STUDY ON HEAT TRANSFER MODEL THEORY AND NUMERICAL SIMULATION USED IN DEEP ROCK IN-SITU TEMPERATURE-PRESERVED CORING

by

Zi-Jie WEI[a], Cong LI[a,b*], Bo YU[c], Wei LUO[d], and Jian-Ping YANG[e]

[a]State Key Laboratory of Hydraulics and Mountain River Engineering,
College of Water Resource and Hydropower, Sichuan University, Chengdu, China
[b]Guangdong Provincial Key Laboratory of Deep Earth Sciences and
Geothermal Energy Exploitation and Utilization, Institute of Deep Earth Sciences and Green Energy,
College of Civil and Transportation Engineering, Shenzhen University, Shenzhen, China
[c]School of Mechanical Engineering, Sichuan University, Chengdu, China
[d]Jinshi Drilltech Co. Ltd., Tangshan, China
[e]College of Polymer Science and Engineering, Sichuan University, Chengdu, China

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Deep rock in-situ temperature-preserved corers are important when evaluating and developing deep resources. The core temperature change law is the basis for realizing thermal insulation coring during coring, and it is explored from the perspective of the theoretical heat transfer model and numerical simulation. The results indicate that at a 150 °C deep rock temperature, the theoretical calculation results only have a difference of approximately 4% compared with the minimum value of numerical simulation. With increasing core lifting speed, the core cooling range decreases, the power demand for active thermal insulation decreases. A core lifting speed of 2.5 m/s can meet the lower energy supply requirements and engineering costs at the same time. The research results can provide theoretical and technical support for deep resource mining.

Key words*: deep rock in-situ temperature-preserved coring, theoretical heat transfer model, numerical simulation*

Introduction

With continuous increases in the total consumption of mineral resources, shallow resource reserves have gradually decreased, and attention has been given to mineral exploitation in deep earth [1]. The mining of deep resources has become the new normal [2-4]. However, the exploitation of deep underground resources often occurs in environments with high ground stress and high ground temperature. Compared with shallow rocks, the physical and mechanical properties of deep rocks are greatly changed during coring [5-9]. Temperature is an important factor that affects rock mechanics and other properties [10-13]. If the rock properties obtained at normal temperature are used in deep engineering, serious engineering problems can result. However, traditional continental drilling technology is unable to maintain the tempera-

*Corresponding author, e-mail: licong@stu.scu.edu.cn

ture of deep continental rocks, and the distortion of temperature leads to incomplete scientific acquisitions of resource reserves and gas phase information.

At present, deep-sea coring studies were the first to carry out technical research on preserving the in-situ environment during sediment coring [14]. However, these studies mainly focused on maintaining the in-situ environmental pressure and less on maintaining the in-situ environmental temperature. In addition, similar to low temperature coal gas desorption technology, based on the characteristics of deep-sea sediments, deep-sea sediment coring places the core in a freezer to maintain the in-situ temperature. These technologies include the multiple autoclave corer (MAC) and the dynamic autoclave piston corer (DAPC) [15]. Only a few deep-sea samplers have included thermal insulation technology. Both the pressure temperature core sampler (PTCS) and the high pressure temperature corer (HPTC) adopt a double-layer inner tube for thermal insulation. The developed pressure and temperature preservation system (PTPS) uses a vacuum layer with an inner surface sprayed with a thermal insulation material and an outer surface sprayed with an anti-UV coating [16]. The fidelity coring device developed by Zhejiang University and the First Institute of Oceanography adopted a thermal insulation coating [17]. However, the aforementioned coring device is only used for deep-sea sediment core extraction, and the environment it faces is significantly different from that of deep rock thermal insulation core. At the same time, due to the complexity of the earth's deep environment, it is very difficult and costly to verify the thermal insulation effect of the designed thermal insulation corer directly by means of tests. Therefore, in the design stage, the thermal insulation effect of the corer should be tested through a theoretical heat transfer model and numerical simulation, which can effectively shorten the design feedback period and improve the design efficiency [18].

Based on traditional deep-sea thermal insulation coring technology, this paper deduces a passive thermal insulation theoretical heat transfer model applicable to an in-situ temperature-preserved corer (ITP-corer) [19, 20]. We further study a numerical heat transfer model considering natural convection and compare the cooling laws of the two approaches under different core lifting speeds for verification. The final research results can provide theoretical guidance for the design of the ITP-corers.

