

Article

Numerical Study on Thermal Damage Behavior and Heat Insulation Protection in a High-Temperature Tunnel

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Abstract: Deepening our understanding of temperature and stress evolution in high-temperature tunnels is indispensable for tunnel support and associated disaster prevention as the rock temperature is remarkably high in hot dry rock (HDR) utilization and similar tunnel engineering. In this paper, we established a two-dimensional thermal–mechanical coupling model through RFPA^{2D}-thermal, by which the temperature and stress field of the surrounding rock in a high-temperature tunnel with and without thermal insulation layer (TIL) were studied, followed by the evolution of thermal cracks. The associated sensitivity analysis of the TIL and airflow factors were then carried out. We found that (1) the tunnel rock is unevenly cooled down by the cold airflow, which induces thermal stress and damages the rock element when it exceeds the tensile strength of the rock mass. Those damaged rock elements accumulate and coalesce into visible cracks in the tunnel rock as the ventilation time goes, reducing the tunnel stability. (2) TIL effectively reduces the heat exchange between the airflow and tunnel rock and weakens the cold shock by the airflow, delaying the crack initiation which provides efficient time to adopt engineering measures for tunnel supporting. (3) TIL parameters are of pivotal importance to the long-term cold shock by the airflow. Increasing the TIL thickness and reducing the TIL thermal conductivity both significantly enhance the thermal insulation effect. The results cover the gap in the study of cold shock in high-temperature tunnels, which is helpful in designs to prevent thermal damage in high-temperature tunnels.

Keywords: high-temperature tunnel; thermal insulation layer; insulation effect; thermal damage

1. Introduction

Tunnel hazards caused by extremely high/low temperatures, such as freeze–thaw damage in cold regions [1,2] and heat disasters in high-temperature zones [3–5], have always been an overwhelming concern [6–8]. Installing a reasonable thermal insulation layer (TIL) is widely accepted as an effective method to weaken the heat exchange between the tunnel wall and the airflow [9–12]. Thus, studying the variation temperature in the tunnel before and after paving TIL is helpful in designing the tunnel TIL to prevent rock failure disasters induced by the temperature variation [13,14].

When the airflow goes through a tunnel, heat exchange occurs due to the temperature difference, leading to their temperatures being simultaneously varied before reaching a balance [1,3,4,15]. In cold regions, the tunnel rock is cooled and frozen in the winter by cold airflow but heated and melted in the spring as the airflow temperature increases [7,16]. Such freezing–thawing cycles induce freeze–thaw damage, weakening the tunnel rock strength and reducing the tunnel safety [17]. Such damage is effectively prevented by installing TIL on the tunnel wall, which decreases the heat flux between tunnel rock and airflow due to low thermal conductivity [8,18]. Numerous studies have focused on the temperature variation before and after TIL installation by analytical [6,19], numerical

[7,20], and experimental methods [21]. They found that the heat exchange is intense at the tunnel entrance and becomes weak with the increased ventilation distance, resulting in the freeze–thaw damage always appearing near the tunnel entrance [22]. Paving TIL near tunnel entrance can efficiently eliminate freeze–thaw damage, which is verified by combining numerical simulation and engineering data in the Yuximolegai tunnel [9], Nan Shan tunnel [2], and other tunnels [7,8,10,23]. In high-temperature tunnels, TIL is paved to prevent the heat flux from the tunnel rock to the airflow, ensuring that the airflow temperature is acceptable for the safety of tunnel excavation and the physical health of workers [4,24]. Thus, TIL needs to be installed on the whole tunnel wall rather than on the entrance area in the cold area [3]. Meanwhile, the TIL insulation capacity is varied with changing the TIL properties and airflow parameters, such as TIL thickness [10,25], TIL thermal conductivity [16,24,26], initial airflow temperature [3,19,20], and airflow speed [19], which are conducted for TIL design optimization to balance the tunnel cost [23,27]. Previous studies play vital roles in the temperature variation in cold region tunnels, ensuring such tunnels avoid freezing–thawing disasters. However, only a limited number of studies have focused on the airflow temperature variation in a high-temperature tunnel. Moreover, the variation in mechanical properties of the tunnel rock with changing temperature induced by the ventilation is rarely studied, whether in cold tunnels or high-temperature tunnels [10]. In some high-temperature tunnels, the maximal rock temperature exceeds 200 °C, such as 208 °C in the Sichuan-Tibet Railway and more than 200 °C in the EGS-E (Enhanced Geothermal System-Based Excavation) tunnel (Figure 1), resulting in considerable temperature difference between the airflow and the tunnel rock [3,5]. The rock temperature remarkably decreases once being ventilated under the cold airflow [3], shrinking the tunnel rock and inducing associated thermal stress. That stress possibly damages the tunnel rock and reduces the tunnel instability if the thermal stress exceeds its tensile strength [28–31]. Therefore, it is key to ensure the effective support and safe operation of high-temperature tunnels to investigate the variation in the temperature and stress field and the damage mechanism of tunnel rock induced by the cold airflow.

