DESIGN AND STRENGTH ANALYSIS OF THE PASSIVE THERMAL INSULATION STRUCTURE OF A DEEP ROCK IN-SITU THERMAL INSULATION CORING SYSTEM

by

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The zero-sum game between the strength of deep in-situ thermal insulation coring structures and the performance of passive thermal insulation materials seriously restricts the exploration and development of deep resources. In this paper, an innovative thermal insulation coring structure based on passive thermal insulation material is designed, and a strength analysis of thermal insulation material is carried out based on the elastic theory of multilayer cylinders, which reveals the stress distribution and deformation law of thermal insulation material in a deep in-situ environment. The reliability of the results is verified by comparisons between the numerical simulation and theoretical derivation. The results show that for deep coring environments of 150 °C and 140 MPa, the wall thickness and diameter of the corer can be greatly reduced by directly coating the insulation material on the surface of the core barrel. This paper can provide a reference for the design and engineering application of deep rock in situ thermal insulation coring systems.

Key words*: deep in-situ thermal insulation coring, thermal insulation material, mechanical properties, numerical simulation*

Introduction

With the gradual depletion of shallow earth resources, it has become inevitable for the development of resources to go deeper [1-3]. However, most of the existing research on deep resource development is based on the ordinary core, ignoring the influence of engineering disturbances and in situ occurrence environments on the physical and mechanical properties of rock [4-9], which have extremely limited the significance of engineering guidance, leading to frequent disasters and accidents during the mining process. Deep resource exploitation is faced with many problems, such as engineering difficulties, high cost, and difficult disaster prediction, which seriously threaten the safety and efficiency of deep resource mining. The rock core of deep resources is always in a high temperature state. Related studies have shown that changes in

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temperature have an obvious influence on the physical, chemical and structural characteristics of rock, leading to the porosity and permeability of rock change obviously and the creep characteristics and seepage laws are considerably changed [10-12], which causes serious distortions in deep oil and gas reserve evaluations. Therefore, it is necessary to develop in situ thermal insulation coring equipment for deep rock exploration and extraction [13].

Various types of thermal insulation coring equipment have been developed at home and abroad, but they are mainly used in deep-sea sediment and combustible ice sampling, and there are few reports on the thermal insulation coring of deep hard rock. The pressure core barrel (PCB), pressure core sampler (PCS), fu-gro pressure corer (FPC), and HYACE rotary corer (HRC) coring tools previously developed in the USA, Japan, and EU do not have insulation functions [14-16]. The First Institute of Oceanography uses a thermal insulation and pressure preservation cylinder and a core pipe to form a double-layer structure, and its passive thermal insulation measures are formed by vacuuming and spraying heat insulation paint and an anti-ultraviolet coating on the inner and outer surfaces [17]. The Institute of Exploration Technology, Chinese Academy of Geological Sciences is designed with a double-layer rock core barrel, which is filled with polyurethane insulation material for passive thermal insulation [18]. The Great Wall Drilling Engineering Co., Ltd. takes passive insulation measures with the vacuum heat insulation of detachable double-layer aluminium alloy tubes and stainless steel liners [19]. The passive heat preservation method of the Beijing Research Institute of Prospecting Engineering adopts a vacuum tube structure design. After the two ends of the sampling pipe are welded, the air between the two layers of pipes is drained to slow down the exchange of heat inside and outside the sampling pipe [20].

In summary, the existing passive thermal insulation measures of the coring device are mainly vacuuming in the double pipe interlayer or filling the insulation material in the interlayer. The maximum design water depth is 3000 m. For deep coring environments with high temperatures and hydrostatic pressures of 150 °C and 140 MPa, if this method is still adopted, the wall thickness and diameter of the coring device will be greatly increased. As a result, the obtained core diameter is reduced, which is contrary to the fact that the larger the core diameter is, the better the stratigraphic information obtained. Therefore, this paper innovatively designs a thermal insulation coring structure based on passive thermal insulation materials. Through a strength analysis of the passive thermal insulation structure of the deep rock in situ insulation coring system, it is verified that this kind of structure can greatly reduce the wall thickness and diameter of the coring equipment and improve the stress condition of thermal insulation materials on the basis of meeting the material strength requirements of a deep coring environment.

