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Thermodynamic Evolution and Semi-Empirical Correlations of Underground Compressed Air Energy Storage Caverns

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Abstract

Compressed air energy storage is a large-scale energy storage technology that bridges intermittent renewable energy and conventional power grids. The safety and operational efficiency of storage caverns are strongly governed by the coupled effects of geometric configuration, operating conditions, and material properties. In this study, a coupled Thermal-Hydro-Mechanical-Damage numerical framework is adopted and adapted to simulate turbulent flow, heat transfer, and gas behavior in the air domain, as well as heat conduction, mechanical deformation, and Darcy seepage in the surrounding rock. The multiphysical responses of the cavern system under a full charge-storage-discharge-storage cycle are systematically analyzed. Compared with linear caverns, full-circular caverns reduce the peak temperature and pressure by 13.85% and 6.46%, and exhibit a lower temperature change rate from 8.07 to 2.75 K/h, effectively alleviating thermal concentration. While the length diameter ratio decreases from 36.64 to 7.38, the peak wall temperature is reduced by about 7.12%, and the stress distribution becomes more uniform. Increasing the charging temperature significantly enhances thermal accumulation and enlarges the high-temperature zone, whereas increasing the convective heat transfer coefficient suppresses heat buildup. Improving the damage resistance of the surrounding rock reduces the extent of the damaged zone. Furthermore, temperature and pressure changing rates are introduced as dynamic indicators, and statistically evaluated semi-empirical correlations are established to describe the relative thermodynamic responses under varying geometric, operating, and material conditions. The proposed correlations are applicable within the investigated parameter ranges and can provide a rapid reference for preliminary cavern design screening and operating-condition assessment.

Keywords: Compressed air energy storage, Thermo-hydro-mechanical-damage coupling, Thermodynamic evolution, Structure optimization, Semi-empirical mathematical correlations

1 Introduction

Driven by the global energy transition, wind and solar power[1] have expanded rapidly with declining renewable-energy costs[2], increasing the demand for sustainable energy storage[3]. However, the intermittency, volatility, and geographic dispersion of these energy sources pose significant challenges to grid stability and limit utilization efficiency of renewable energy[4]. Therefore, large-scale long-duration energy storage (LDES) technologies have become essential for bridging intermittent renewable generation and grid-side demand. Among them, underground lined cavern-based compressed air energy storage (CAES) systems have attracted increasing attention due to its large storage capacity, long service life and high operational safety. When integrated with thermal energy storage, seawater desalination, and pumped hydro storage, CAES can form more efficient energy storage systems, playing a key role in ensuring grid stability and promoting the large-scale utilization of renewable energy[5]. Building on existing studies[6], fig.1 further supplements typical CAES projects worldwide and 11 demonstration projects in China. By 2024, the cumulative operational capacity of CAES in China has exceeded 500 MW, with under-construction and planned projects totaling over 5 GW, primarily concentrated in renewable energy-rich regions such as North China and Northwest China[7]. Globally, the cumulative operational capacity of CAES is approximately 466 MW, while the total capacity of under-construction and planned projects exceeds 10 GW, mainly concentrated in North America and Europe. CAES projects and research initiatives have achieved significant results in enhancing grid flexibility, improving renewable energy accommodation and supporting future low carbon power systems.

Nomenclature

P	Cavern pressure (MPa)	ν	Poisson's ratio
T	Surrounding rock temperature (K)	E	Young's modulus (GPa)
T_a	Air temperature (K)	λ	Thermal conductivity ($W / (m \cdot K)$)
V	Cavern volume (m^3)	α	Biot coefficient
D	Cavern diameter (m)	ρ	Rock density (kg / m^3)
C_p	Specific heat capacity ($J / (kg \cdot K)$)	d	Pore diameter (m)
ρ_a	Air density (kg / m^3)	G	Shear modulus (Pa)
h_c	Heat transfer coefficient ($W / (m^2 \cdot K)$)	α_g	Coefficient of thermal expansion ($1 / K$)
k	Permeability (m^2)	ε_{th}	Thermal strain (MPa)
$\dot{m}_c$	Inlet mass flow rate (kg / s)	ε_{eq}	Equivalent strain (MPa)
Z	Compressibility factor	q_T	Total heat flux (W)
ϕ	Porosity of the surrounding rock	ε_v	Volumetric strain (MPa)
v_g	Air seepage velocity (m / s)	Q_{cr}	Creep activation energy
P_0	Initial air pressure (MPa)	T_0	Initial air temperature (K)
m_c	Charging mass flow rate (kg / s)	m_d	Discharging mass flow rate (kg / s)
k_T	Temperature changing rate ($^{\circ}C/h$)	α_{shape}	Shape factor for temperature changing rate
k_P	Pressure changing rate (MPa/h)	β_{shape}	Shape factor for pressure changing rate

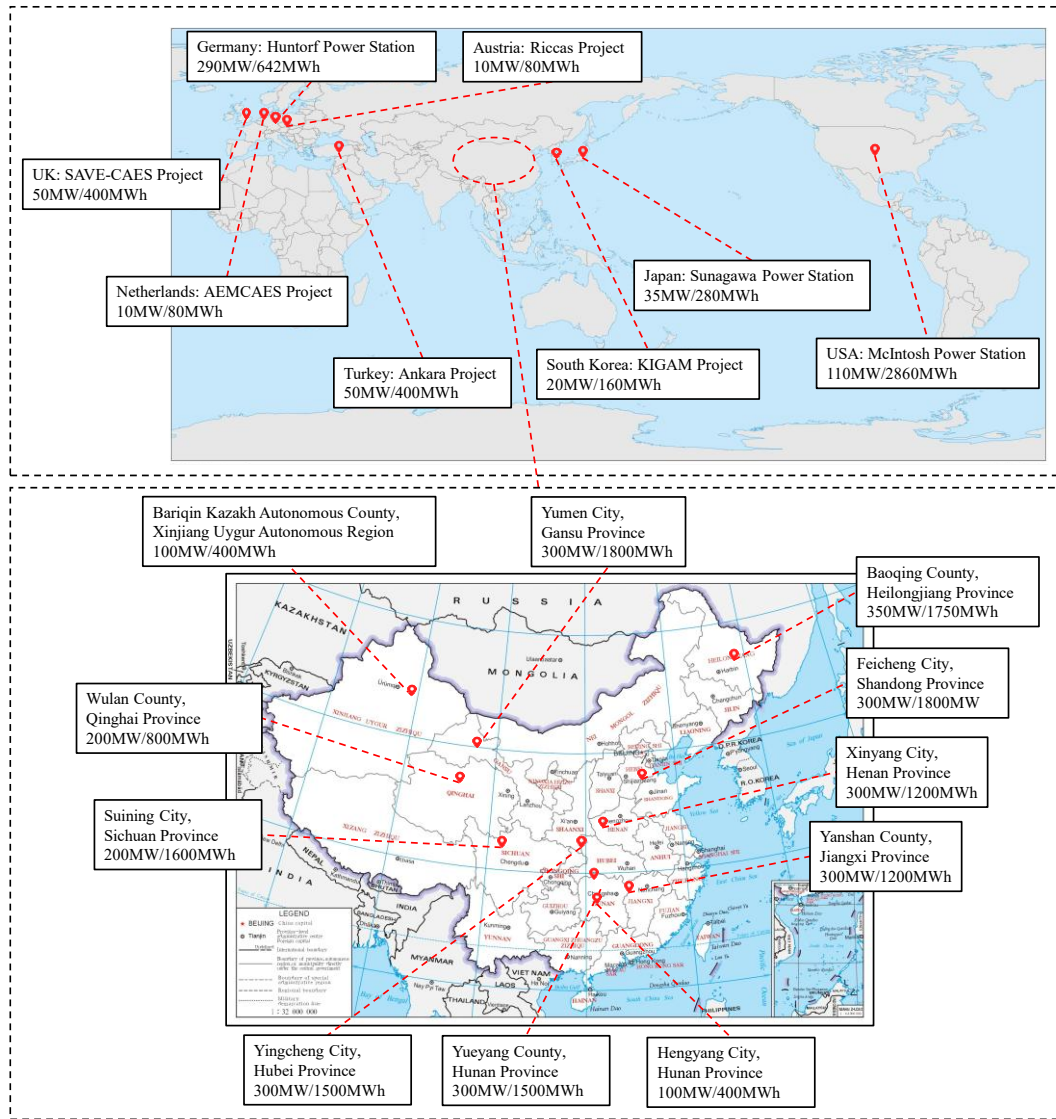


Fig.1. Global and China distribution of CAES

In recent years, CAES research has focused on variable-condition dispatch[8], hybrid system sizing and scheduling[9], and dynamic safety control[10], with emphasis on renewable-energy integration and grid regulation. However, less attention has been paid to the dynamic evolution of physical parameters within storage caverns during charging and discharging. In fact, the dynamic response of these physical parameters not only directly constrains the operational boundaries of the system but also affects the dispatchability of CAES[11], which constitutes a critical challenge in system-level scheduling. Underground air storage caverns typically operate in daily cycling mode, completing the full process of charging, storing, and discharging, during which coupled multiphysics interactions occur. This coupling mechanism is the primary cause of large fluctuations in temperature and pressure within the cavern. The operational state of the air storage cavern directly determines the stability of the overall energy storage system, and its thermodynamic characteristics are jointly governed by structural parameters[12], operating characteristics[13], and structural fatigue failure[14]. Temperature-dependent creep and thermal damage may further influence cavern stability under elevated-temperature conditions[15]. Based on these broad categories, eight representative factors are considered in this study, numerical simulations are conducted to quantify key dynamic responses and support structural and operational optimization.

Extensive numerical studies have investigated the multiphysical behavior of underground CAES caverns, particularly their thermo-mechanical and material-dependent responses. Miao et al[16] performed a thermo-mechanical analysis of mine roadway-type caverns, while Liu et al[17] investigated fatigue-damage accumulation under cyclic loading using experiments and finite-element modeling. Li[14] developed a creep-fatigue damage model to evaluate pressure-induced cavern deformation, and Liao[18] examined the thermo-mechanical behavior of cavern linings and surrounding rock. Seepage effects have also been incorporated into multiphysics analyses. Ma et al[19] investigated coupled temperature, seepage, and stress fields in caverns with different structural configurations, while Wu et al[20] evaluated temperature, pressure, and seepage responses under leakage conditions with limited characterization of damage evolution. Wang et al[21] investigated lining cracking and sealing-system responses, Zhao et al[22] examined leakage induced by localized sealing-layer damage, and Wang et al[23] evaluated stress and crack-width responses of lined rock caverns, whereas Gao[24] and Zhou[25] focused on long-term stability and damage evolution. These studies indicate that creep and damage parameters are material and condition-dependent constitutive quantities. Accordingly, the ranges adopted here are treated as representative sensitivity ranges, while site-specific applications require further experimental calibration.

Existing studies have investigated individual effects on cavern temperature and stress. Thermodynamic models have been developed for various cavern configurations, including large-vault caverns[12, 26], tunnel-type caverns[27], and ring-shaped caverns[28]. A THM model was constructed considering the lining and surrounding rock structures[29], to analyze the effects of parameters such as pore fractal dimension and injection rate on gas leakage. Fang et al developed a THM coupled model incorporating cavern temperature and pressure variations to study the influence of cavern radius on gas tightness[30]. Lyu et al further proposed a Thermal-Hydro-Mechanical-Damage (THMD) coupled model, analyzing the evolution of cavern temperature and pressure as well as the expansion of damage zones[19]. Xu[31] investigated cavern thermodynamic responses under different operating conditions, focusing on air temperature and pressure variations. Although thermodynamic models have been used to analyze operational responses of underground gas storage caverns, most studies focus on specific cavern configurations, individual factors. The coupled effects of cavern geometry, operating conditions, and material properties on CAES thermodynamic behavior remain insufficiently understood. Therefore, this study develops a multi-field coupled framework to investigate the evolution of temperature, pressure, and structural responses. Temperature and pressure changing rates are introduced as dynamic indicators, and semi-empirical correlations with defined applicability ranges and statistical metrics are established for rapid assessment and engineering parameter screening.

To address the identified research gaps, this study adopts and adapts an existing THMD framework as a unified physical platform for cavern-scale multiphysics analysis. The framework of the proposed method is shown in Fig.2, the main contributions are summarized as follows:

(1) A THMD-based framework is adopted and adapted to characterize coupled cavern thermodynamic responses throughout a complete operating cycle.

(2) Multi-dimensional and multi-factor effects are systematically investigated within a unified framework, covering structural geometry, operating conditions, and material-related parameters.

(3) Transient responses are evaluated using both peak values and dynamic indicators to identify the dominant controls on temperature and pressure responses.