Theoretical heat transfer model based on ITP-coring

Overview of the coring process

Deep land exists in a complex *three high* state [1, 2]. High ground temperature is one of the main problems faced by ITP-coring. The average temperature gradient in deep land is 4 °C per 100 m [1]. Therefore, this research group proposes a scheme of active thermal insulation combined with passive thermal insulation. Through passive thermal insulation, the core heat dissipation power is reduced, thus reducing the power demand for active thermal insulation. Combining passive thermal insulation with active thermal insulation can maintain the in-situ temperature during the thermal insulation coring process under a deep small space [19, 21]. Assuming that the ground temperature gradient is ΔT °C per 100 m. The change in the ground temperature, T_a, at the time of core lifting t is given:

$$T_a = T(0) - \left(\frac{vt}{6000}\right)\Delta T \tag{1}$$

where T_a is the formation temperature, $T(0)$ – the initial one, v – the core lifting speed, t – the time, and ΔT – the ground temperature gradient.

Physical heat transfer model in ITP-coring

Before establishing the heat transfer model of the ITP-corers, the following assumptions should be made:

– 1. The contact thermal resistance between the materials of each layer and the heat storage capacity of the materials comprising the corer are not considered, that is, the heat flow during the core heat dissipation process is constant and does not change with the radius.
– 2. Only consider the heat transfer of the core along the radial direction of the corer during the core lifting process (*i.e.*, considered a 1-D heat dissipation problem).
– 3. The sleeve is ignored, and it is considered that the core and formation water are in direct contact with each other for heat conduction but do not experience mutual penetration.
– 4. In the heat dissipation process, it is considered that the corer temperature distribution is relatively stable in each extremely short time interval and is calculated as a quasi-steady state.

As shown in fig. 1, the corer within the core length is taken as the research object in this paper. Based on the previous coring assumptions, the ITP-corers can be generalized into the following parts. The dimension parameters of the simplified corer model are shown in tab. 1.

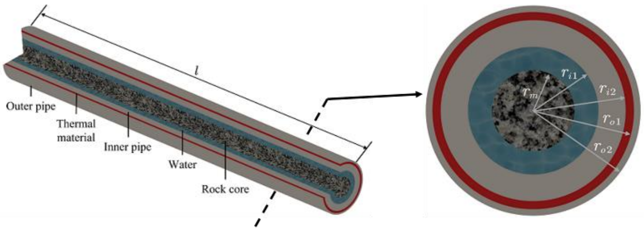

Figure 1. Simplified physical model of the corer

Table 1. Dimensional parameters of the simplified corer model

r_m [m]	r_{i1} [m]	r_{i2} [m]	r_{o1} [m]	r_{o2} [m]	l [m]
0.025	0.0395	0.056	0.061	0.065	1

Theoretical heat transfer model in ITP-coring

The ITP-coring can be affected by many factors (such as the ground temperature gradient, core lifting speed, *etc.*) during the core lifting process, which makes it impossible for the heat transfer process of the corer to maintain an absolute steady state. Based on the previous hypothesis – 4, the study at each extremely short time interval can be treated as a steady-state heat transfer process [19, 20].

According to the single-layer cylinder wall model, the radial cylinder wall thermal resistance R of the simplified physical model of the corer considering heat convection and heat conduction can reads:

$$R=\frac{1}{2\pi r_m l h_f}+\frac{1}{2\pi r_{i1} l h_f}+\frac{\ln(r_{i2}/r_{i1})}{2\pi l\lambda_g}+\frac{\ln(r_{o1}/r_{i2})}{2\pi l\lambda_c}+\frac{\ln(r_{o2}/r_{o1})}{2\pi l\lambda_g}+\frac{1}{2\pi r_{o2} l h_a} \tag{2}$$

where λ_g and λ_c are the thermal conductivity of the metal cylinder and insulation material, and h_f and h_a are the convective heat transfer coefficients between the inner and outer fluid and the inner and outer metal cylinder walls, respectively. For the details of other parameters, see tab. 1.

If the water temperature at any time is $T(t)$, the water temperature in the cabin is uniform. According to the law of energy conservation, we arrive at:

$$m_w c_w[T_o - T(t)] = \int \frac{T(t)-T_a}{R}\mathrm{d}t \tag{3}$$

where m_w and c_w are the mass of water and the specific heat capacity, $T(t)$ and $T(0)$ are the temperature and initial temperature of formation water at any time, T_a – the ambient temperature, R – the total thermal resistance, and t – the time.