The passive thermal insulation structure design

Aiming at the special application environment of high temperature and hydrostatic pressure at depth, we identified an epoxy resin-based hollow bead composite material as the passive thermal insulation material for the coring device based on the thermal insulation mechanism of the thermal insulation material. Meanwhile, based on an independently developed deep rock in situ thermal insulation and coring system test device, the applicability of this insulation material in a deep temperature-pressure coupled coring environment (150 °C, 140 MPa) was verified [21]. Based on this kind of thermal insulation material, this paper designs a thermal insulation core structure, that is, the passive thermal insulation material is directly coated on the surface of the core barrel, and a composite thermal insulation structure means that a thin-walled outer pipe is added around the insulation layer, as shown in fig. 1.

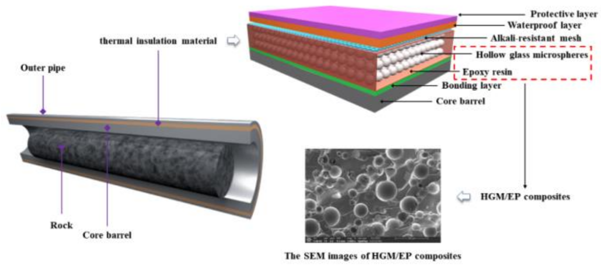

Figure 1. The passive thermal insulation structure of a deep rock in-situ thermal insulation coring system

The insulation layer is composed of an adhesive layer, epoxy resin base hollow bead composite material, acid- and alkali-resistant mesh cloth, waterproof layer and protective layer. By wrapping the core barrel with thermal insulation material with low thermal conductivity, the heat exchange rate between the rock core and the external environment is reduced, and the temperature loss of the rock core in situ is reduced. To avoid internal seepage of the drilling fluid caused by surface cracks or other reasons from the insulation material, a waterproof and anti-corrosion treatment is applied after the insulation material is fully solidified to maintain an excellent insulation effect.

Strength analysis of the passive thermal insulation structure

Mechanical model and calculated parameters

According to the designed passive thermal insulation structure of the deep rock in situ thermal insulation and coring system, a mechanical model is established, fig. 2. In the figure, R_1 is the inner radius of the core barrel, R_2 is the inner radius of the insulation layer, R_3 is the inner radius of the outer pipe, and R_4 is the outer radius of the outer pipe. The p is the uniform pressure acting on the inner wall of the core barrel (R_1 = 39.5 mm, R_2 = 55 mm, R_3 = 60 mm, R_4 = 64 mm, p = 140 MPa).

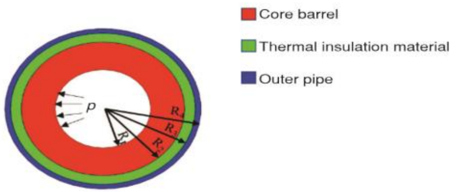

Figure 2. Mechanical model of the passive thermal insulation structure

The insulation layer and outer pipe are in an environment of high temperature and hydrostatic pressure during the core-taking operation. 35CrNi3MoVR is selected as the material for the core barrel and outer pipe, and the insulation layer is an epoxy resin-based hollow glass bead composite insulation material. The elastic modulus of the core barrel and outer pipe at 150 °C is E_1 = 200 GPa, the Poisson's ratio μ_1 = 0.3, and the yield strength of the material at 150 °C is σ_{s1} = 857 MPa, which conforms to the ideal elastic-plastic constitutive relationship. At 150 °C and 140 MPa hydrostatic pressure, the elastic modulus E_1 = 1000 GPa and the Poisson's ratio μ_1 = 0.38. The uniaxial compressive strength of the insulation material is σ_b = 55 MPa and the uniaxial tensile strength is σ_s = 5 MPa.