(4) Semi-empirical correlations for temperature and pressure changing rates are established to

support rapid parameter screening and preliminary engineering assessment. The remainder of this paper is organized as follows: Section 2 presents the THMD model and validation; Section 3 describes the simulation setup; Section 4 analyzes the effects of geometry, operating conditions, and materials; Section 5 discusses governing mechanisms and semi-empirical correlations; and Section 6 summarizes the main conclusions.

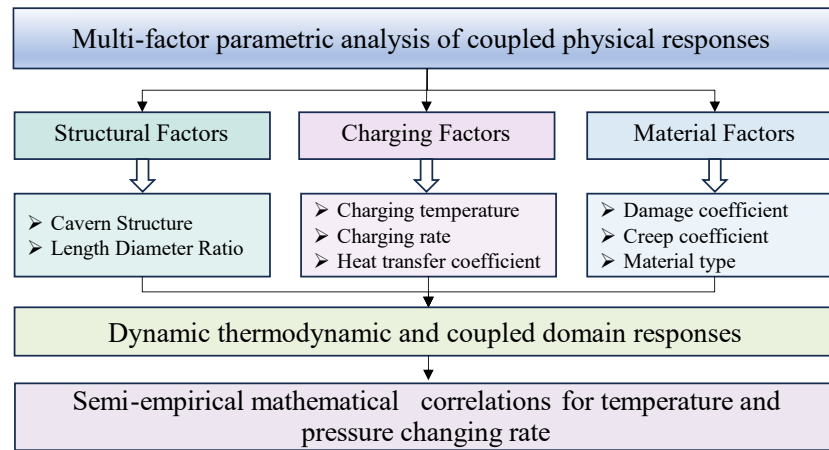


Fig.2. Framework for multi-factor parametric analysis of multiphysics responses

2 Theoretical Framework of the Multiphysics Coupled Model

2.1 Model Assumptions

To ensure computational feasibility and improve solution efficiency, the model was simplified with the following assumptions:

(1) At the initial moment, the cavern is in thermal equilibrium with the environment, and the initial temperatures of the air, sealing steel plates, concrete lining, and surrounding rock are all equal to the ambient temperature.

(2) Minor structures such as the cavern slip layer and drainage system are neglected, and only the sealing steel plates, concrete lining, and surrounding rock are considered.

(3) The energy transfer between auxiliary equipment such as valves and pipelines and the airflow are neglected, with air assumed to enter and exit directly through the cavern inlet/outlet.

(4) The sealing steel plates are assumed to be reliable, with no gas leakage during operation.

(5) The surrounding rock is treated as a homogeneous and isotropic porous medium. Spatial heterogeneity, joints, and explicit fracture networks are not included.

Based on these assumptions, a CFD model covering the full operation cycle is established, considering the air's thermophysical properties and transient flow and heat transfer.

2.2 Governing equations of the multiphysics coupled model

The operation of metallic storage devices involves mass and heat transfer between internal gas and external environment, coupled with fluid-solid-thermal interactions. The governing equations for the fluid domain include the conservation of energy, mass and momentum.

2.2.1 Thermodynamic governing equation of air

The energy conservation equation describes the transient energy balance of cavern gas, relating changes in internal energy to the enthalpy fluxes of inflowing and outflowing gas and to heat exchange with the surrounding environment[32, 33].

$$V \frac{d\rho}{dt} = (F_i + F_e) \dot{m}_c - \dot{m}_i \quad (1)$$

Based on energy conservation, the thermodynamic governing equation for air in CAES caverns can be expressed, which enables quantitative analysis of dynamic energy balance within the storage cavern.

$$V \rho_a C_v \frac{dT_a}{dt} = F_i \dot{m}_c \left(C_p (T_i - T_a) + ZRT_a + \rho_a \frac{\partial u}{\partial \rho} \Big|_{T_a} \right) + \left(F_e \dot{m}_c - \dot{m}_i(t) \right) \left(ZRT_a - \rho \frac{\partial u}{\partial \rho} \Big|_{T_a} \right) + \dot{Q} \quad (2)$$

Where, ρ_a is the air density inside the cavern, V is the cavern volume, and T_a is the air temperature. C_v, C_p are the specific heats at constant volume and constant pressure under the initial state. $\dot{Q}$ represents the total convective heat transfer between the air and surrounding rock, u denotes the specific internal energy. $(F_i + F_e) \dot{m}_c$ denotes the instantaneous mass flow rate, $\dot{m}_c$ is the mass flow rate.

This study uses Reynolds-Averaged Navier-Stokes (RANS) model to compute the airflow field inside the storage cavern and adopts the realizable $k - \varepsilon$ turbulence model.

$$\frac{\partial(\rho_a k)}{\partial t} + \nabla(\rho_a k u) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \nabla k \right] + P_k - \rho_a \varepsilon \quad (3)$$

A correction based on the ideal gas law is applied using the gas compressibility factor Z [34, 35], which accounts for deviation from ideal gas assumption and is used to calculate cavern's initial air density.

$$\rho_a = \frac{P}{ZR_a T_a} \quad (4)$$

The compressibility factor is calculated using the Berthelot equation of state, where P_c and T_c are the critical air pressure and critical temperature.

$$Z = 1 - \frac{9P}{128P_c} \cdot \frac{T_c}{T_a} \cdot \left(\frac{6T_c^2}{T_a^2} - 1 \right) \quad (5)$$

$$\frac{\partial Z}{\partial T_a} = \frac{9\rho_a R_a T_c^3 (18T_c^2 - T_a^2)}{T_a^3 [128P_c T_a + 9\rho_a R_a T_c (6T_c^2 - T_0^2)]} \quad (6)$$

2.2.2 Governing equation for gas flow for porous media

The seepage of air within the porous medium follows Darcy's law. Neglecting inertia and viscous effects, the mass continuity equation for air can be expressed.

$$\nabla \cdot (\rho_g v_g) + \frac{\partial(\rho_g \phi)}{\partial t} = Q_s \quad (7)$$

Where, ϕ is the porosity of the surrounding rock, Q_s is the mass source term, ρ_g is the air density within the pores, and v_g is the air seepage velocity. According to the ideal gas law, M represents the molar mass of the gas. The parameters governing the above seepage process can be determined by simultaneously solving Equations 4 and 5.

$$\rho_g = \frac{PM}{ZR_a T_a} = \frac{128P_c T_g^2 P_g}{128R_a P_c T_g^3 + 9R_a T_c P_g (T_g^2 - 6T_c^2)} \quad (8)$$

During cavern operation, considering thermal expansion, the porosity and permeability of the

surrounding rock vary as expressed[36].

$$\phi = 1 - \frac{(1 - \phi_0)}{1 + \varepsilon_v} \left(1 - \frac{\Delta p}{K_s} + \alpha_T \Delta T \right) \quad (9)$$

$$k = k_0 \left(\frac{\phi}{\phi_0} \right)^3 \quad (10)$$

Where, K_s is the bulk modulus of the solid matrix, ϕ_0 and k_0 are the initial porosity and permeability respectively, and ε_v is the volumetric strain, the Klinkenberg effect significantly influences gas permeability[37].

$$k_g = k \left(1 + \frac{b}{p} \right) \quad (11)$$

$$b = \frac{16c\mu}{d} \sqrt{\frac{2RT}{\pi M}} \quad (12)$$

Where, k is the apparent permeability, and b is the Klinkenberg coefficient, which depends on temperature, gas type, and the pore structure of the porous medium. c is a constant, taken as 0.9, d is the pore diameter.

2.2.3 Mechanical equilibrium equation for porous media

The porous medium can be regarded as an isotropic, gas-saturated elastic body. Considering the coupling of seepage and thermal stress, the constitutive relation for deformation can be expressed as follows.

$$\sigma_{ij} = 2G\varepsilon_{ij} + \frac{2\nu G}{1 - 2\nu} \delta_{ij} \varepsilon_v - \alpha p \delta_{ij} - K \alpha_T \Delta T \delta_{ij} \quad (13)$$

Where, $G = E / 2(1 + \nu)$; $\varepsilon_{ij} = (u_{i,j} + u_{j,i}) / 2$; $K = E / [3(1 - 2\nu)]$, $\sigma_{ij}, \varepsilon_{ij}$ represent the second-order stress and strain tensors. G is the shear modulus of the surrounding rock, and α_T is the thermal expansion coefficient of the solid matrix. p represents the pore pressure, α is the Biot coefficient, δ_{ij} is the Kronecker delta, where $i = j$, $\delta_{ij} = 1$, if $i \neq j$, $\delta_{ij} = 0$. The thermal strain ε_{th} is the volumetric strain induced by temperature change.

$$\varepsilon_{th} = \alpha_T (T - T_{in}) \quad (14)$$

Creep is a time-dependent, non-elastic deformation that occurs when a material is subjected to stress at sufficiently high temperatures. The creep strain ε_{cr} is commonly described using the Norton mode[38].

$$\frac{\partial \varepsilon_{cr}}{\partial t} = A \left(\frac{\sigma_{mises}}{\sigma_{ref}} \right)^\psi \exp \left(-\frac{Q_{cr}}{RT} \right) \quad (15)$$

Where, σ_{mises} and σ_{ref} are applied stress and reference stress; A and ψ are the creep rate coefficient and stress exponent; Q_{cr} is the creep activation energy. Gas injection and withdrawal induce coupled thermal, fluid and mechanical effects, causing structural damage. The strain-based Scalar damage and Mazal damage models are applicable to concrete[39].

$$F = \varepsilon_{eq} - \kappa \quad (16)$$

Where, $F \leq 0, \kappa \geq 0, \kappa F = 0$, ε_{eq} is the equivalent strain. The evolution of the state variable κ

follows the Kuhn-Tucker loading conditions[40]. Define damage evolution laws based on key components within the scalar damage model, the Exponential strain softening law defines the damage variable.

$$d(\kappa) = \begin{cases} 1 - \frac{\varepsilon_0}{\kappa} \exp\left(-\frac{\kappa - \varepsilon_0}{\varepsilon_f - \varepsilon_0}\right), & \kappa \geq \varepsilon_0 \\ 0, & \kappa < \varepsilon_0 \end{cases} \quad (17)$$

Where, ε_0 denotes the initial damage value, computed from the tensile strength and Young's modulus.

2.2.4 Energy conservation equation for porous media

Under the assumption that the pressure gradient has a negligible effect on heat transfer, the total heat flux $\mathbf{q}_T$ can be expressed according to Fourier's law.

$$\mathbf{q}_T = -\lambda_M \nabla T + \rho_g C_g \mathbf{q}_g T \quad (18)$$

$$(\rho C)_M = \phi(\rho_g C_g) + (1 - \phi)(\rho_s C_s) \quad (19)$$

$$\lambda_M = \phi \lambda_g + (1 - \phi) \lambda_s \quad (20)$$

Neglecting thermal radiation and viscous dissipation, and assuming instantaneous local thermal equilibrium between the fluid and the solid matrix, the heat transfer governing equation in the surrounding rock is expressed[41].

$$\frac{\partial[(\rho C)_M T]}{\partial t} + TK_g \alpha_g \nabla \cdot \mathbf{q}_g + TK \alpha_T \frac{\partial \varepsilon_v}{\partial t} = -\nabla \cdot \mathbf{q}_T \quad (21)$$

Where, K is the bulk modulus of the surrounding rock, and α_g is the thermal expansion coefficient of air. For ideal gas, $K_g = p, \alpha_g = 1/T$, and relevant parameters can be found in the literature[42]. By combining Equations 18-21 and performing further derivation, the final heat transfer governing equation for surrounding rock is obtained.

$$(\rho C)_M \frac{\partial T}{\partial t} - TK_g \alpha_g \nabla \cdot \left(\frac{k_g}{\mu} \nabla p \right) + TK \alpha_T \frac{\partial \varepsilon_v}{\partial t} = \lambda_M \nabla^2 T + \rho_g C_g \frac{k_g}{\mu} \nabla p \nabla T \quad (22)$$

It should be noted that no explicit damage-induced heat source term is included in the present energy conservation equation. In this model, the damage variable is introduced mainly to characterize material degradation and the evolution of localized damage zones in the solid domain, rather than to describe the direct conversion of damage-dissipated energy into heat. Its coupled influence is therefore primarily reflected in stress redistribution, deformation localization, and damage-zone development.

The numerical model was solved in COMSOL Multiphysics, as shown in Fig.3.

