four cross-sections from the top to the bottom of the ITP-coring tool when raised to the surface after coring completion. As shown in the figure, the passive thermal insulation material demonstrates a significant thermal insulation effect. The temperature within the insulation layer remains around 120 °C, while the core temperature maintains approximately 140 °C, with the maximum core temperature reaching 142 °C. The core temperature gradually decreases from the top to the bottom.

To further understand the temperature variation law of the core during the coring process, temperature monitoring lines were placed axially at the location where the radial temperature decline of the core is the greatest (i.e., at a model radius of 0.025 m). From Fig. 7, it is evident that during the coring process, the temperature decline rate at the bottom of the core is consistently greater than that at the top, resulting in an increasing temperature difference along the height dire-

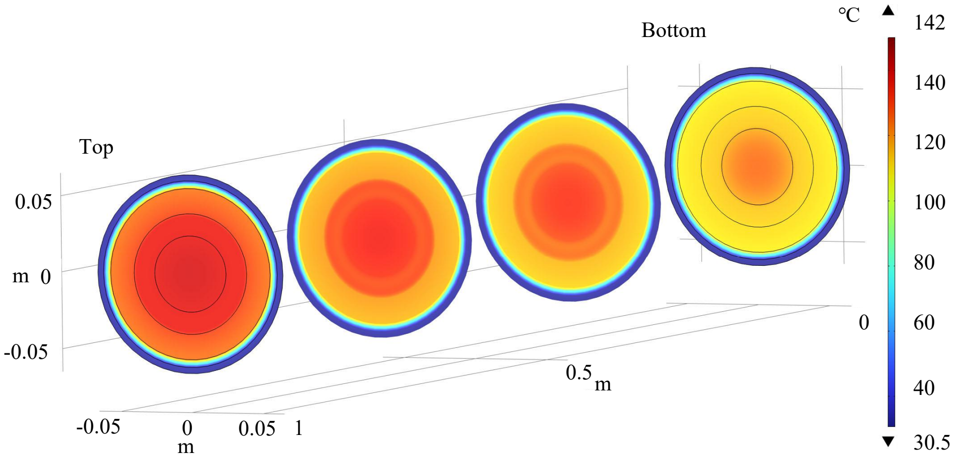

Fig. 6. Temperature distribution of the core when lifting to the ground.

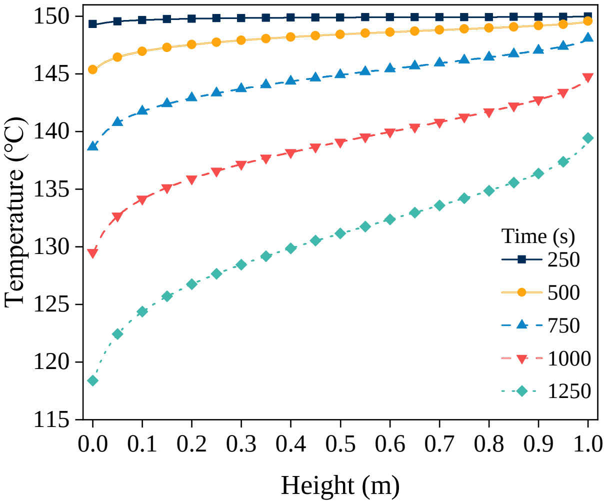

Fig. 7. Core temperature change curve along the axial direction at 0.025 m radius.

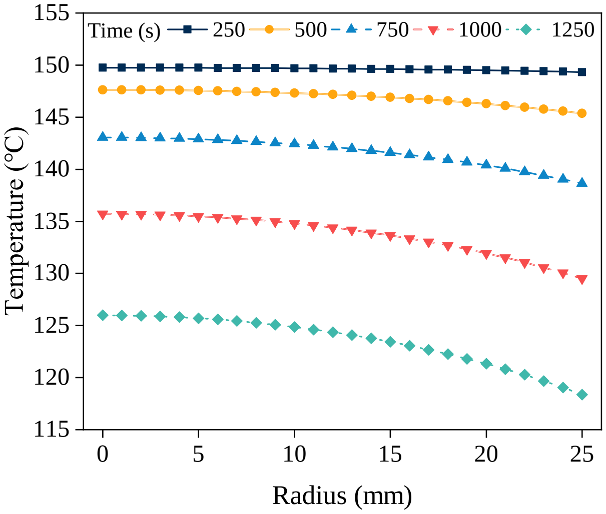

Fig. 8. Temperature change curve along the radial direction of the core at 0 m height.

ction. When the core is lifted to the ground, the temperature difference between the bottom and top of the core reaches its maximum value of 21 °C, indicating an axial temperature gradient of 21 °C/m.