Stress distribution of the passive thermal insulation structure

The passive thermal insulation structure subjected to uniform internal pressure can be regarded as a combined cylinder composed of a core barrel, insulation layer, and outer pipe sleeve, which has no nesting pressure after nesting in theory and can be simplified as an axisymmetric plane strain problem.

Therefore, the core barrel stress is:

$$\sigma_{r1} = \frac{A_1}{r^2} + 2C_1 = -4.2009 \cdot 10^5 \frac{1}{r^2} + 129.246 \tag{1}$$

and

$$\sigma_{\theta 1} = -\frac{A_1}{r^2} + 2C_1 = 4.2009 \cdot 10^5 \frac{1}{r^2} + 129.246 \tag{2}$$

where σ_{r1} is the core barrel radial stress, $\sigma_{\theta 1}$ – the core barrel circumferential stress, and r – the distance between the stress point and the axis of the cylinder.

The thermal insulation layer stress is:

$$\sigma_{r2} = \frac{A_2}{r^2} + 2C_2 = -7.8263 \cdot 10^3 \frac{1}{r^2} - 7.04 \tag{3}$$

and

$$\sigma_{\theta 2} = -\frac{A_2}{r^2} + 2C_2 = 7.8263 \cdot 10^3 \frac{1}{r^2} - 7.04 \tag{4}$$

where σ_{r2} is the thermal insulation layer radial stress and $\sigma_{\theta 2}$ – the thermal insulation layer circumferential stress.

The stress of the outer pipe is:

$$\sigma_{r3} = \frac{A_3}{r^2} + 2C_3 = -2.\ 7392 \cdot 10^5 \frac{1}{r^2} + 66.875 \tag{5}$$

and

$$\sigma_{\theta 3} = -\frac{A_3}{r^2} + 2C_3 = 2.\ 7392 \cdot 10^5 \frac{1}{r^2} + 66.875 \tag{6}$$

where σ_{r3} is the outer pipe radial stress and $\sigma_{\theta 3}$ is the outer pipe circumferential stress.

According to the stress expression, it can be seen that due to the different materials of the three parts of the passive thermal insulation structure, the circumferential stress will suddenly change at the interface between the core barrel and the insulation layer and between the insulation layer and the outer pipe. However, the radial stress is continuously distributed and reaches the maximum at the inner wall of the core barrel, gradually decreases outward, and approaches zero on the outer wall of the outer pipe. At $r = R$ on the inner wall of the core barrel, σ_r = 140 MPa, at the contact interface $r = R_2$ between the core cabin and insulation layer, σ_r = 9.63 MPa

According to the von Mises yield failure criterion, we can obtain:

$$\frac{2}{\sqrt{3}} R_{eL} = 989.58\text{MPa} > \sigma_\theta - \sigma_r = 538.49\text{MPa} \tag{7}$$

where the R_{eL} is the material yield strength.

So the core barrel and outer pipe are in an elastic state. The insulation layer is a brittle material, and the compressive property is much higher than its tensile property. The radial stress and circumferential stress are compressive stresses, and the insulation material's strength limit at failure is greater than the uniaxial compressive strength, so the insulation material will not be destroyed.

The physical equation of the plane strain problem is expressed:

$$\varepsilon_r = \frac{1-\mu^2}{E}\left(\sigma_r - \frac{\mu}{1-\mu}\sigma_\theta\right),\ \varepsilon_\theta = \frac{1-\mu^2}{E}\left(\sigma_\theta - \frac{\mu}{1-\mu}\sigma_r\right) \tag{8}$$

where μ is the Poisson's ratio and E is the elastic modulus. Here, eq. (8) has the general case considered in [22].

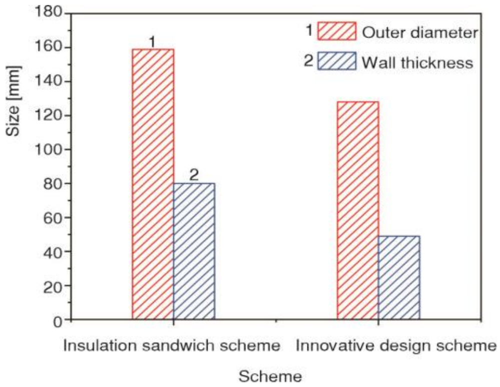

Figure 3. Size comparison between the insulation sandwich scheme and innovative design scheme

The radial strain on the outer wall of the core barrel is –0.057%, and the radial strain on the inner wall of the insulation layer is –0.59%, which is 10.35 times the deformation coordination strain condition. Therefore, this structure can meet the strength requirements and sealing requirements of materials in a deep coring environment.