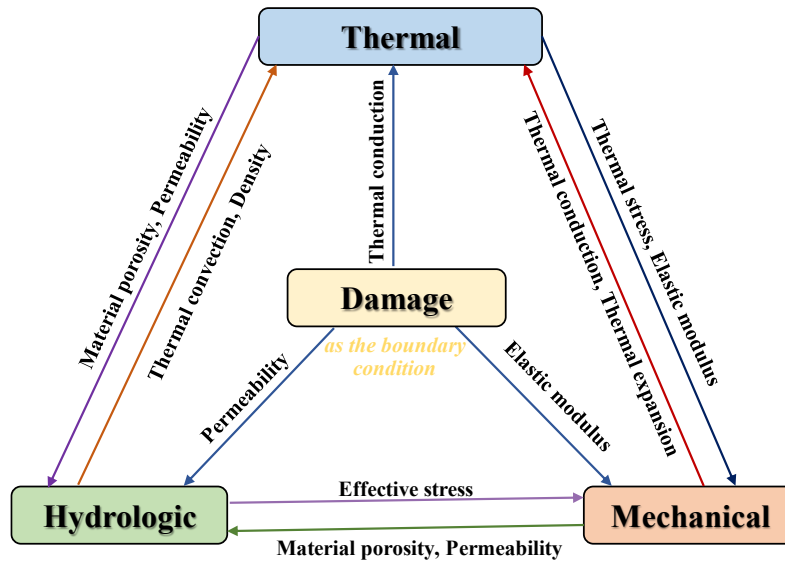
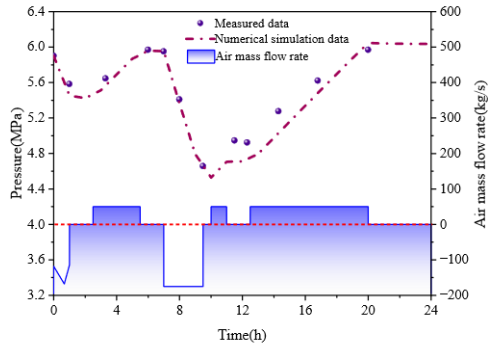


Fig.3.THMD coupling in CAES caverns

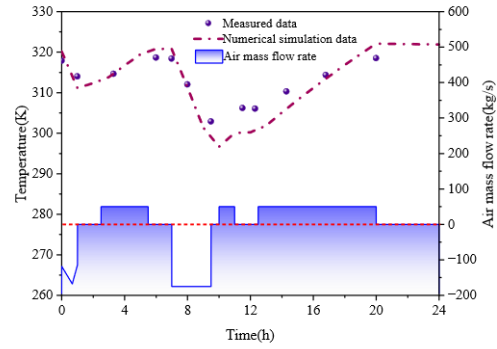
2.3 Model validation and reliability assessment

To assess the reliability of the air-domain thermodynamic response predicted by the developed numerical framework, the Huntorf CAES plant was selected for comparison with field measurements. The simulation parameters are listed in Table 1[43]. Initially, the cavern air and surrounding rock were in thermal equilibrium at 313.15 K. During the charging stage, air was injected in three batches with corresponding injection temperatures of 324.11 K, 319.10 K and 322.23 K. The simulation focused on the dynamic evolution of air pressure and temperature, which was compared with on-site measurement from the Huntorf plant[44] for model validation. As shown in Fig.4, the maximum relative errors in pressure and temperature were 1.96% and 5.91%, respectively, indicating that the model can reasonably reproduce the transient thermodynamic response in the air domain during charging. In particular, the agreement in air temperature supports the model's capability to capture transient energy accumulation and gas-wall heat transfer, which are central to the subsequent analysis of cavern thermal behavior. Accordingly, the Huntorf comparison serves as the primary validation of the air domain thermodynamic response, consistent with the main focus of this study on the thermal and thermodynamic behavior of compressed air energy storage caverns under varying geometric, operational, and material conditions.

As a supplementary assessment, an analytical benchmark for a lined rock cavern was introduced to examine the numerical consistency of the basic thermo-mechanical implementation. A simplified model with consistent geometry, material properties, initial conditions, and boundary conditions was established, retaining only heat-transfer and linear thermo-elastic processes[45]. The maximum relative errors of radial stress and radial displacement were 3.23% and 6.60%, respectively, indicating good agreement between the numerical and analytical results. Combined with the primary Huntorf validation of air temperature and pressure, this supplementary benchmark further supports the numerical consistency of the basic thermo-mechanical response.



(a) Pressure validation



(b) Temperature validation

Fig.4. Comparison between numerical simulation and measured data

Table 1 Parameters of the Huntorf plant used for model validation

Item	Value	Unit
Cavern volume	141000	m^3
Cavern diameter	20	m
Initial temperature of cavern	313.15	K
Initial air pressure in the cavern	5.93	MPa
Rock density	2100	kg / m^3
Thermal conductivity	4	$W / (m \cdot K)$
Specific heat of rock mass	840	$J / (kg \cdot K)$
Heat transfer coefficient	30	$W / (m^2 \cdot K)$
Gas constant	286.7	$J / (kg \cdot K)$

3 Numerical Simulation Setup

3.1 Cavern prototype parameter settings

The underground CAES cavern studied is located in Fushun, Liaoning Province, China, with planned commissioning in 2028. The location and topography of the study area are shown in Fig.5(a) and(b). The cavern has an effective storage volume of $1.01 \times 10^5 m^3$, with initial pressure and temperature are 7 MPa and 288.15 K. Under rated condition, the charging and discharging mass flow rates are 156.77 kg/s and 235.16 kg/s. The simulation geometry is shown in Fig.5(d), and further parameters details are listed in the Supplementary Material.

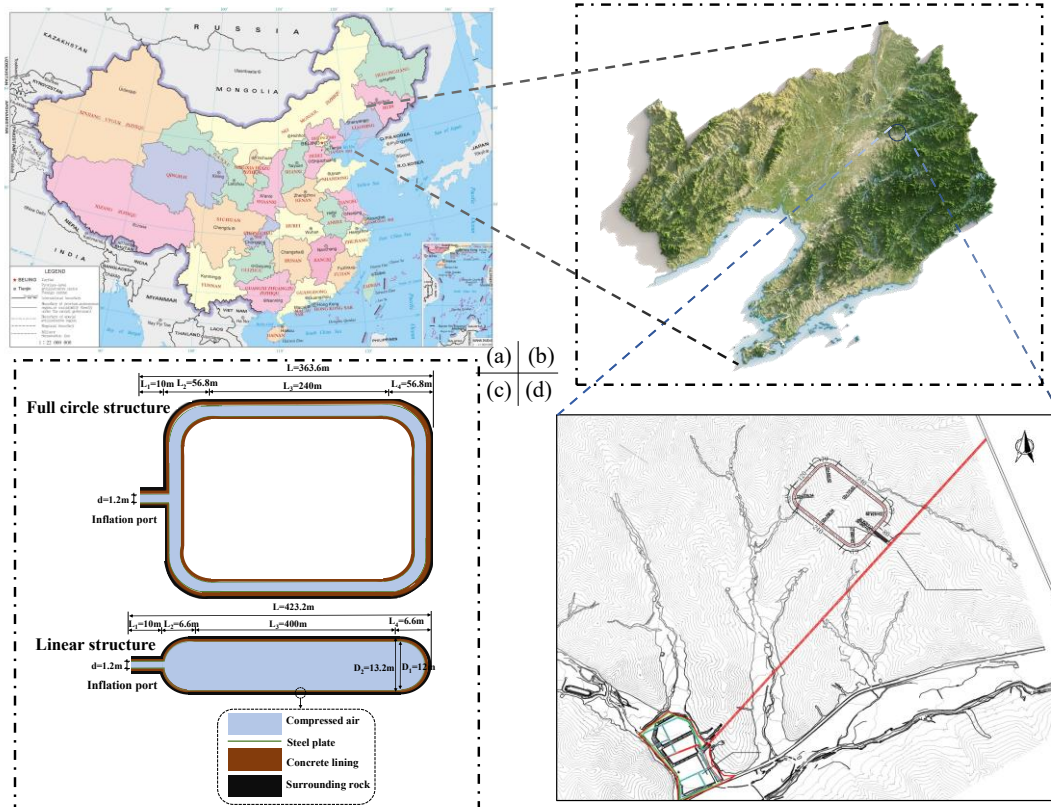


Fig.5. (a) Location of Liaoning Province; (b) Topography of Liaoning Province; (c) Location of the storage cavern; (d) Simulated geometry of the storage cavern

3.2 Numerical simulation procedure

COMSOL Multiphysics provides a unified platform for solving coupled problems. As shown in Fig.6, the software framework was developed for underground storage caverns, ensuring consistent dependent variables across all physical fields and regions.

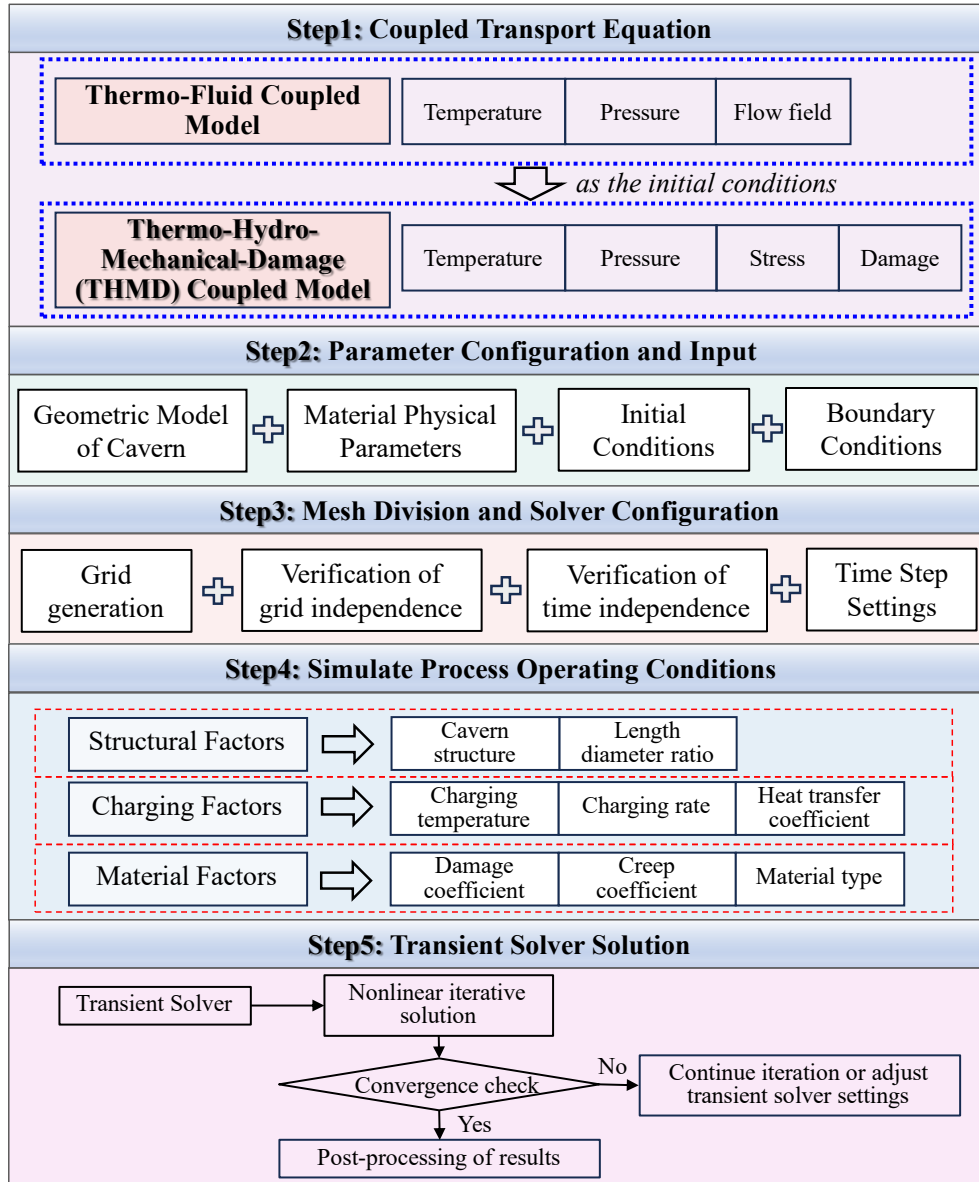


Fig.6. Workflow of coupled modeling for CAES cavern

3.3 Material properties

The properties of wall materials are essential parameters in the simulation, including thermal conductivity, specific heat capacity, and density. Thermal conductivity reflects the material's ability to conduct heat, specific heat capacity indicates its ability to store thermal energy, and density affects thermal inertia and mass transfer characteristics. The material parameters of the various components of the storage cavern used in this study are listed in [Table 2](#).

Table 2 Material properties

Material	Density	Elastic modulus	Poisson's ratio	Compressive strength	Thermal expansion coefficient	Thermal conductivity	Specific heat capacity
	kg/m ³	GPa	-	MPa	/°C	W/(m·K)	J/(kg·K)
Concrete	2400	30	0.18	30	1.0*10 ⁻⁵	2	900
Steel plate	7850	206	0.3	490	1.1*10 ⁻⁵	55	480
Surrounding rock	2690	25	0.26	60	8*10 ⁻⁶	3.5	850

3.4 Mesh independence verification

Mesh and time-step independence tests were conducted to minimize numerical errors. For the full-circular cavern, three mesh sizes 916544, 1390177, and 2041218 elements were compared. Considering both computational accuracy and efficiency, the error was controlled within 5% when using 1390177 elements, which was therefore selected as the final mesh, with an average mass per element of 0.8519. In addition, time-steps of 0.5 h, 1 h, and 2 h were tested. Considering both computational accuracy and efficiency, the time-step of 1 h was selected to ensure independence of the results from both mesh size and time step.