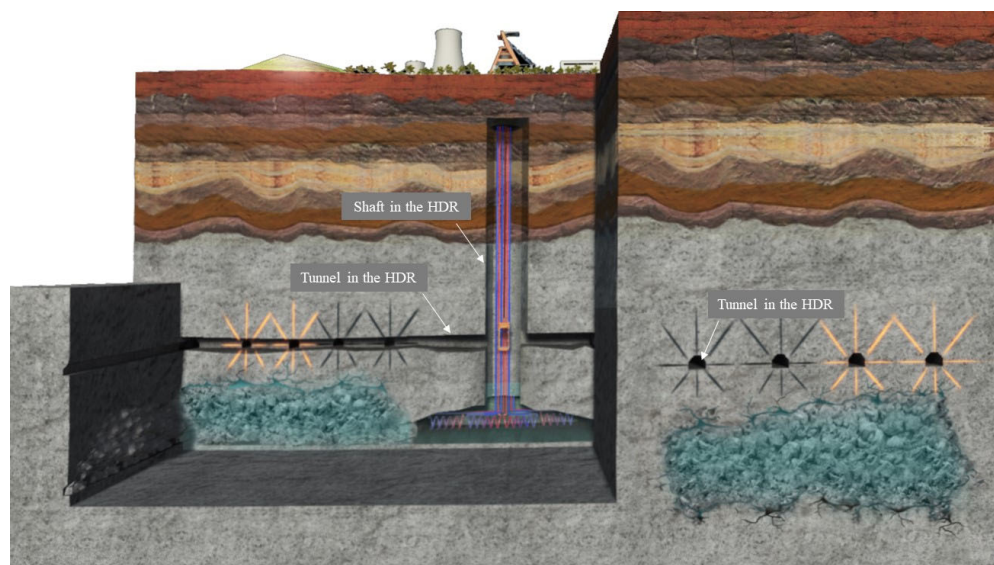


Figure 1. EGS-E model (after Kang et al. [32]).

In this study, we investigate the temperature and stress variation in a high-temperature tunnel with and without TIL, using a mechanical–thermal coupled numerical model in RFPA^{2D}-Thermal, during which the thermal crack evolution in the tunnel rock is performed. We also carry out the sensitivity analysis on TIL insulation capacity and crack propagation by varying TIL properties and airflow parameters.

2. Methodology

The Realistic Failure Process Analysis (RFPA) is a finite element method-based computing code, considering the heterogeneity of rock mass via the Weibull distribution, thereby transforming the problem of non-linear failure on the macro scale into the problem of linear failure on the mesoscale [33–35]. RFPA^{2D}-Thermal can accurately investigate the temperature and stress field variations under the thermal effect, as well as the associated crack initiation, propagation, and coalescence [36]. The simulation results agree well with the analytical solutions [29] (Figure 2a,b) and experimental results [37] (Figure 2c). Thus, RFPA^{2D}-Thermal is capable of predicting the temperature and stress distribution of the tunnel rock, reproducing the thermal damage and thermal crack evolution induced by the cold airflow [29,36].