If a passive thermal insulation structure is adopted, vacuuming or thermal insulation materials are filled in the interlayer, the outer diameter of the coring device is 159 mm, and the wall thickness is 80 mm. This structure increases the diameter and wall thickness of the coring device by 1.24 and 1.67 times, respectively, fig. 3.

Numerical simulation analysis of the passive thermal insulation structure

Model setup

Considering the symmetry of the passive thermal insulation structure and load, 1/4 of the structure was taken for study, and a numerical model was established according to the designed passive thermal insulation structure, fig. 4. The boundary conditions applied to the finite element model are: 140 MPa hydrostatic pressure is applied to the inner surface of the numerical model, the displacement constraint in the *x*-direction is applied parallel to the edge of the *Y*-axis, and the displacement constraint in the *y*-direction is applied parallel to the edge of the *X*-axis.

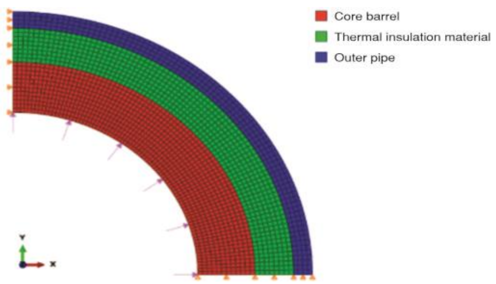

Figure 4. The numerical model

Numerical results

The radial stress cloud diagram and radial strain cloud diagram of the passive thermal insulation structure are shown in fig. 5.

The maximum radial stress appears at the inner wall of the core barrel, which is –139.7 MPa (theoretical value –140 MPa), and gradually decreases outward until the outer wall of the outer pipe, decreasing to –0.04 MPa (theoretical value 0 MPa). At the contact interface between the core barrel and the insulation layer: $r = R_2$, σ_r = 9.69 MPa (theoretical value –9.63 MPa). At the contact interface between the insulation layer and the outer pipe: $r = R_3$ and σ_r = 8.84 MPa (theoretical value –9.21 MPa).

According to the von Mises yield failure criterion, we can obtain:

$$\frac{2}{\sqrt{3}} R_{eL} = 989.58\text{MPa} > \sigma_\theta - \sigma_r = 624.7\text{MPa} \tag{9}$$