A radial temperature monitoring line was arranged at the location where the axial core cooled down the most (i.e., at a model height of 0 m). From Fig. 8, it can be observed that the temperature variation amplitude along the radius of the core is relatively small, with the temperature gradually decreasing outward along the radial direction. When the core is lifted to the ground, the maximum temperature difference along the radial direction of the core does not exceed 7.7 °C, indicating that the radial temperature gradient is no more than 308 °C/m.

From the above description of the core temperature changes along the axial and radial directions, it is found that the change rule of core temperature along the two directions in the coring process is obviously different. The temperature difference of the core in the axial direction reaches 21 °C, while it is only 7.7 °C in the radial direction, and the maximum temperature difference on the core is 28.7 °C. However, the axial temperature gradient (21 °C/m) is much smaller than the radial temperature gradient (308 °C/m), with a difference of nearly 15 times, which indicates that the core mainly dissipates heat along the radial direction.

5.2 Effect of the natural convection of strata water on core temperature during ITP-coring

During the deep rock ITP-coring process, as the strata temperature decreases, the strata water inside the coring tool flows due to the temperature difference between the inner and outer sides. To understand the flow law of strata water, axial velocity monitoring lines (Fig. 9(a)) and radial velocity monitoring lines (Fig. 9(b)) were arranged respectively. The velocity profiles were obtained at different directions of the strata water when the core is lifted to the ground. The axial velocity from the bottom end to the top is positive, and the radial velocity from the core to the outside is also positive.

The axial velocity variation curves along the axial direction are shown in Fig. 10(a). The axial velocities on lines 1 and 3 initially increase and then decrease. For the same radius, the axial velocity on line 3 is almost twice that of line 1, while the

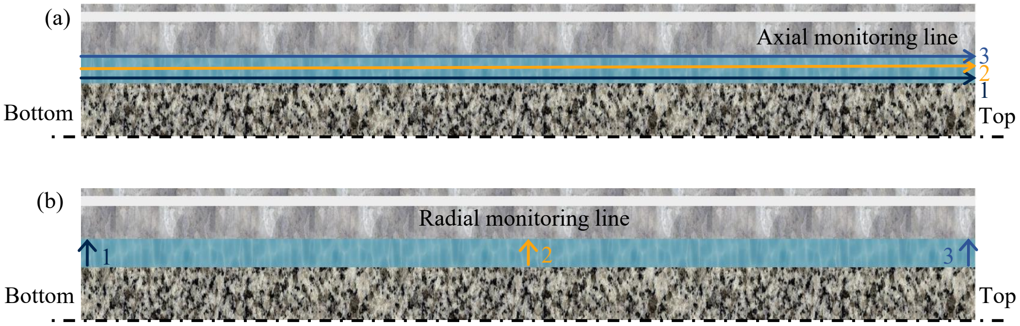

Fig. 9. Velocity monitoring line layout diagram. (a) Axial and (b) radial monitoring line.