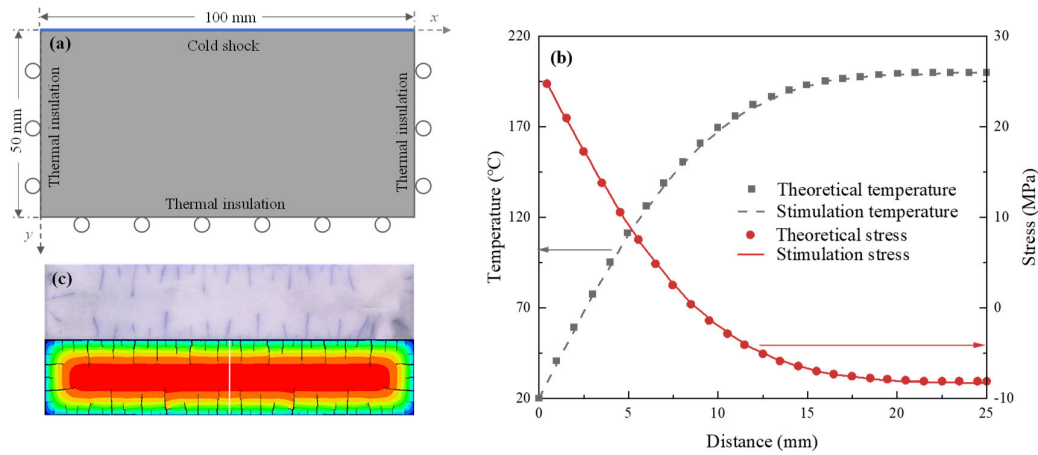


Figure 2. Comparison of analytical and RFPA solutions: (a) the geometric model, (b) temperature and stress field of analytical and numerical results (after Tang et al. [28]), and (c) crack patterns obtained from the experimental tests and RFPA simulations spectra fitting. Reproduced from [37] with permission from Elsevier.

2.1. Governing Equations

2.1.1. Heat Conduction Equation

$$\frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) = \rho c \frac{\partial T}{\partial t} \quad (1)$$

where k is the thermal conductivity, T is the temperature, ρ is the density, c is the specific heat capacity, and t is the time [38].

2.1.2. Deformation Compatibility Equation

$$\sigma_{ij,j} + F_{bi} = 0 \quad (2)$$

$$\sigma_{ij} = \lambda \varepsilon_{kk} \delta_{ij} + 2G \varepsilon_{ij} - (3\lambda + 2G) \alpha \Delta T \delta_{ij} \quad (3)$$

$$\varepsilon_{ij} = (u_{i,j} + u_{j,i})/2 \quad (4)$$

$$G = E/2(1 + \nu) \quad (5)$$

$$\lambda = 2\nu G/(1 - 2\nu) \quad (6)$$

where σ_{ij} is the stress tensor, ε_{ij} is the strain tensor, F_{bi} is the body force, α is the thermal expansion coefficient, ΔT is the temperature difference, δ_{ij} is the Kronecker function, G is the shear modulus, λ is the Lamé constant, E is the elastic modulus, and ν is the Poisson's ratio [33,34,39].

2.2. Heterogeneity of Rock Materials

The unit strength, elastic modulus, Poisson's ratio, and other parameters of rock materials have great spatial heterogeneity, which can be expressed by specific mathematical-statistical distribution functions, such as the Weibull distribution [33]. The expression of parameter heterogeneity based on Weibull statistics is [33]:

$$\varphi(\beta) = \frac{m}{\beta_0} \cdot \left(\frac{\beta}{\beta_0}\right)^{m-1} \cdot e^{-\left(\frac{\beta}{\beta_0}\right)^m} \quad (7)$$

where $\varphi(\beta)$ is the statistical distribution density of the mechanical properties, β is the mechanical property parameters of meso elements (strength, elastic modulus, etc.), β_0 is the average macro parameters, and m is the uniformity coefficient of the rock mass which reflects the homogeneity. As shown in Figure 3, the mechanical properties of the unit are distributed in a narrower range near its average value with a larger m .

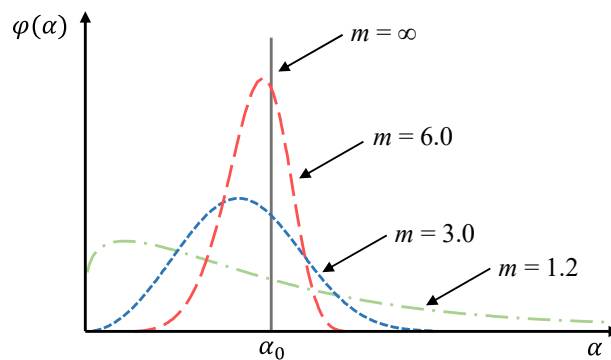


Figure 3. Weibull distribution with different m index.

2.3. Mechanical Property and Thermophysical Property Evolution

The deformation and failure process of the element obeys the constitutive relationship of elastic damage mechanics. When the stress state of the element meets the specific failure criterion, the element is damaged. We introduce a damage variable D to describe the cumulative damage expression of the elastic modulus:

$$E = (1 - D)E_0 \quad (8)$$

where E is the elastic modulus value after damage, E_0 is the initial value of elastic modulus, and D is the damage variable.