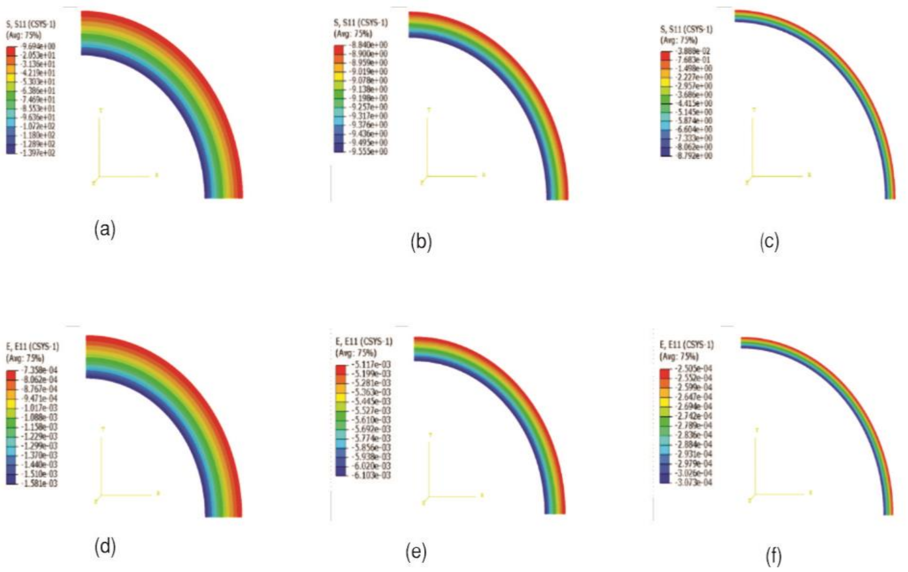

Figure 5. Radial stress cloud diagram and radial strain cloud diagram; (a) radial stress cloud diagram of the core barrel, (b) radial stress cloud diagram of the insulation layer, (c) radial stress cloud diagram of the outer pipe, (d) radial strain cloud diagram of the core barrel, (e) radial strain cloud diagram of the insulation layer, and (f) radial strain cloud diagram of the outer pipe

So the core barrel and the outer pipe were in an elastic state, and the radial stress and circumferential stress of the thermal insulation material were also compressive stress, which was consistent with the theoretical derivation results, figs. 6 and 7. It meets the strength requirements of material under a deep coring environment. The maximum radial strain that appears in the inner wall of the insulation layer is –0.61% (theoretical value –0.59%), the radial strain of the outer wall of the core barrel is –0.073% (theoretical value –0.057%), and the radial strain of the insulation layer is greater than that of the core barrel, so the insulation layer will not flake off and meet the sealing requirements, which is consistent with the theoretical results.

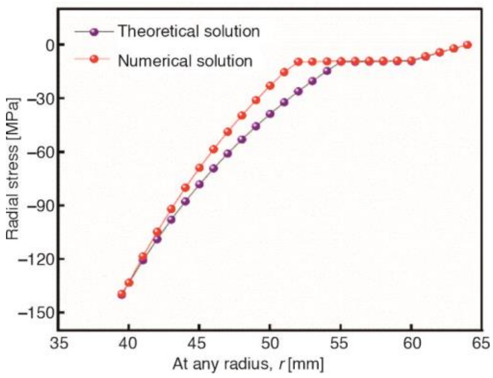

Figure 6. Comparison of theoretical solution and analytical solution of radial stress

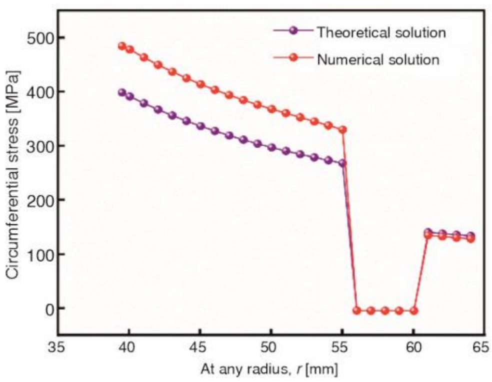

Figure 7. Comparison of theoretical and analytical solutions of axial stress

Conclusion

To address the wall thickness and diameter of corer passive thermal insulation structures significantly increasing in deep coring environments (150 °C, 140 MPa), a reduced rock core diameter was obtained. This article innovatively designs a thermal insulation coring structure based on a passive thermal insulation material and conducts a detailed analysis of its strength through theoretical derivation and numerical simulation. The composite thermal insulation structure in which the passive thermal insulation material is directly coated on the surface of the core barrel reduced the diameter and wall thickness of the corer by 1.24 times and 1.67 times, respectively, compared with the traditional structure. Based on the elastic theory of multilayer cylinders, the stress expression of the passive thermal insulation structure in the deep coring environment is established, which reveals the stress distribution and deformation law of thermal insulation material in the deep in-situ environment. By comparing the numerical simulation results with the theoretical derivation, the reliability of the results is verified. This thermal insulation structure can meet the material strength requirements of a deep coring environment (150 °C, 140 MPa).

Nomenclature

E – elastic modulus, [GPa]
R_{eL} – yield strength, [MPa]
r – distance, [mm]
σ_r – radial stress, [MPa]
σ_θ – circumferential stress, [MPa]

Greek symbols

μ – Poisson's ratio, [–]

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