Using the initial conditions and substituting (1) into (3) and making the deformation, the fluid temperature at any time can be obtained:

$$T(t)=\frac{v\Delta T}{100}\left[m_w c_w R\left(1-\mathrm{e}^{-\frac{t}{m_w c_w R}}\right)-t\right]+T(0) \tag{4}$$

To design the active insulation coring according to the passive insulation effect, the heat loss during the core lifting process is suggested:

$$Q(t)=m_w c_w \Delta T(t) \tag{5}$$

where $\Delta T(t)$ is the temperature change during core lifting, Q – the heat lost, and t_1 and t_2 are the times before and after heat dissipation, respectively.

Numerical heat transfer simulation based on ITP-coring

According to the simplified physical model of the corer, the two ends of the coring device are set to be insulated, and the heat transfer problem of the coring device is converted into a 2-D problem. Since the temperature distribution of the corer can be considered symmetrical about the core center, half of the model can be used for analysis, and the symmetry axis is set as adiabatic. The dimensional parameters of the numerical heat transfer model are the same as those of the theoretical model, and the geometric model is shown in fig. 2. The physical parameters used for modeling are shown in tabs. 1 and 2. Marble is selected as the core, and conventional water is selected as the in-situ formation water.

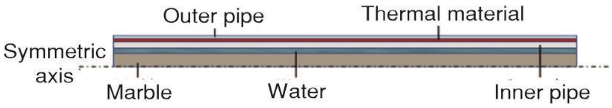

Figure 2. Numerical simulation geometric model

Table 2. Relevant physical property parameters

λ_3, λ_5 [Wm^{-1}K^{-1}]	λ_c [Wm^{-1}K^{-1}]	h_a [Wm^{-2}K^{-1}]
16.27	0.257008	1000.00
h_f [Wm^{-2}K^{-1}]	ρ [kgm^{-3}]	C_R [Jkg^{-1}K^{-1}]
50.00	2687.00	816.96

Based on the grid independence and time step verification, the number of grid divisions for numerical simulation is 55000, and the time step is 2.0 seconds. According to the analysis of the core temperature distribution, the lowest temperature point in the lower right corner of core is selected to analyze the temperature change law to control the overall core temperature.

Results and discussion

Variation law of core temperature during coring when adopting passive insulation

It is assumed that the coring formation temperature is 150 °C, the ground temperature gradient is 4 °C per 100 m, the ground temperature is 25 °C, and the coring depth is 3125 m. The core lifting speed *v* ranges from 1.5 m/s to 3.5 m/s. Five levels of core lifting speed are set to assess the influence of lifting speeds on core temperature during coring. Only passive insulation is considered.

Figure 3 shows the core temperature change curve under different core lifting speeds. With increasing core lifting speed, the time required for core lifting to the ground decreases, and the cooling range also decreases. For fig. 3(a), when the core lifting speed is the maximum value of 3.5 m/s or minimum value of 1.5 m/s, respectively. The core lifting time is 893 seconds or 2084 seconds, the temperature drop is 26.71 °C or 51.36 °C, and the temperature drop ratio is 17.81% or 34.24%. Figure 3(b) shows the numerical simulation temperature change law which is similar to the theoretical calculation.

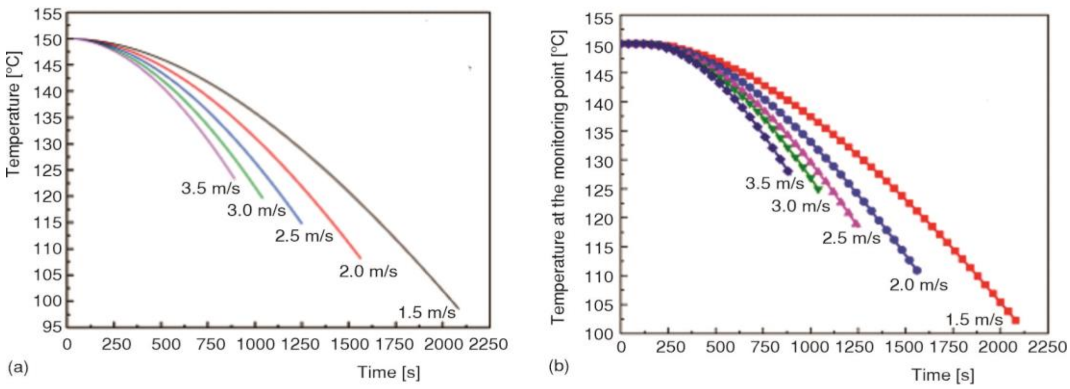

Figure 3. Variation curve of core temperature with core lifting time under different core lifting speeds; (a) theoretical calculation and (b) numerical simulation