We adopt the Mohr–Coulomb strength theory with the tensile criterion as the criterion of elementary failure. The characteristics of rocks in tension are non-linear and additionally, rocks also experience plastic deformations in tension [40]. However, the non-linear problem in macro-scale can be changed into linear problem in meso-scale, by considering the heterogeneity of rock in meso-scale [33]. When the maximum tensile principal strain of the element reaches its given strain threshold, it begins to undergo tensile damage (Figure 4). The damage variable D is transformed into:

$$D = \begin{cases} 0 & \varepsilon < \varepsilon_{t_0} \\ 1 - \frac{\sigma_{tr}}{\varepsilon E_0} & \varepsilon_{t_0} \leq \varepsilon \leq \varepsilon_{t_u} \\ 1 & \varepsilon > \varepsilon_{t_u} \end{cases} \quad (9)$$

where σ_{tr} is the residual strength after the tensile damage, ε_{t_0} is the tensile strain corresponding to the ultimate elastic state of the element, and ε_{t_u} is the ultimate tensile strain of the element. $D = 0$, $0 < D < 1$, and $D = 1$ corresponds to the non-damaged, incomplete damaged, and completely damaged, respectively.

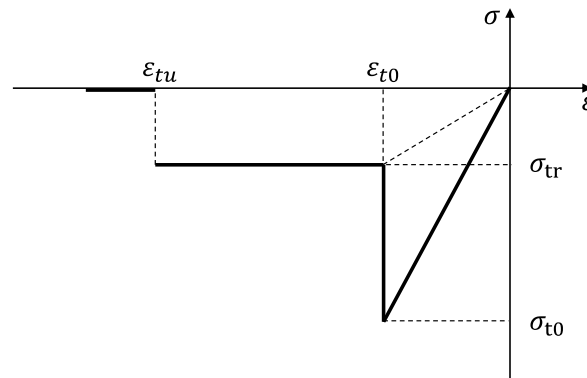


Figure 4. Theoretical damage constitutive law of the element under the tensile stress.

Meanwhile, the thermal conductivity and heat capacity of the element varies with the temperature and damage variable D when the element exceeds the damage threshold, according to the following equation [41]:

$$\lambda_T = \begin{cases} 1 + \frac{\lambda_0}{0.99 + T(a - b/\lambda_0)} & (0 < D < 1) \\ \xi_1 \lambda_0 & (D = 1) \end{cases} \quad (10)$$

$$c_T = \begin{cases} c_0(1 + \varpi T) & (0 < D < 1) \\ \xi_2 c_0 & (D = 1) \end{cases} \quad (11)$$

where λ_T is the thermal conductivity, c_T is the heat capacity at T , λ_0 and c_0 are the thermal conductivity and heat capacity at 0°C , a and b are empirical parameters [41], and ϖ is the empirical coefficient that is $3 \times 10^{-3}^\circ\text{C}^{-1}$ in general. ξ_1 and ξ_2 are the damage effect coefficient of thermal conductivity and heat capacity, respectively, equal to the ratio of the thermal conductivity and heat capacity of the element to the air.

2.4. Numerical Model and Associated Conditions

When the cold air flows into a high-temperature tunnel, the tunnel is subjected to cold shock under the temperature difference between airflow and tunnel rock. The heat exchange at the tunnel entrance is the most severe [22], so it is representative to study the cold shock at the tunnel entrance. The cold shock model can be simplified to a coupled thermal-mechanical plane strain model with a hole and an insulation layer. The geometric model is shown in Figure 5, consisting of the circular tunnel, the insulation layer, and the surrounding rock.

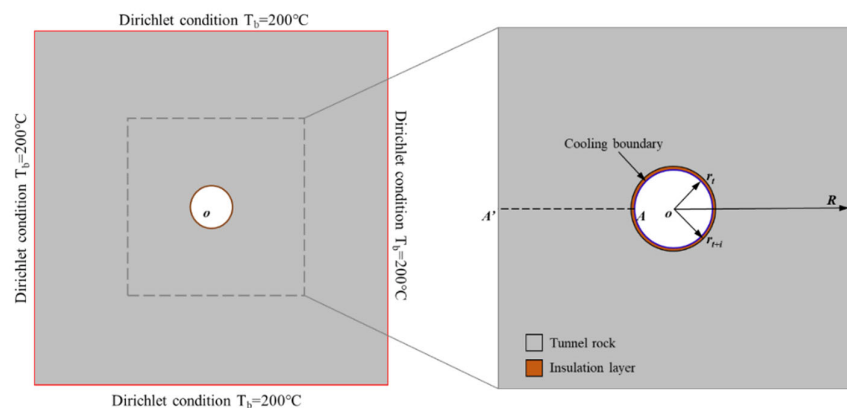


Figure 5. Diagram of numerical model.