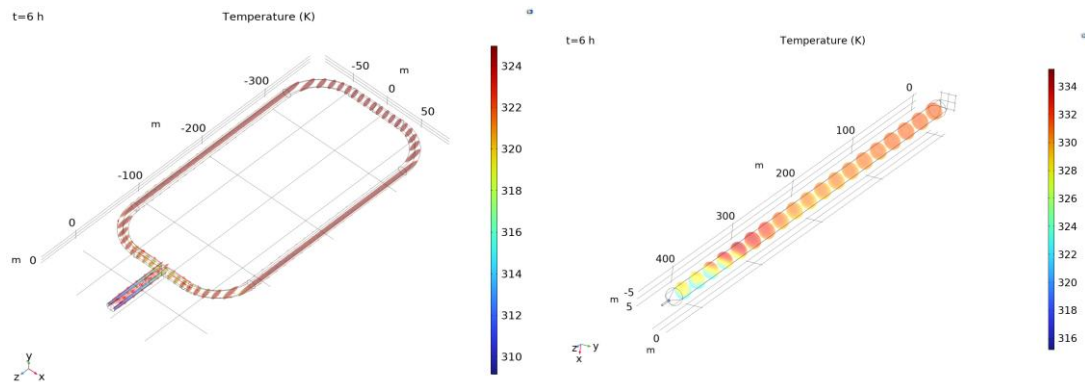
4 Results and analysis

4.1 Effects of structural factors on physical response

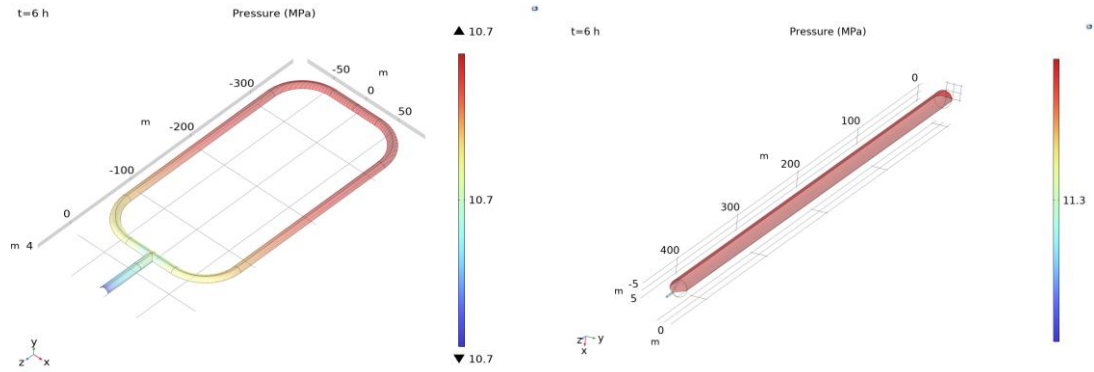
4.1.1 Effects of cavern structure

Under the same charge-storage-discharge-store strategy, thermal-fluid-solid simulations were performed for linear and full-circular CAES caverns. The thermodynamic responses of temperature, flow and pressure fields were compared throughout a full cycle. As shown in Fig.7, the dynamic variations of key parameters were quantified.

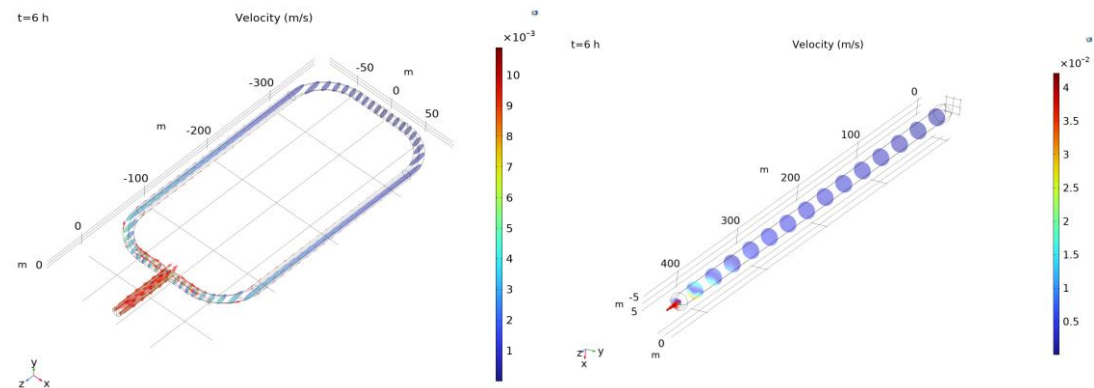
This study focuses on air domain responses, as they directly reflect cavern thermodynamic performance. Air-domain temperature and pressure are retained as the primary variables for characterizing cavern-scale thermodynamic evolution and establishing the semi-empirical correlations, as they directly reflect the operating boundaries and thermodynamic performance of the CAES cavern. Representative solid-domain indicators, including principal stress, displacement or equivalent strain, damage variable, and damage-zone extent, are also presented in the main text to quantify stress redistribution, deformation localization, and damage evolution under coupled THMD conditions. Complete solid-domain contour distributions and auxiliary parametric cases are provided in the Supplementary Material to maintain the clarity and conciseness of the main text. In the absence of direct field measurements for these solid-domain quantities, they are interpreted as coupled-model predictions for mechanism analysis, parametric sensitivity assessment, and evaluation of structure responses.



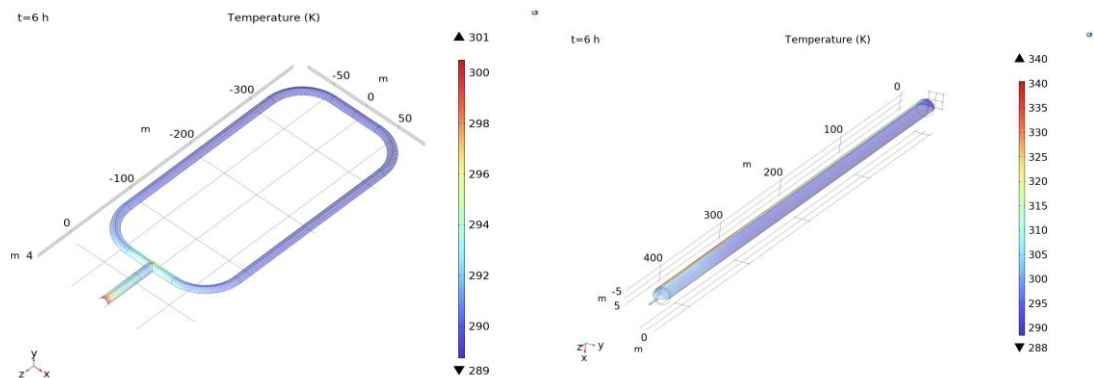
(a) Temperature distribution



(b) Pressure distribution



(c) Velocity distribution



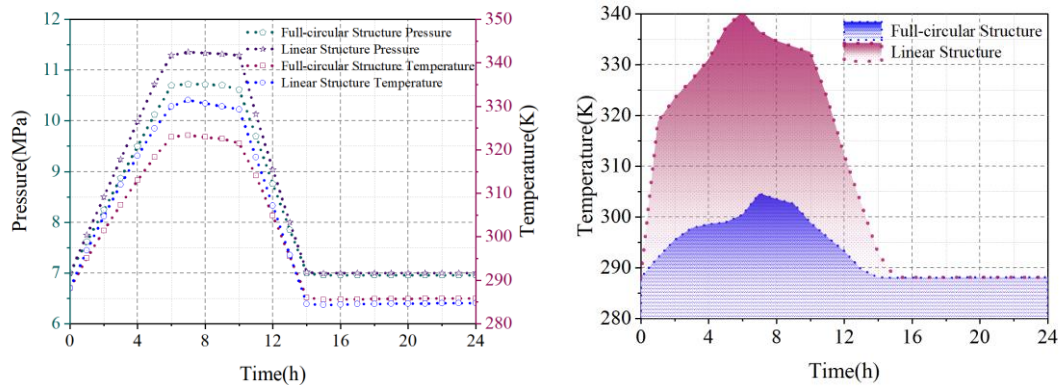
(d) Wall temperature distribution

Fig.7. Air domain physical distributions of different cavern structure

By comparing the temperature and pressure distributions in the air domain of the linear and circular caverns in Fig.7(a) and Fig.7(b), at the end of the 6 h charging stage, both configurations reached peak temperature and pressure. However, the linear cavern exhibited a more pronounced thermal accumulation effect. Throughout a complete cycle, the overall temperature of the linear cavern remained consistently higher than that of the circular cavern. The maximum air temperature within the linear cavern reached 331.46 K, whereas the peak temperature of the circular cavern was 323.38 K, representing an increase of 8.08 K, this reduction is 13.85%. Corresponding pressure peaks were 11.46 MPa and 10.72 MPa, with the linear cavern exceeding the circular one by 0.74 MPa, approximately 6.46%.

At the solid-fluid interface, the difference in wall temperature between the two configurations was even more pronounced. The maximum wall temperature of the linear cavern reached 336.55 K,

while that of the circular cavern was only 304.66 K, representing a reduction of approximately 50.3% in peak wall temperature, indicating substantially weaker wall thermal accumulation in the latter.



(a) Temperature and pressure variations

(b) Wall temperature variations

Fig.8. Comparison of physical parameter variations under different cavern structure

The influence of cavern geometry can be interpreted from the coupled momentum and energy transport processes. The thermodynamic differences between linear and circular caverns are primarily governed by internal airflow organization and characteristic heat-transfer characteristics. In the linear cavern, elongated flow paths and local stagnation regions, particularly near the roof, weaken thermal mixing and gas-wall heat exchange, causing compression heat to accumulate locally and producing a pronounced roof-heating effect. In contrast, the full-circular cavern facilitates recirculation and more uniform gas mixing, which enhances spatial heat redistribution and gas-wall heat transfer, thereby reducing local high temperature regions and improving temperature field uniformity.

4.1.2 Effects of length diameter ratio

Under a constant total storage volume, cavern length and diameter were varied to adjust the aspect ratio. As shown in Table 3, five models with different aspect ratios were established, with diameters ranging from 12 m to 20 m and corresponding lengths from 147.6 m to 439.7 m. The length diameter ratios are 36.64, 27.94, 15.05, 10.37 and 7.38.

Table 3 Design of cavern length diameter ratio

Type	Cavern diameter	Cavern length	Length diameter ratio	Description
G1	12	439.7	36.64	Tunnel-type
G2	14	391.1	27.94	Tunnel-type
G3	16	240.8	15.05	Medium-length tunnel
G4	18	186.6	10.37	Medium-length tunnel
G5	20	147.6	7.38	Large-tank type