Table 3 lists the temperature comparison between the results of theoretical calculation and numerical simulation under different core lifting speeds when lifting the core to the ground. Table 3 shows that the difference between the two calculation results is approximately 5 °C, the maximum difference is 5.2 °C, the minimum difference is 2.7 °C, indicating that the numerical simulation results are in good agreement with the theoretical calculation.

Table 3. Comparison of core temperature between theoretical calculation and numerical simulation

Different core lifting speeds, [ms^{-1}]	1.5	2.0	2.5	3.0	3.5
Theoretical calculation, [°C]	98.64	108.18	114.81	119.61	123.29
Numerical simulation, [°C]	102.12	110.80	118.42	124.83	127.42

Figure 4 shows the change in core temperature with lifting speed at different core lifting times.

Variation law of core temperature during coring when combining active insulation

Through the aforementioned temperature drop curve, it is found that it is necessary to combine active insulation measures to maintain the in-situ temperature. Taking a temperature fluctuation range of less than 3% as an example, when the temperature drop ratio under each core lifting speed reaches 3%, it is assumed that the active insulation equipment will immediately increase the temperature to the in-situ temperature. The calculation results are shown in fig. 5.

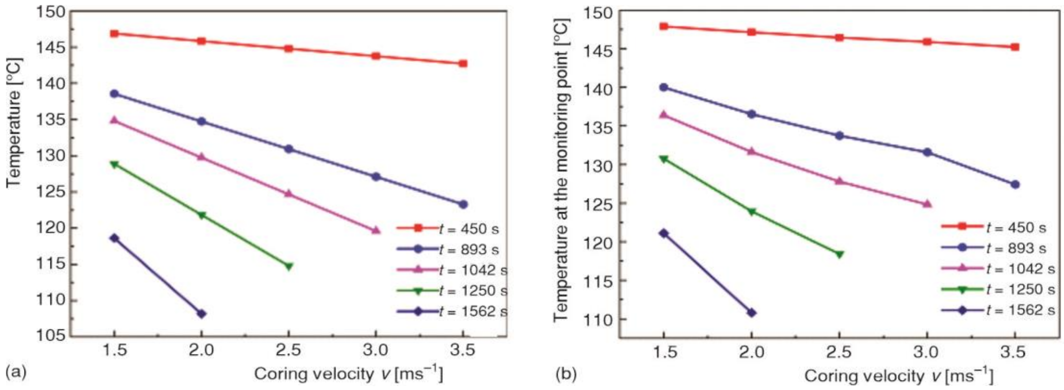

Figure 4. Variation curve of core temperature with core lifting speed at different times; (a) Theoretical calculation and (b) numerical simulation

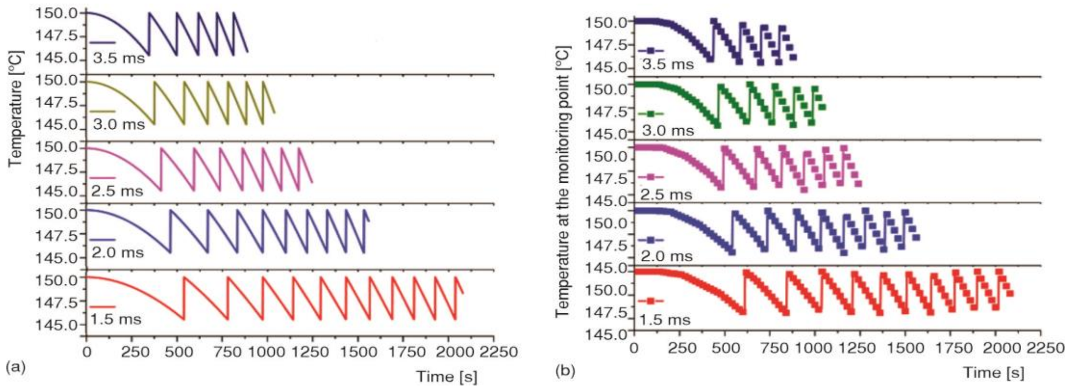

Figure 5. Variation curve of core temperature with core lifting time under different core lifting speeds when adopting active insulation; (a) theoretical calculation and (b) numerical simulation