The model size is 50×50 m, divided into 1000×1000 elements. The central circle radius (r_t) is set to 2.75 m, which equals to the tunnel radius in the EGS-E project [3]. The insulation layer is 0.1 m of thickness and 0.1 W/(m·K) of thermal conductivity. The initial rock temperature (T_r) is 200 °C, and the temperature of airflow (T_a) is 20 °C. The Dirichlet condition ($T_b = 200$ °C) is set to the outer boundaries, while the Robin condition is used for the heat exchange between the tunnel and the airflow as follows [37]:

$$-\lambda \frac{\partial T}{\partial n} = h(T_a - T_r) \quad (12)$$

where h is the heat convective coefficient on the tunnel wall that is 100 W/(m²·K).

The mechanical and thermal properties of tunnel rock and TIL are listed in Table 1 in detail.

Table 1. Physical and mechanical parameters in the numerical model.

Parameters	Values	Parameters	Values
Rock compressive strength σ_{sr}	233.05 MPa	TIL compressive strength σ_{si}	200 MPa
Rock tensile strength σ_{tr}	11.61 MPa	TIL tensile strength σ_{ti}	30 MPa
Rock thermal conductivity λ_r	2.86 W/m/K	TIL thermal conductivity λ_i	0.1 W/m/K
Rock specific heat capacity c_r	0.85×10^6 J/(m ³ ·K)	TIL specific heat capacity c_i	1×10^6 J/(m ³ ·K)
Rock Young's modulus E_r	37.46 GPa	TIL Young's modulus E_i	20 GPa
Rock Poisson's ratio ν_r	0.25	TIL Poisson's ratio ν_i	0.25
Rock thermal expansion coefficient α_r	8×10^{-5} 1/K	TIL thermal expansion Coefficient α_i	1×10^{-5} 1/K
Rock initial temperature T_r	200 °C	TIL initial temperature T_i	200 °C

3. Results and Analysis

3.1. Temperature and Stress Distribution of Tunnel under Ventilation without TIL

A uniform numerical model ($m = 1000$) is adopted to analyze the evolution of the temperature and stress field in the ventilated tunnel. Figure 6a shows the temperature variation in the $A-A'$ section under different ventilation times. Affected by the cold airflow, a cold front appears in the tunnel rock, disturbing the temperature field near the tunnel wall and forming a thermal disturbance circle [42]. The rock temperature in this area displays a decrease along the radial direction from the tunnel wall to the interior. The cold front spreads into the rock interior as the ventilation time goes, enlarging the thermal disturbance circle in which the rock temperature decreases further. The rock temperature T_r of the tunnel wall drops from 200 °C to 38.2 °C as the ventilation time t goes to 100 h. The temperature drop in the thermal disturbance zone causes a temperature gradient, thereby generating corresponding thermal stress (σ_T) [29,37] (negative represent tensile stress). Figure 6b presents the thermal stress of the $A-A'$ section under different ventilation times. Similar to the temperature evolution, the thermal stress descends from the tunnel wall to the interior but ascends with the increased ventilation time. The stress σ_T on the tunnel wall increases from −116.11 MPa to −123.48 MPa when the ventilation time t increases from 10 h to 100 h. It exceeds the tensile strength of most rock mass, which can possibly cause rock failure and crack initiation.

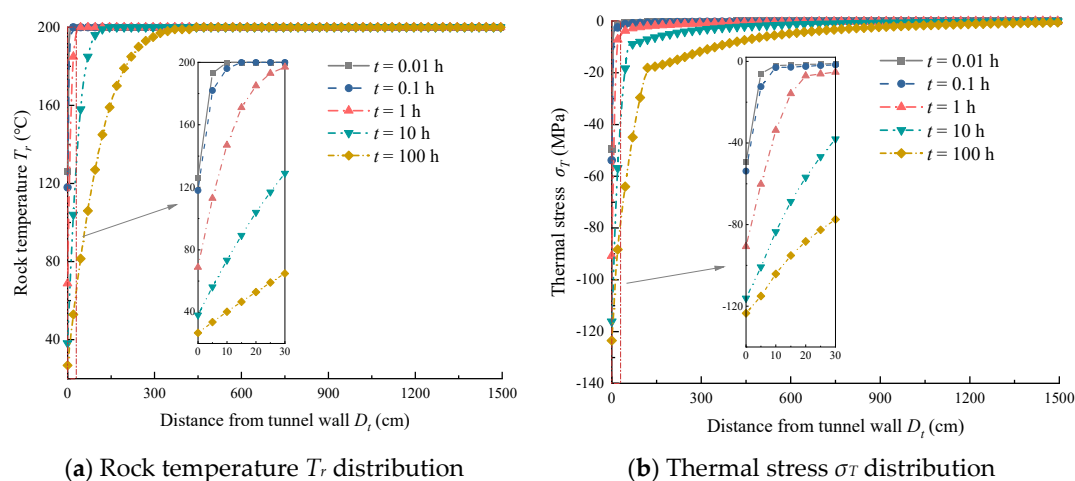


Figure 6. Temperature T_r and stress σ_T variations with varying ventilation time in tunnel without TIL.