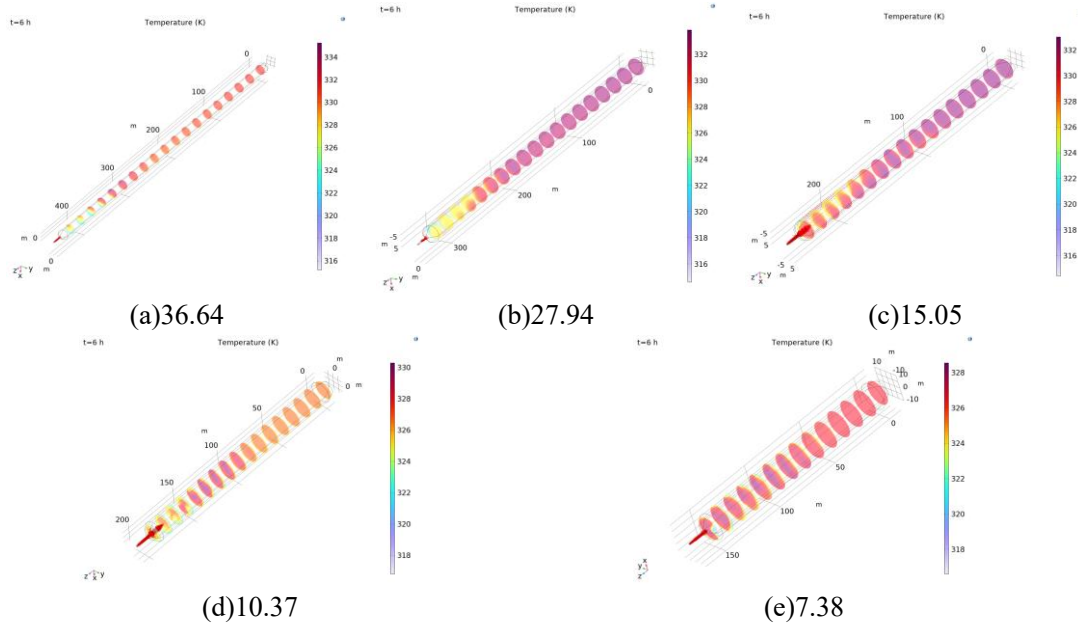


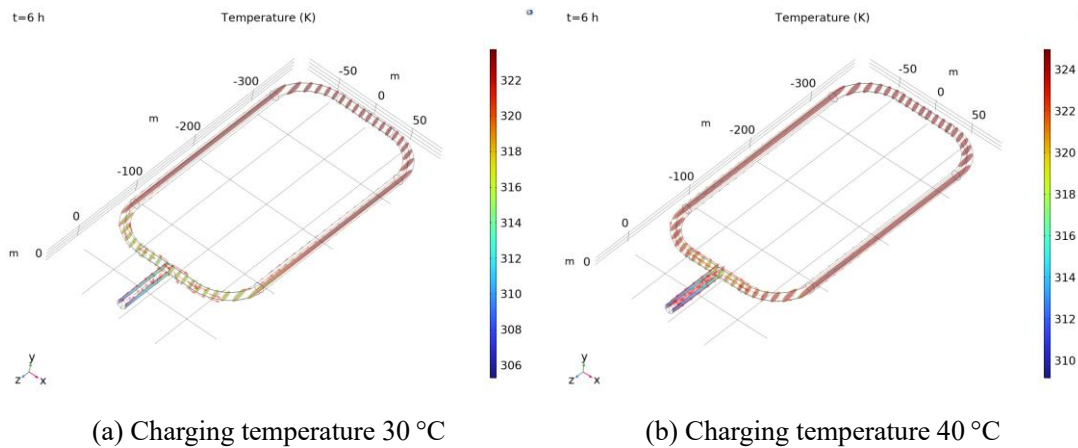
Fig.9. Temperature distributions under different length diameter ratio

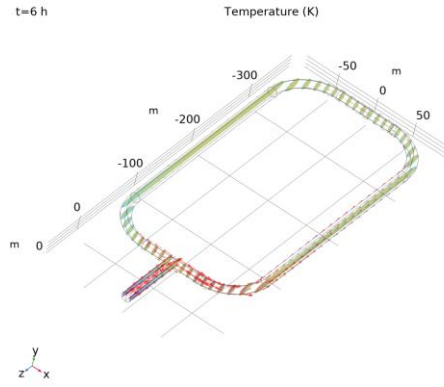
As the length diameter ratio decreases, the peak air temperature within the cavern shows an overall decreasing trend, and the extent of high-temperature regions is reduced at the end of 6 h. As the ratio decreases from 36.64 to 7.38, the corresponding maximum wall temperatures are 316.71 K, 316.36 K, 316.24 K, 315.57 K, and 313.61 K, respectively, indicating a decrease of 3.10 K in the peak wall temperature, corresponding to a reduction of 7.12%. The length diameter ratio influences temperature distributions by regulating the gas flow path length, turbulence development and heat transfer on thermal distribution. High length diameter ratio caverns have longer airflow paths, enhancing turbulence and kinetic energy dissipation, which raises internal temperature and forms concentrated high-temperature zones. As the aspect ratio decreases, the shortened flow path stabilizes the flow field, weakens turbulence intensity, and reduces heat generation from kinetic energy dissipation, thereby lowering peak temperature and enhancing thermal uniformity.

4.2 Effects of operational factors on physical response

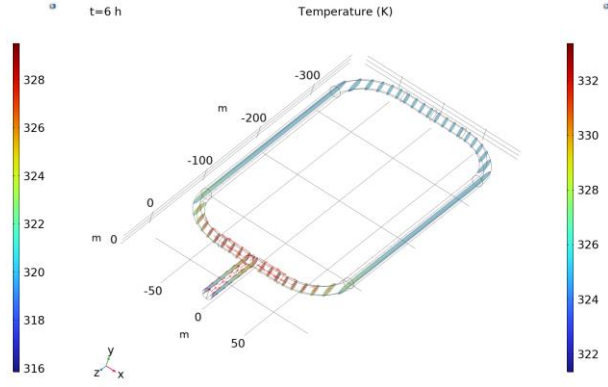
4.2.1 Effects of charging temperature

Under constant charging pressure, charging rate, and cavern geometry, different charging temperature scenarios of 30 °C, 40 °C, 50 °C, and 60 °C were applied. The thermodynamic responses of the cavern at the end of the 6 h charging stage were then compared and analyzed.





(c) Charging temperature 50 °C



(d) Charging temperature 60 °C

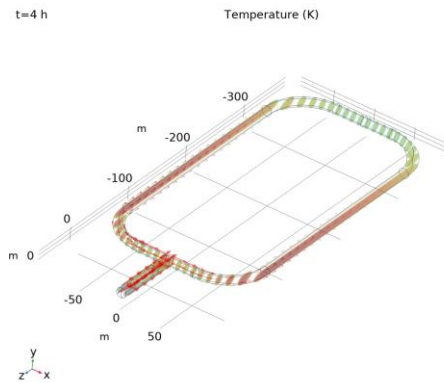
Fig.10. Air domain temperature distributions under different charging temperature

The results indicate that charging temperature significantly affects cavern thermal behavior. As shown in Fig.10, charging temperature significantly affects cavern thermal behavior. After 6 h of charging, peak air temperatures reach 321.46 K, 322.20 K, 323.37 K, and 324.03 K for charging temperatures from 30 °C to 60 °C, corresponding to an overall increase of 2.57 K.

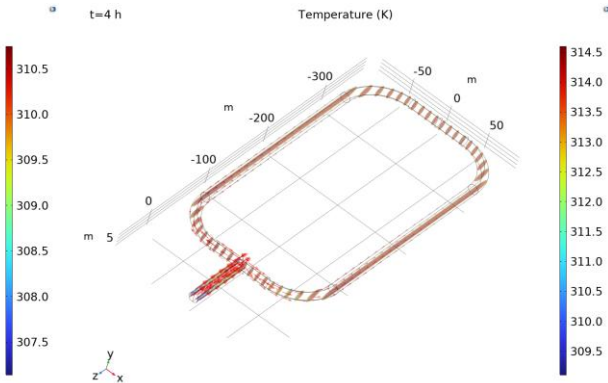
Higher charging temperatures also enhance turbulence and intensify thermal non-uniformity, raising gas temperature and temperature gradient with the cavern walls, thereby enhancing the convective heat transfer driving force. Due to limited thermal conductivity of rock, resulting in heat accumulation, leading to a greater rise in wall temperature than in air temperature.

4.2.2 Effects of charging rate

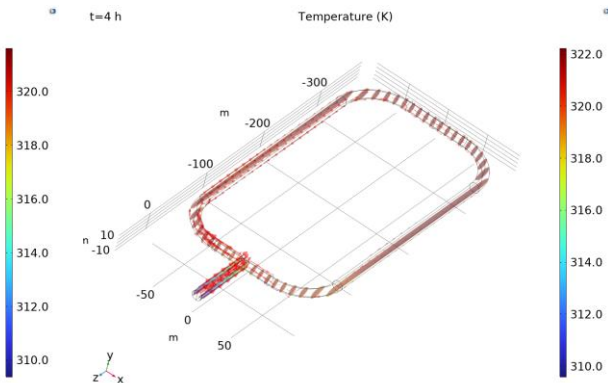
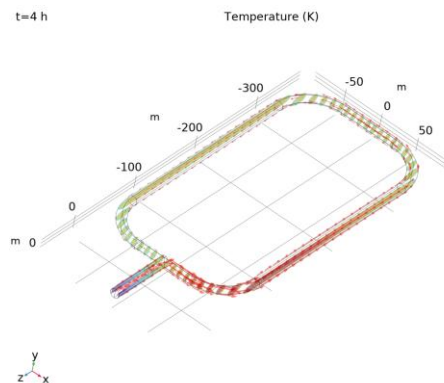
Under the conditions of constant cavern geometry, charging temperature, and initial pressure, four charging rate scenarios of 125.42 kg/s, 156.78 kg/s, 188.14 kg/s, and 219.22 kg/s were applied.



(a) 125.42 kg/s



(b) 156.78 kg/s



(c)188.14 kg/s

(d)219.22 kg/s

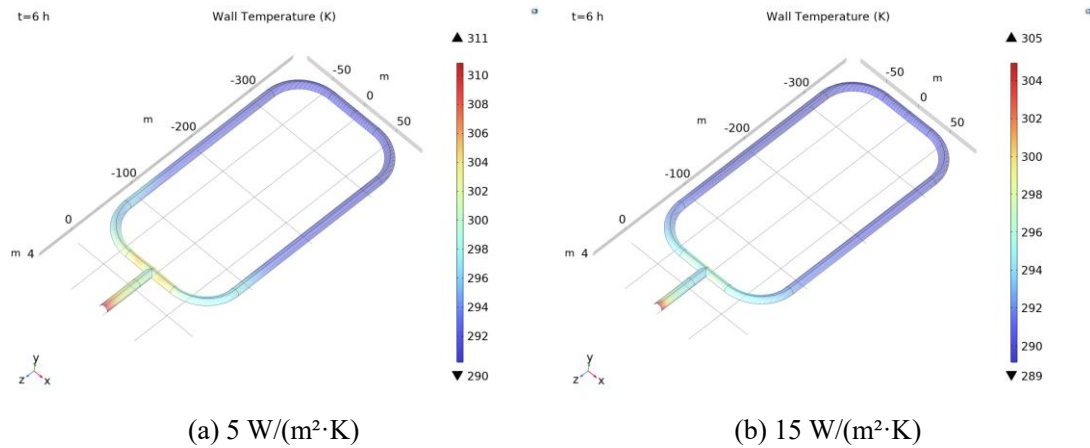
Fig.11. Air domain temperature distributions under different charging rate

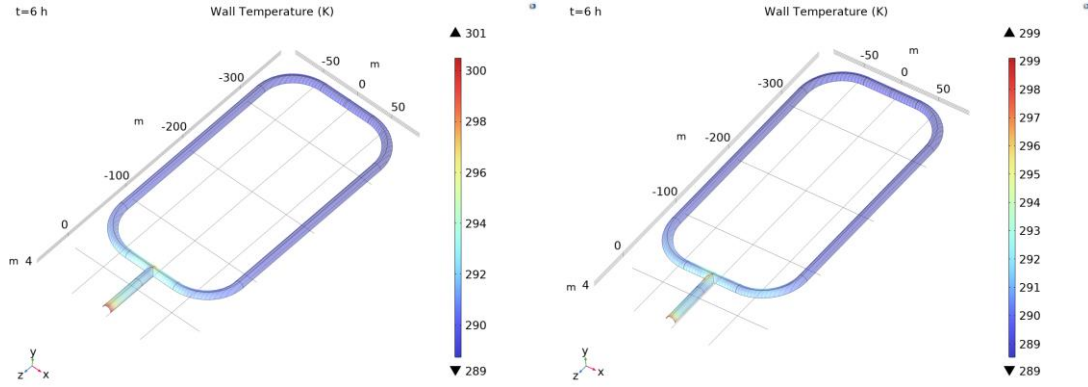
Increasing the charging rate significantly affects cavern thermal responses. Firstly, higher mass flow rates accelerate gas filling and compression, allowing the system to reach quasi-equilibrium state in pressure, temperature, and heat exchange more quickly. At the lowest charging rate, the system stabilizes in 8 h, shortening to 6, 5, and 4 h at higher rates.

Both pressure and temperature within the cavern increase with the charging rate. At 4 h, the air domain pressure are 8.99 MPa, 9.49 MPa, 9.98 MPa, and 10.44 MPa, with temperatures of 308.57 K, 313.02 K, 314.18 K, and 319.77 K. When the charging rate increases from 125.42 kg/s to 219.22 kg/s, the air temperature rises by over 11 K and pressure by 1.45 MPa. The surrounding-rock and wall temperatures also increase, although the rise is less pronounced compared with the air temperature, with peak wall temperatures of 297.85 K, 298.64 K, 298.95 K, and 299.47 K. The air temperature also increases with charging mass flow rate, indicating enhanced compression heating and local thermal accumulation, its influence on wall-temperature accumulation is weaker than that on pressure buildup. Therefore, it mainly controls pressure dynamics and pressure changing rate rather than thermal accumulation. Increasing the charging rate enhances the gas flow velocity and turbulence intensity. The strengthened turbulence accelerates the thermal homogenization, but also induces stronger flow disturbances and temperature gradients near the inlet and in local regions, leading to flow non-uniformities and localized overheating. Rapid gas injection causes heat to concentrate on the cavern walls over a short period, the input heat cannot diffuse quickly to the far field, resulting in a pronounced transient thermal accumulation effect.