Figure 6 shows the change of the total energy required for active insulation with the core lifting speed obtained by theoretical calculation and numerical simulation. The total energy required decreases with increasing core lifting speed. When the core lifting speed is 1.5-2.5 m/s, the reduction rate is large, which can effectively reduce the power demand of the active insulation of the corer. When the core lifting speed is 2.5-3.5 m/s, the reduction rate decreases, that is, the effect of reducing the active insulation power demand by increasing the core lifting speed is weakened.

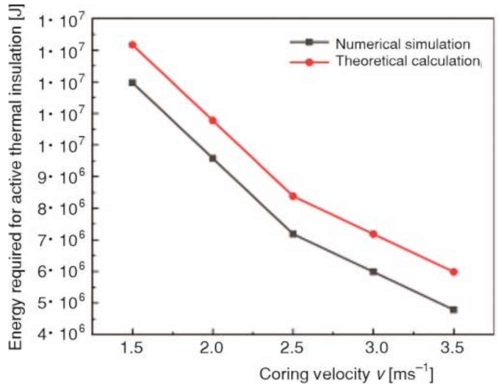

Figure 6. Curve of the total energy required for active insulation with core lifting speed

From the previous discussion, it can be seen that increasing the core lifting speed not only helps to improve the passive insulation effect but also reduces the power demand of active insulation. However, with the continuous increase in the core lifting speed, the effect of reducing the power demand is weakened. Therefore, based on the passive insulation materials considered and the corer generalized structure adopted by the simplified model, it is suggested to set the core lifting speed at 2.5 m/s in the actual core-taking process to reduce the engineering cost brought by the continuous improvement of the core lifting speed and improve the success rate of insulation coring while reducing the demand of active insulation power.

Conclusion

By calculating and simulating the variation law of core temperature during coring, the following conclusions are obtained. A theoretical heat transfer model that can meet the engineering requirements is proposed. The difference between the theoretical heat transfer model and numerical simulation results is approximately 4%, which indicates that the engineering applicability of the theoretical heat transfer model and the calculation process is relatively simple.

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Nomenclature

C_R – specific heat capacity, [$\mathrm{Jkg^{-1}K^{-1}}$]
c_w – specific heat capacity, [$\mathrm{Jkg^{-1}{}^\circ C^{-1}}$]
h_a – coefficient of forced convection, [$\mathrm{Wm^{-2}K^{-1}}$]
h_f – coefficient of natural convection, [$\mathrm{Wm^{-2}K^{-1}}$]
l – length of the corer, [m]
m_w – mass of water, [kg]
Q – heat lost, [J]
R – total thermal resistance, [$\mathrm{{}^\circ CW^{-1}}$]
r_{o1} – inside radius of outer pipe, [m]
r_{o2} – outside radius of outer pipe, [m]
r_{i1} – inside radius of inner pipe, [m]
r_{i2} – outside radius of inner pipe, [m]
r_m – radius of rock core, [m]
T_a – formation temperature, [°C]
$T(0)$ – initial formation temperature, [°C]
ΔT – ground temperature gradient, [°C/100 m]
$\Delta T(t)$ – temperature change during core lifting, [°C]
$T(t)$ – temperature of formation water, [°C]
t – time, [minute]
v – core lifting speed, [$\mathrm{ms^{-1}}$]

Greek symbols

λ_g – thermal conductivity of metal cylinder, [$\mathrm{Wm^{-1}K^{-1}}$]
λ_c – thermal conductivity of insulation material, [$\mathrm{Wm^{-1}K^{-1}}$]
λ_3 – thermal conductivity of inner metal cylinder, [$\mathrm{Wm^{-1}K^{-1}}$]
λ_5 – thermal conductivity of outer metal cylinder, [$\mathrm{Wm^{-1}K^{-1}}$]
ρ – density of rock corer, [$\mathrm{kgm^{-3}}$]

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