The temperature and stress evolution illustrates that the increase in the thermal stress corresponds well to the decrease in the rock temperature, showing that a greater temperature drop causes more thermal stress increase. The surface temperature drops the fastest, resulting in the maximum temperature gradient and associated maximum thermal stress, which is consistent with Liu et al. [22]. Thus, reducing the temperature decrease rate of the tunnel rock, such as paving TIL on the tunnel wall, can effectively weaken the induced thermal stress and alleviate the associated rock damage.

3.2. Temperature and Stress Distribution of Tunnel with TIL

Lining a TIL on the tunnel wall plays a critical role in reducing the heat exchange between tunnel rock and airflow [3,10,12]. Figure 7 shows the temperature and associated thermal stress in the tunnel after paving a TIL with 0.1 m of thickness and 0.1 W/(m·K) of thermal conductivity. The temperature distribution in the tunnel with TIL is significantly different from that without TIL. A noticeable regional characteristic in the temperature variation is observed in the TIL and rock region, respectively, showing a sharp rise in the TIL and a slow growth in the tunnel rock. In the TIL area, a considerable temperature difference appears between the TIL outer and inner boundaries (Figure 7a). The TIL temperature (T_i) of outer boundary (tunnel wall) is 61.14 °C after being ventilated for 10 h, whereas that of the inner boundary (rock surface) is 179.33 °C, resulting in a 118.19 °C temperature difference. In the rock matrix, the temperature increases gently from the rock surface to the interior, which is similar to that in the tunnel without TIL. However, the rock temperature with TIL is higher than that without TIL at the same ventilation time. After 100 h of ventilation, the rock temperature T_r of the tunnel wall without TIL is 26.80 °C, while temperature T_r with TIL is 143.93 °C, resulting in a difference of 117.31 °C. Such a zoning characteristic of the temperature field is consistent with previous studies [1,2,9].

The resulting temperature difference reduces the thermal stress induced by the temperature variation. Thus, the thermal stress in the tunnel with TIL is significantly lower than that without TIL. As shown in Figure 7b, the stress σ_T on the tunnel wall reaches −123.48 MPa in the tunnel without TIL as the ventilation time t grows to 100 h, which reduces to −24.66 MPa after paving a TIL. The decrease in thermal stress can remarkably reduce the possibility of rock damage [29]. It suggests that the TIL significantly decreases the tunnel rock temperature and associated thermal stress, thereby protecting the rock mass from the cold shock damage.

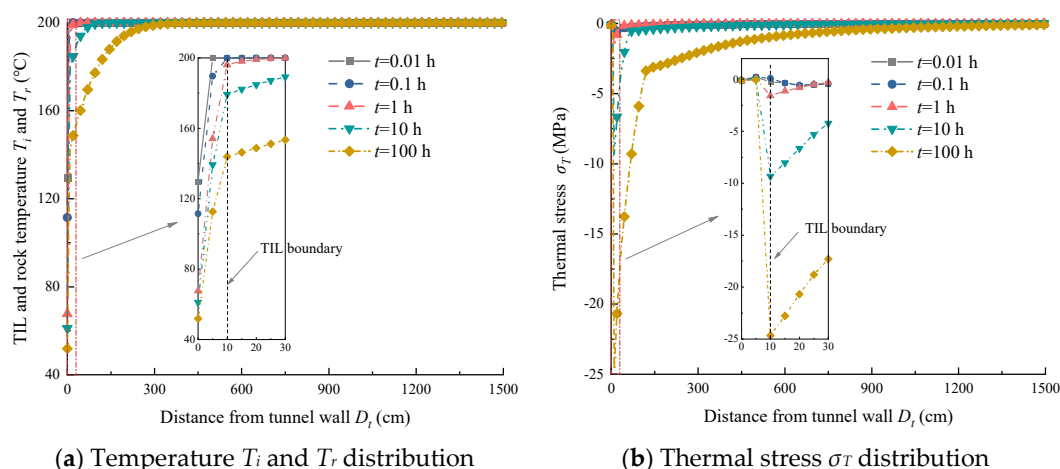


Figure 7. Temperature T_i and T_r and stress σ_T variations with varying the ventilation time in tunnel with TIL.