4.2.3 Effects of convective heat transfer coefficient

The convective heat transfer coefficient reflects the intensity of heat exchange between the gas and surrounding rock, directly influencing cavern thermal equilibrium and stress distribution. In this study, convective heat transfer coefficients of 5, 15, 30, and 50 W/(m²·K) were considered, covering a typical range from weak to enhanced heat transfer conditions.



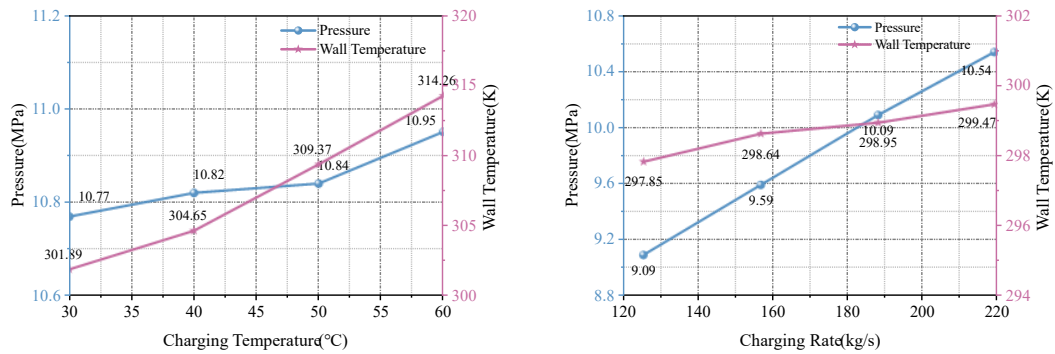


(c) 30 W/(m²·K)

(d) 50 W/(m²·K)

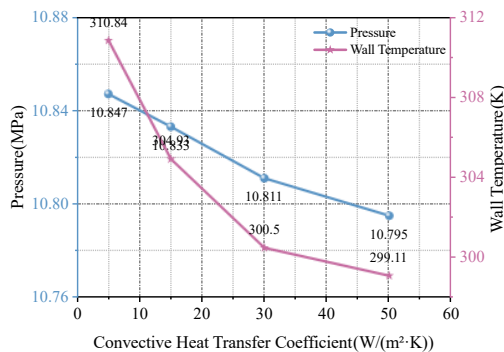
Fig.12. Wall temperature distributions under different convective heat transfer coefficient

As the convective heat transfer coefficient increases, the wall temperature maximum decreases to 310.84 K, 304.93 K, 300.50 K, and 299.11 K, with a peak reduction of 11.73 K, corresponding to a decrease of 31.1%, exhibiting a monotonically decreasing trend with increasing heat transfer coefficient. The convective heat-transfer coefficient mainly affects the thermal response through gas-wall heat exchange. A higher coefficient reduces convective resistance and suppresses thermal accumulation, but has limited influence on pressure, which is mainly governed by gas mass accumulation and compression, indicating that temperature and pressure are controlled by different dominant pathways despite their thermodynamic coupling.



(a) Charging temperature

(b) Charging rate



(c) Convective heat transfer coefficient

Fig.13. Effects of charging factors on the evolution of pressure and wall temperature

As shown in Fig.13, increasing charging temperature raises cavern pressure and wall temperature, intensifying heat accumulation. The charging rate has a weaker effect, accelerating the thermo-pressure rise. In contrast, a higher convective heat transfer coefficient markedly reduces both pressure and wall temperature. Overall, charging temperature and convective heat transfer dominate the thermo-pressure response, while charging rate is relatively mild.

4.3 Effects of material factors on physical response

4.3.1 Effects of damage coefficient

To investigate the coupled effects of peak strength and fracture energy on cavern damage evolution, damage characteristics were represented by two parameters: peak strength and fracture energy. The peak strength characterizes the stress threshold for material damage, while the fracture energy represents the energy consumed per unit area during cracking. Three scenarios were considered with peak strengths σ_p of 1.2×10^6 , 1.5×10^6 , and 2.5×10^6 N/m², and fracture energy G_f of 30, 50, and 150 J/m². Under constant charging conditions, the distributions of principal stress and damage after 6 h of charging were analyzed.

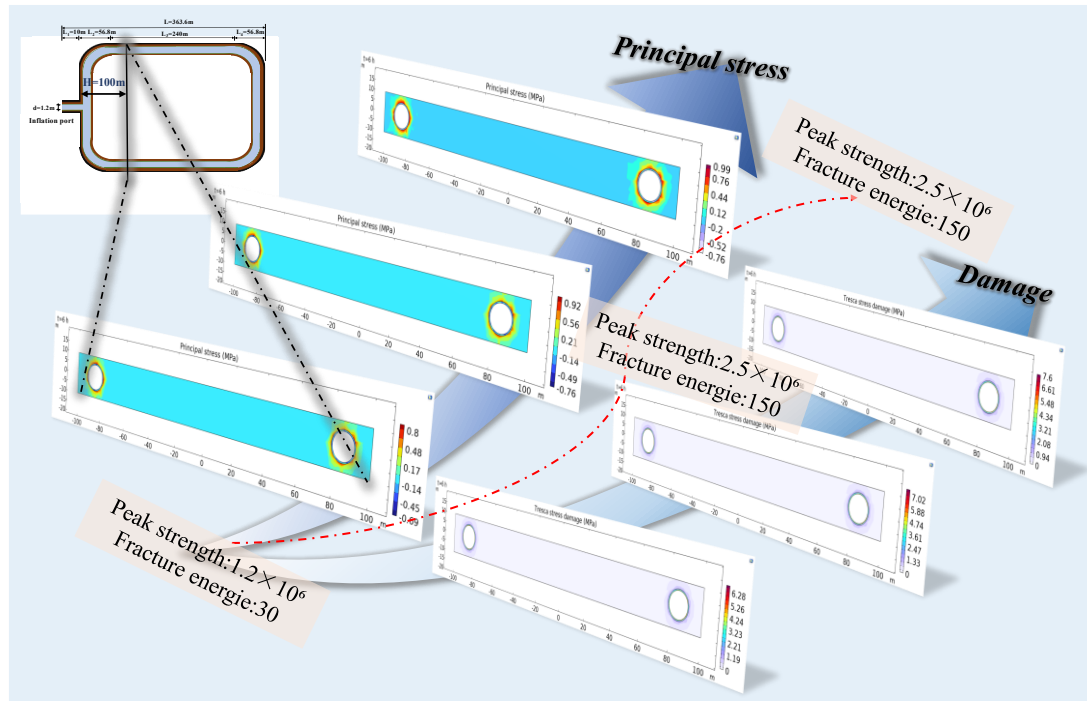


Fig.14. Cavern physical field distributions under different damage levels

As shown in Fig.14, increasing the surrounding rock's peak strength and fracture energy enhances compressive capacity and alleviates stress concentration. Consequently, the maximum wall temperature decreases from 305.27 K to 303.26 K while the peak principal stress decreases from 2.62 MPa to 2.41 MPa. The extent of the damage zone shrinks, with stress-damage values decreasing from 10.26 MPa to 9.67 MPa, indicating enhanced load-bearing capacity and suppression of local failure.

These effects of surrounding rock damage parameters on thermodynamic response arise from the coupled effects of damage evolution and energy dissipation mechanisms. Since no explicit damage-induced heat source is included in the energy equation, the wall temperature variation should not be attributed to direct conversion of mechanical damage energy into heat. Instead, it reflects indirect effects of stress redistribution, deformation localization, damage-zone evolution, and gas-solid thermal interaction. Increasing peak strength and fracture energy suppresses damage

evolution and local stress concentration, thereby improving overall thermo-mechanical stability.

4.3.2 Effects of creep coefficient

Study on the distribution patterns of physical fields in a gas storage cavern considering the coupled effects of the creep coefficient and stress exponent. Under consistent conditions for all other parameters, three creep scenarios were considered, with creep coefficients 4.8×10^{-7} , 1.4×10^{-6} , 1.92×10^{-6} /day, and stress exponents are 3, 4, 4.5. The distributions of principal stress and strain fields under 6 h charging conditions were analyzed.

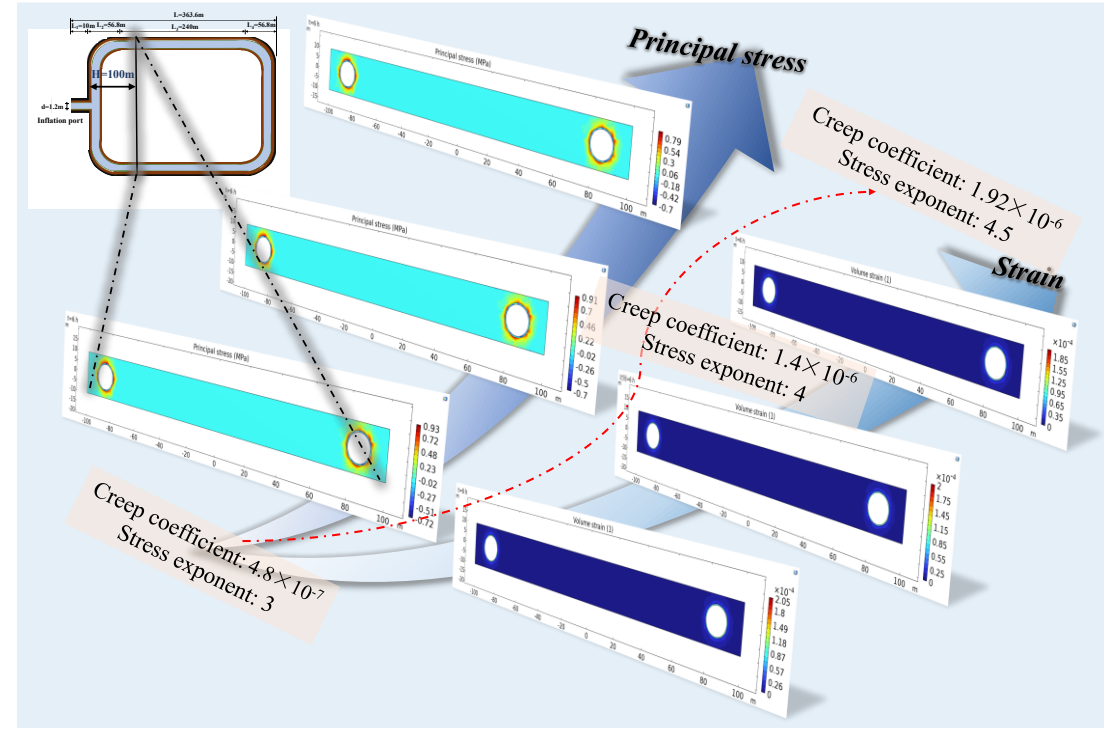


Fig.15. Cavern physical field distributions under different creep coefficient

The simulation results indicate that as both the creep coefficient and stress exponent increase, the time-dependent deformation of surrounding rock is enhanced, intensified strain in stress concentration regions and reduced structural stability. The maximum wall temperatures reach 302.79 K, 303.02 K, and 304.09 K, indicating a slight increase in thermal dissipation due to creep. Meanwhile, the peak principal stress rises from 2.31 to 2.45 MPa, with corresponding strains of 3.04×10^{-4} , 3.10×10^{-4} , and 3.41×10^{-4} . The peak differences in stress concentration regions increase, making the localization of high-stress zones more pronounced.

The creep coefficient and stress exponent control creep rate and stress sensitivity, amplifying strain and stress redistribution in concentrated zones. Under short-term loading, nonlinear creep raises stress peaks, worsening local concentrations and reducing structural stability, creep parameters should be limited in long-term cavern design.

4.3.3 Effects of sealing materials

Four sealing materials-steel plate, fiberglass, polyurethane, and butyl rubber were selected to investigate the thermodynamic response. When the permeability of sealing material is below 10^{-18} m^2 , it ensures that high-pressure gas leakage remains under 1% of injected air mass. The properties of sealing materials listed in Table 4 satisfy the operational requirements.