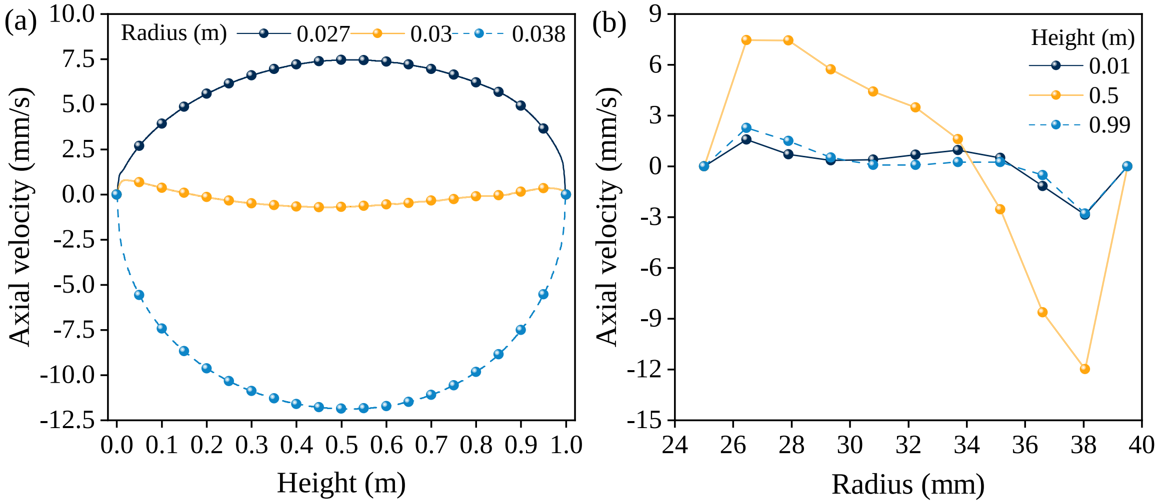

Fig. 10. Curves of (a) axial velocity along the axial and (b) radial monitoring lines.

axial velocity on line 2 is essentially zero. The axial velocity variation curves along the radial direction are shown in Fig. 10(b). The axial velocities on lines 1 and 3 are essentially zero, while the axial velocity on line 2 increases from zero, peaks near the midpoint of the line, decreases to zero, and then produces velocity in the negative axial direction, which initially increases and subsequently decreases to zero.

The radial velocity variation curve along the axial direction is shown in Fig. 11(a). The strata water only exhibits radial movement near the top and bottom ends and there is a clear boundary layer effect. At the boundaries near the top and bottom ends, the radial velocity is initially zero, which then sharply rises to around 1 mm/s, followed by a steep drop back to nearly zero. The radial velocity variation curve along the radial direction is depicted in Fig. 11(b). For lines 1 and 3, the radial velocity of the strata water first increases and then decreases. The radial velocity on line 2 remains essentially zero.

From the above results, it can be deduced that during the coring process, as the ambient temperature decreases, the temperature drop of the outer layer strata water is greater than that of the inner layer. Consequently, density differences between the inner and outer strata water generate buoyancy, leading to natural convection within the confined space. The flow is particularly intense near the boundaries of the core barrel on both sides. As seen in Fig. 12, the strata water in the geometric model exhibits counterclockwise flow. At the two end faces, the strata water primarily undergoes radial flow, while it mainly undergoes axial flow at the two lateral faces, both showing clear boundary layer effects. The axial velocity on the outer side is twice that on the inner side, which is primarily due to the higher density of the strata water on the outer side, while the strata water on the inner side flows towards the top due to the counter-gravity effect.

Due to the counterclockwise natural convection of strata water, the heat loss rate at the bottom of the core is the highest, leading to the greatest cooling rate at the exterior of the core's bottom. This exacerbates the temperature non-uniformity within the core, resulting in a significant temperature gradient along the axial direction.

The purpose of ITP-coring is to ensure that the overall temperature of the obtained core remains uniform at the deep *in-situ* temperature state; therefore, it is necessary to suppress the occurrence of natural convection of strata water. Active thermal insulation is the key to maintaining the core at *in-situ* temperature, which should be optimized in conjunction with the law of natural convection of strata water on core temperature uniformity. For example, the active thermal insulation heating frequency may be set to correlate with the ambient temperature, increasing the heating frequency as the