3.3. Influence of TIL and Airflow Parameters on Temperature and Thermal Stress Evolution

3.3.1. Influence of TIL Thickness

TIL thickness plays a crucial role in the temperature evolution of the airflow and the tunnel rock. Figure 8a presents the temperature and thermal stress variations in the tunnel ventilated for 100 h. The rock temperature T_r of rock surface increases with the thickened TIL, which grows from 83.70 °C to 143.93 °C and 169.90 °C as the TIL thickens (th_i) from 5 cm to 10 cm and 20 cm, respectively. This means that increasing the TIL thickness enhances the TIL insulation capacity. However, the enhanced insulation capacity by per TIL thickness significantly weakens as the total TIL thickness increases. For example, the rock temperature T_r of rock surface increases 39.77 °C when the TIL thickens from 5 cm to 10 cm, decreasing to 25.97 °C as the TIL thickness th_i grows from 10 cm to 20 cm. This attenuation has also been observed by Kang et al. [3] and Ma et al. [11], in which they indicated that the insulation capacity caused by per TIL thickness decreases with the total thickened TIL.

The decrease in the temperature variation reduces the thermal stress caused by cold shock on the tunnel rock. Figure 8b shows the thermal stress variation with varying TIL thicknesses at $t = 100$ h. The thermal stress σ_T on the rock surface decreases with thickening TIL, which weakens from −57.19 MPa to −13.46 MPa as the TIL thickness th_i increases from 5 cm to 20 cm. Note that the reduction in thermal stress caused by increasing per TIL thickness, similar to that of the temperature evolution, also decreases with the thickened TIL. The stress σ_T difference caused by the TIL increases from 5 cm to 10 cm is 32.53 MPa, decreasing to 11.20 MPa as the TIL thickness th_i ascends from 10 cm to 20 cm.

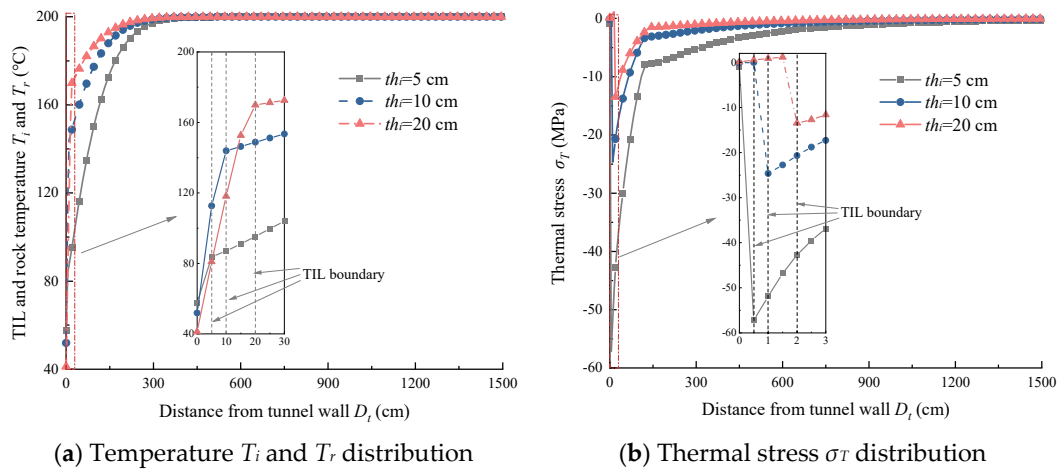


Figure 8. Temperature T_i and T_r and stress σ_T variations with varying TIL thickness.

In summary, laying a TIL increases the temperature of the rock surface and decreases associated thermal stress, but the insulation capacity by per thickness significantly decrease as the total TIL thickness increases. Thus, only increasing the TIL thickness is unable to enhance the insulation effect infinitely.