Table 4 Physical properties of four sealing materials

Sealing material	Density	Elastic modulus	Poisson's ratio	Compressive strength	Thermal expansion coefficient	Thermal conductivity	Specific heat capacity
	kg/m ³	GPa	-	MPa	/°C	W/(m·K)	J/(kg·K)
Steel plate	7850	206	0.3	490	1.1×10^{-5}	55	480
Glass fiber-reinforced plastic	1900	3	0.25	250	2×10^{-5}	0.4	900
Polyurethane	1200	0.0003	0.42	8	1.5×10^{-4}	0.22	1700
Butyl rubber	920	0.01	0.45	15	2×10^{-4}	0.18	1900

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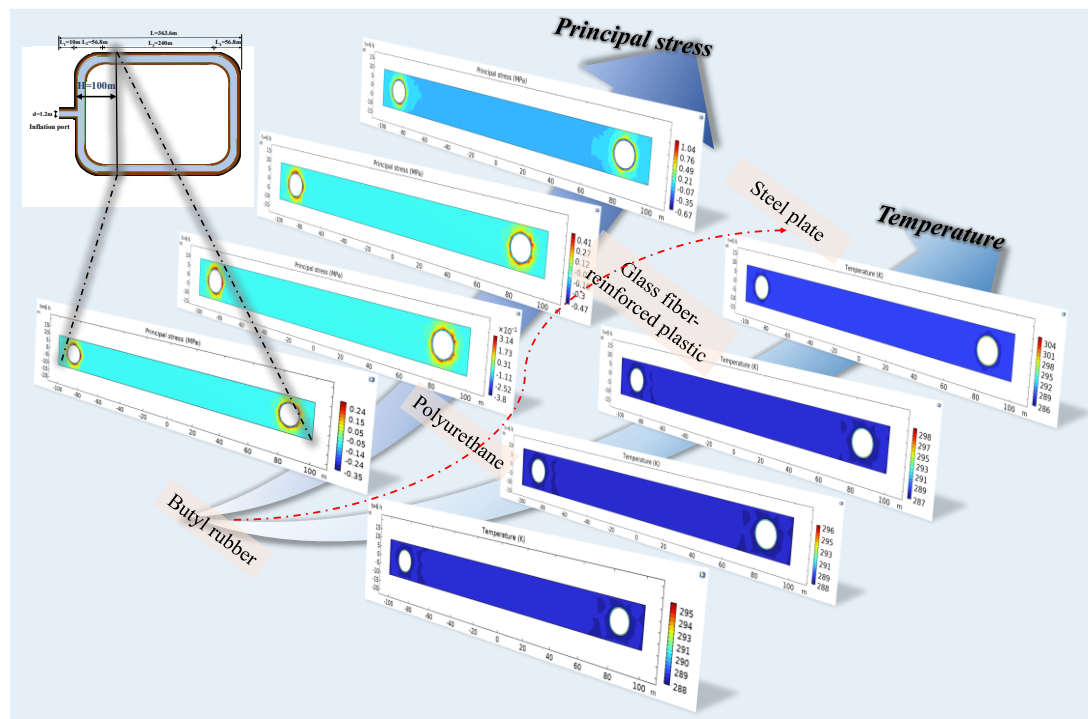


Fig.16. Cavern physical field distributions under different sealing materials

459 The thermo-mechanical responses of cavern during a 6 h charging process were compared in
 460 Fig.16. The results indicate that the sealing material exerts a pronounced regulatory effect on the
 461 cavern's thermo-mechanical behavior, with influence following a consistent ranking: steel liner >
 462 fiberglass > polyurethane > butyl rubber. As the material shifts from high-conductivity, high-
 463 stiffness materials to low-conductivity, low-modulus types, both thermal accumulation and stress
 464 concentration are mitigated.

465 For the thermal response, the peak air temperature decreases from 313.06 K to 305.28 K,
 466 302.16 K, and 301.12 K, corresponding to reductions of 7.78 K, 10.90 K, and 11.94 K, respectively.
 467 Meanwhile, the wall temperature decreases from 304.09 K to 297.41 K, 295.20 K, and 294.52 K,
 468 with reductions of about 21.6%, 28.7%, and 30.9%. For mechanical response, the maximum first
 469 principal stress at the cavern boundary decreases from 2.51 MPa to 1.46 MPa, 1.15 MPa, and 1.05
 470 MPa, with a maximum reduction of about 58.2%, indicating that reducing the stiffness of the sealing
 471 layer can significantly weaken stress transfer from the internal pressure to the surrounding rock and
 472 thereby alleviate local stress concentration.

473 Material-related responses should be interpreted as the combined effects of thermal and
 474 mechanical properties. Lower thermal conductivity can reduce heat penetration into the lining and
 475 surrounding rock, but can also weaken heat dissipation from the compressed air. Therefore, the
 476 observed air-temperature reduction cannot be attributed to thermal conductivity alone, but reflects

the combined effects of thermal inertia, gas-solid heat exchange, and pressure-temperature coupling. Mechanically, a lower elastic modulus reduces stress transfer and mitigates local stress concentration and damage evolution.

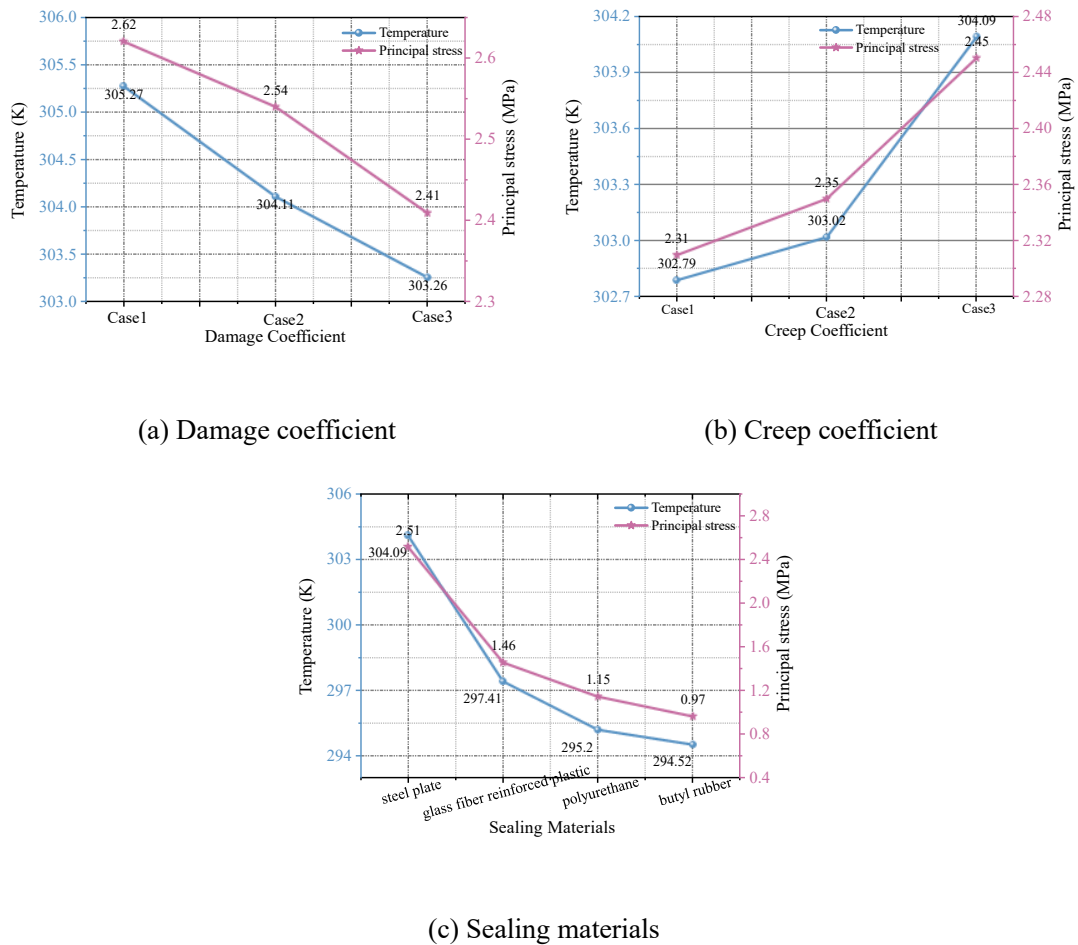


Fig.17. Effects of material factors on the evolution of pressure and wall temperature

As shown in Fig.17, material properties markedly affect cavern temperature and principal stress. Increased damage weakens the thermo-mechanical response, while creep enhances heat accumulation and stress concentration, making high-creep materials unfavorable for stability. Sealing materials also cause significant differences, confirming their critical role in controlling the thermo-mechanical behavior. The material-related parameters play a different role from geometric and operating parameters. Damage and creep parameters mainly affect local stress redistribution, deformation concentration, and damage-zone evolution, whereas their direct influence on short term air-domain temperature and pressure is relatively limited.

5 Discussion and limitations

5.1 Dynamic rate analysis and semi-empirical correlations

During cavern charging, key physical responses are governed by the coupled effects of structural configuration, operational conditions and material properties. The air domain responses are taken as the primary focus for quantitative analysis and law extraction, especially temperature and pressure, since they directly characterize the thermodynamic performance of the CAES cavern. Under this multiphysics coupling framework, the sensitive targets and influence magnitudes of key governing factors are identified. The solid domain responses are mainly used to interpret the fluid-

solid coupling mechanisms, while the air domain temperature and pressure responses are adopted as the primary quantitative indicators for comparative analysis.

The parametric evolution of temperature and pressure changing rates reveals a clear separation in their dominant control mechanisms. The temperature changing rate is primarily controlled by cavern geometry and convective heat transfer condition, whereas the pressure changing rate is mainly governed by the charging rate. Although thermal evolution and gas compression are intrinsically coupled during cavern operation, their transient responses are dominated by different controlling factors.

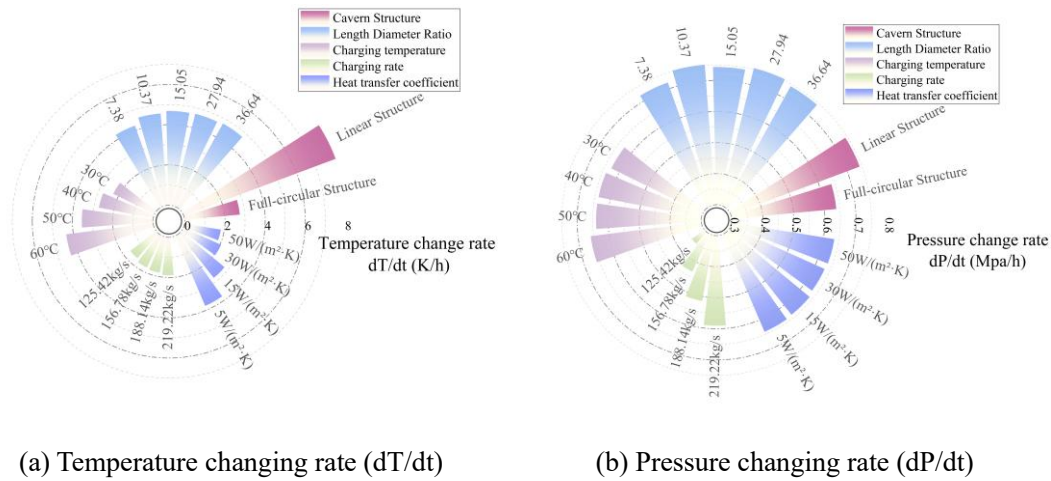


Fig.18. Sensitivity of temperature and pressure changing rate to parameters

As shown in Fig.18, cavern structure exhibits a decisive influence on the temperature changing rate. The full-circular cavern exhibits about 2.75 K/h, while the linear cavern reaches 8.07 K/h, nearly three times higher, due to differences in heat transfer area and flow patterns. By contrast, the influence of the aspect ratio on the temperature changing rate is relatively limited. As the aspect ratio decreases from 36.64 to 7.38, the temperature changing rate decreases from 4.76 K/h to 4.24 K/h. For pressure changing rate, the geometric parameters only induce minor variations of 0.72-0.75 MPa/h, indicating that geometry plays only a secondary role in the pressure buildup dynamics.

The injection temperature mainly affects the thermal response. As the injection temperature increases from 30 °C to 60 °C, the temperature changing rate increases from 2.29 K/h to 4.35 K/h, whereas the pressure changing rate increases slightly from 0.63 MPa/h to 0.66 MPa/h, indicating that a higher inlet temperature primarily accelerates thermal accumulation. In contrast, the charging rate exerts the most significant control over the pressure dynamics. When the charging rate increases from 125.42 kg/s to 219.22 kg/s, the pressure changing rate rises from 0.35 MPa/h to 0.59 MPa/h, with an increase of 68.57%, while the temperature changing rate only increases from 1.62 K/h to 1.89 K/h. This shows that cavern geometry dominates thermal accumulation, injection temperature mainly accelerates thermal response, and charging rate primarily controls pressure buildup.

The convective heat transfer coefficient suppresses the thermal response. As the convective heat transfer coefficient increases from 5 to 50 W/(m²·K), the temperature changing rate decreases from 3.78 K/h to 1.83 K/h, with a reduction of 51.5%, indicating that enhancing the heat dissipation capacity can effectively inhibit thermal accumulation. Meanwhile, the pressure changing rate remains almost constant at 0.63-0.64 MPa/h, confirming that heat transfer primarily affects thermal dynamics with little impact on pressure buildup.