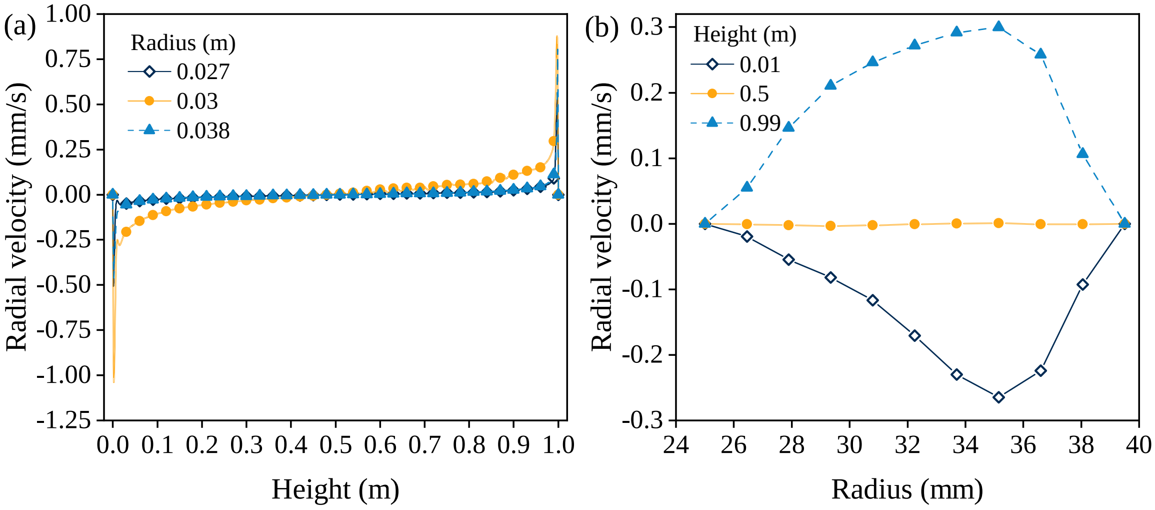

Fig. 11. Curves of (a) radial velocity along the axial and (b) radial monitoring lines.

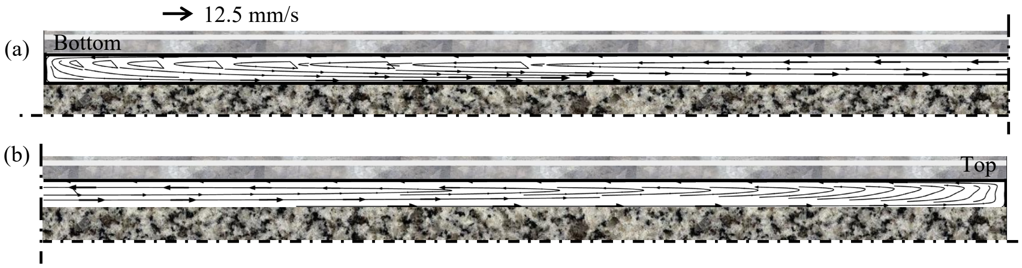

Fig. 12. Streamline diagram near the (a) bottom and (b) top of the corer.

temperature difference between the core and the ambient temperature becomes greater.

6. Conclusions

Deep rock ITP-coring is crucial for obtaining the physical parameters of deep-seated rocks. To deeply understand the influence of strata water on core temperature during coring, numerical simulations considering natural convection were conducted to elucidate the temperature variation laws of the core during coring. The following main conclusions could be drawn:

1) Under conditions of 150 °C *in-situ* temperature, 4 °C/100 m geothermal gradient, and 2.5 m/s core lifting speed of the deep rock, only passive temperature-preserved coring to the ground is employed. During the coring process, the density difference caused by temperature changes in the strata water inside the coring tool leads to buoyancy, thus generating counterclockwise natural convection within the confined space.
2) The temperature difference along the axis of the core is 21 °C, with a temperature change rate of 21 °C/m per unit length; along the radial direction, the temperature difference is 7.7 °C, with a temperature change rate of 308 °C/m per unit length. The greatest temperature drop occurs on the outer side of the bottom of the core. The counterclockwise natural convection of strata water exacerbates the temperature difference along the core axis, intensifying the unevenness of the core temperature.
3) Based on the relationship between strata water and core temperature during ITP-coring, it is recommended to compress the space between the core and the inner pipe as much as possible during coring and also to increase the water-blocking mechanism to reduce the entry of strata water into the coring apparatus. Additionally, during the coring process, as the ambient temperature gradually declines, the frequency of active thermal insulation heating should be gradually increased to reduce the temperature difference between the inner and outer sides of the strata water, suppress the occurrence of natural convection, mitigate the influence of natural convection of strata water on the core temperature, and thus maintain a more uniform temperature of the core in its deep *in-situ* state.

This study delves into the natural convection patterns of strata water inside the coring apparatus and its impact on core temperature variation. Future research should focus on exploring quantitative methods to control active thermal insulation modules effectively to ensure uniform core temperature distribution. Overall, it is important to prioritize the impact of strata water within the coring apparatus on temperature-preserved coring. Via an optimized design of the coring apparatus and active thermal insulation, efforts should be made to ensure the maintenance of stable and uniform temperature of the core in its original *in-situ* state.

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Conflict of interest

The authors declare no competing interest.

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