Overall, the temperature changing rate is mainly governed by cavern geometry, charging temperature, and gas-wall heat transfer, whereas the pressure changing rate is dominated by charging mass flow rate. A normalized local sensitivity and reduced-order uncertainty analysis further confirm these response-specific control mechanisms. Detailed formulations, sensitivity coefficients, uncertainty settings, and complete data are provided in the Supplementary Material. Single-factor scans and regression analyses reveal distinct functional relationships between the influencing factors and the temperature changing rate. Cavern geometry has the strongest effect, aspect ratio shows a weak negative influence, charging temperature has a strong positive effect, charging mass flow rate has a secondary influence, and the convective heat-transfer coefficient exerts a nonlinear suppressing effect. Based on these characteristics, a multiplicative separable correlation is established to represent the combined geometric, operational, and heat-transfer effects.

To facilitate the development of unified semi-empirical correlations, the governing parameters were expressed in dimensionless form using normalized response factors. The reference values for the aspect ratio, charging gas temperature, charging mass flow rate, and convective heat-transfer coefficient were taken as 10.37, 313.15 K, 156.78 kg/s, and 15 W/(m²·K), respectively. Based on these reference conditions, the dimensionless variables were defined.

$$\begin{aligned}\xi &= \ln\left(\frac{L/D}{10.37}\right) \\ \theta &= \frac{T_m - 40}{10} \\ M &= \frac{m_c}{156.78} - 1 \\ H &= \ln\left(\frac{h}{5}\right)\end{aligned}\quad (23)$$

$$k_T = C_T \cdot \alpha_{shape} \cdot (1 + 0.15\xi - 0.1\xi^2) \cdot (1 + 0.2\theta + 0.05\theta^2) \cdot (1 + 0.2M) \cdot (1 - 0.3H) \quad (24)$$

Where, k_T is the temperature changing rate, K/h; T_m is the charging temperature, K; m is the charging mass flow rate, kg/s; h is the convective heat transfer coefficient, W/(m²·K); α_{shape} is the shape factor for temperature changing rate, with 1.0 for full-circular cavern and 2.93 for linear cavern.. The coefficient C_T represents the rate of pressure change under reference operating conditions and is set at 2.75 K/h.

Applying the same modeling strategy to the pressure changing rate, and all relevant parameters are incorporated into a multiplicative separable-variable framework to construct a prediction model that preserves physical consistency. The resulting model is a semi-empirical correlation obtained by regression of the numerical simulation results and is applicable for rapid estimation and trend analysis within the parameter ranges considered in this study.

$$k_p = C_p \cdot \beta_{shape} \cdot (1 + 0.06\xi - 0.05\xi^2) \cdot (1 + 0.02\theta) \cdot (1 + 0.9M - 0.1M^2) \cdot (1 - 0.01H) \quad (25)$$

Where, k_p is the pressure changing rate, MPa/h; β_{shape} is the shape factor for pressure changing rate, with 1.0 for full-circular cavern and 1.16 for linear cavern. The coefficient C_p represents the rate of pressure change under reference operating conditions and is set at 0.64 MPa/h.

The performance of the proposed semi-empirical model was evaluated using four metrics: R², RMSE, MAE and MRE, all of which were calculated using Equations (26)-(29).

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$$\alpha_{shape} R^2 = 1 - \frac{\sum_{i=1}^n (Y_i - \hat{Y}_i)^2}{\sum_{i=1}^n (Y_i - \bar{Y}_i)^2} \quad (26)$$

563

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (Y_i - \hat{Y}_i)^2} \quad (27)$$

564

$$MAE = \frac{1}{n} \sum_{i=1}^n |Y_i - \hat{Y}_i| \quad (28)$$

565

$$MRE = \max \left(\left| \frac{Y_i - \hat{Y}_i}{Y_i} \right| \right) \times 100\% \quad (29)$$

566

Where, Y_i and $\hat{Y}_i$ represent the results calculated by the numerical model and the semi-empirical model, respectively; $\bar{Y}_i$ is the average of all numerical simulation results; and n is the sample size.

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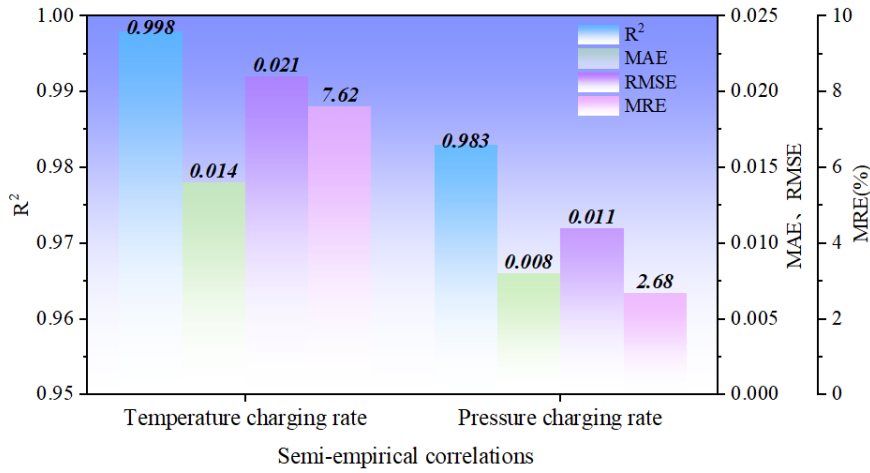


Fig.19. Performance of the normalized semi-empirical correlations

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Fig.19 presents the prediction performance of the proposed normalized semi-empirical correlations. The temperature changing rate correlation gives the R^2 of 0.998, with MAE and RMSE of 0.014 and 0.021, respectively. The pressure changing rate correlation also shows statistical accuracy, with the R^2 of 0.983, MAE of 0.008 and RMSE of 0.011. The maximum relative errors are 7.62% for temperature and 2.68% for pressure, indicating that the proposed correlations can reliably estimate the thermodynamic changing rates within the investigated parameter ranges.

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5.2 Thermodynamic response under repeated cycles

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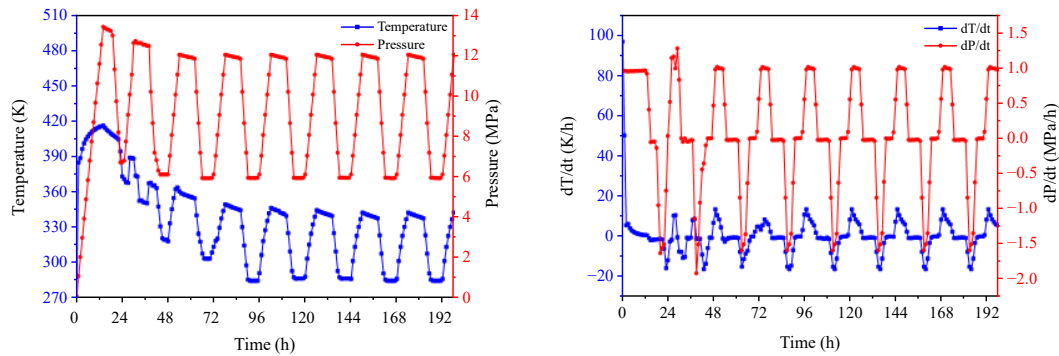
To preliminarily examine the influence of cyclic loading, a supplementary repeated charge-discharge scenario was analyzed from the initial charging stage to the eighth cycle. During the stable repeated cycles, the cavern pressure mainly varies between 6 MPa and 12 MPa.

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As shown in Fig.20, the strongest thermodynamic response occurs during the initial charging stage, with peak average temperature and pressure reaching 415.95 K and 13.39 MPa, respectively. After repeated cycling, the peak responses gradually attenuate and approach a quasi-stable periodic state. In the eighth cycle, the peak temperature and pressure decrease to 342.30 K and 12.02 MPa,

582

583 corresponding to reductions of approximately 17.71% and 10.23%, respectively.



(a) Evolution of average air temperature and pressure

(b) Evolution of temperature and pressure changing rates

Fig.20. Preliminary thermodynamic response under repeated cycles

584 The changing-rate curves show that large temperature and pressure fluctuations mainly occur
 585 during transitions between charging, storage and discharging. The single-cycle analysis can capture
 586 the main transient thermodynamic mechanism, the conclusions related to cyclic behavior should be
 587 interpreted as preliminary trends. Future studies should incorporate long-term field monitoring,
 588 laboratory-calibrated creep and damage parameters, and longer-term simulations to evaluate the
 589 cumulative evolution of stress, deformation, damage and leakage risk.

590 5.3 Model limitations and future research perspectives

591 This study focuses on short-term cavern responses under representative operating conditions.
 592 In practical engineering applications, underground CAES caverns experience long-term, multi-cycle
 593 operation, where THMD responses accumulate over time. Future annual-cycle modeling should
 594 preserve the state evolution between successive cycles and incorporate seasonal and time-varying
 595 boundary conditions. Due to the scope of this study, the evolution of thermal-mechanical responses
 596 of the surrounding rock under multi-cycle operations and the associated potential instability
 597 mechanisms were not addressed and should be investigated in future work. Under rapid charging
 598 and large temperature rises, the temperature dependence of material thermal properties may
 599 influence heat transfer. Future studies could incorporate temperature-dependent thermal property
 600 models to improve simulation accuracy. Furthermore, although the present results are physically
 601 reasonable, their reliability is still limited by the lack of direct validation against field measurements
 602 or experimental data. Future studies should incorporate field monitoring data to support model
 603 calibration and validation.

604 The surrounding rock is simplified as a homogeneous and isotropic porous medium without
 605 explicitly considering fractures, joints or spatial heterogeneity, which may affect seepage paths,
 606 local stress redistribution, heat transfer, and pressure loss under complex geological or imperfect
 607 sealing conditions. Under the controlled conditions considered, full-circular caverns exhibit better
 608 thermodynamic performance by reducing local heat accumulation and improving temperature
 609 uniformity. However, this should not be interpreted as a universal engineering optimum. Actual
 610 cavern selection also depends on geological stability, excavation and support requirements,

construction feasibility, and life-cycle cost, which should be integrated into future multi-objective engineering optimization.

6 Conclusions

This study adopts and assesses a THMD-based numerical framework for CAES caverns. Field comparison with the Huntorf plant validates the air domain thermodynamic responses, while the mechanical, seepage, creep and damage responses are interpreted as physically constrained coupled responses and sensitivity indicators.

The multiphysics responses of CAES caverns are governed by the interplay of cavern structure, operating parameters and material properties, with cavern geometry dominating thermal behavior. Under identical conditions, the peak air temperature is 331.46 K in linear and 323.38 K in circular caverns, while the peak pressure are 11.46 MPa and 10.72 MPa, circular caverns reduce wall temperature variation by 50.3%, mitigating local thermal accumulation. Furthermore, as the aspect ratio decreases from 36.64 to 7.38, the peak wall temperature is reduced by 7.12%, highlighting the role of geometric optimization in field uniformity.

Operating parameters significantly regulate thermo-mechanical responses. Increasing the injection temperature from 30 °C to 60 °C, the peak air temperature rises by 2.57 K and expands high-temperature zone. While increasing mass flow rate from 125.42 kg/s to 219.22 kg/s, the air temperature rise exceeds 11K and pressure increases by 1.45MPa. Optimizing parameters contributes to a more uniform temperature field.

Material properties critically affect cavern stability. Compared with the steel liner, the use of fiberglass, polyurethane, and butyl rubber reduces the peak air temperature by 19.5%, 27.3% and 29.9%, and decreases the maximum boundary principal stress by 58.2%. This indicates that the selected non-metallic sealing materials improve the coupled thermo-mechanical response mainly by reducing stress transfer and enhancing deformation compatibility, while the observed temperature reduction should be interpreted as a combined effect of multiple material properties rather than the isolated effect of low thermal conductivity.

Dynamic responses are further clarified by analyzing temperature and pressure change rates. The temperature changing rate is 2.75 K/h in circular cavern but reaches 8.07 K/h in linear cavern; while the convective heat transfer coefficient increases from 5 to 50 W/(m²·K), the temperature changing rate decreases by 51.6%, while the pressure change remains nearly unchanged; when the injection rate increases, the pressure changing rate increases by 68.57%, whereas the temperature changing rate increases by 16.67%. Based on these results, semi-empirical mathematical correlation models are established to guide structural optimization, parameter selection, and rapid mathematical assessment.

From an engineering perspective, the present results suggest that cavern geometries with smoother curvature, relatively smaller aspect ratios within the investigated range, appropriate control of inlet air temperature, and optimized charging strategies can effectively mitigate thermal accumulation and pressure fluctuations in CAES caverns. In contrast, material parameters play a more important role in evaluating structural safety margins, local damage evolution, and long-term durability than in directly regulating the short-term thermodynamic response of the air domain. Overall, the proposed multiphysics coupling framework and semi empirical correlation models extend the analysis of CAES cavern behavior from qualitative interpretation to quantitative characterization based on correlations. These findings provide a theoretical basis for parameter

654 optimization, preliminary engineering design, and performance assessment of the coupled
655 thermodynamic and mechanical evolution of underground CAES caverns.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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