3.3.2. Influence of TIL Thermal Conductivity

Figure 9 presents the variations in the temperature and thermal stress with the changed TIL thermal conductivity (λ_i). Increasing TIL thermal conductivity decreases the rock temperature and increases the associated thermal stress. The rock temperature T_r of rock surface presents a decrease from 166.99 $^{\circ}\text{C}$ to 114.41 $^{\circ}\text{C}$ as the TIL thermal conductivity λ_i increases from 0.05 W/(m·K) to 0.20 W/(m·K), whereas the associated thermal stress σ_T displays an increase from -14.78 MPa to -37.41 MPa. However, the insulation capacity enhancement via reducing per thermal conductivity gradually weakens, consistent with that of TIL thickness. The temperature growth, induced by decreasing the thermal conductivity λ_i from 0.20 W/(m·K) to 0.10 W/(m·K), is 29.52 $^{\circ}\text{C}$, which reduces to 23.06 $^{\circ}\text{C}$ as the thermal conductivity λ_i decreases from 0.10 W/(m·K) to 0.05 W/(m·K). Similarly, the thermal stress σ_T exhibits a decrease of 12.73 MPa when the thermal conductivity λ_i reduced from 0.20 W/(m·K) to 0.10 W/(m·K), which decreases to 9.90 MPa when λ_i decreased from 0.10 W/(m·K) to 0.05 W/(m·K). Moreover, it is impossible to reduce the TIL thermal conductivity indefinitely limited to the technical. However, the insulation cost of high-temperature tunnels increases exponentially with thickening TIL and decreasing TIL thermal conductivity [43,44]. Therefore, finding how to balance the TIL cost and insulation effect is the most crucial issue to address in high-temperature tunnel engineering [44].

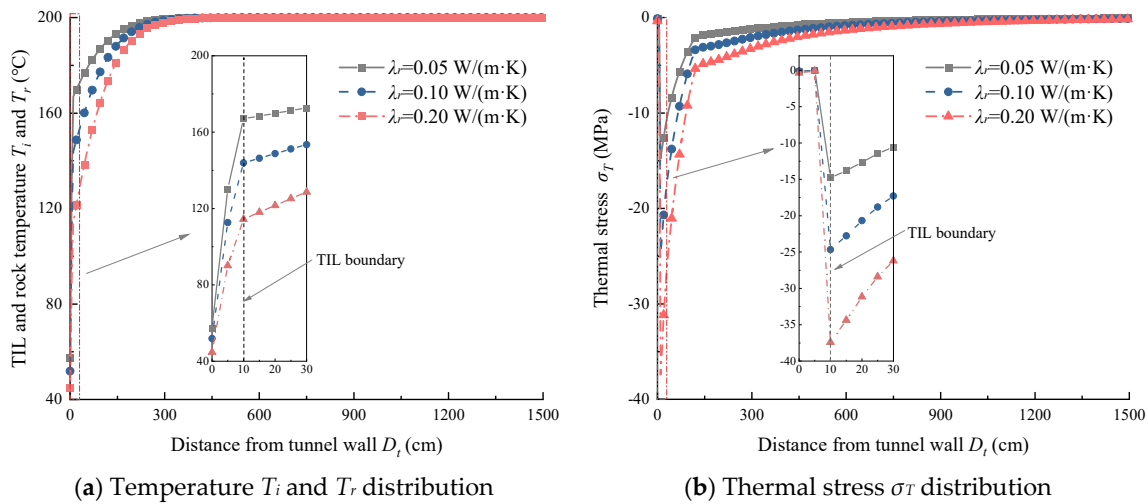
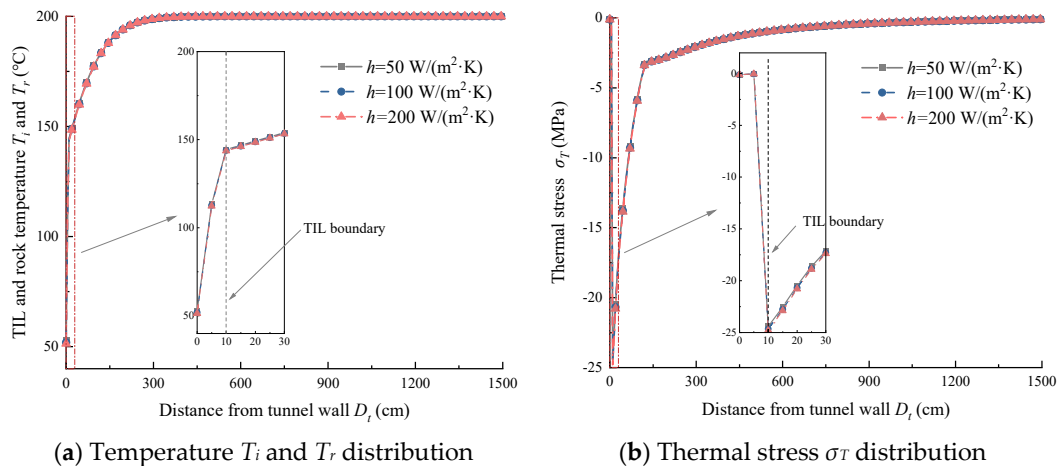


Figure 9. Temperature T_i and T_r and stress σ_T variations with varying TIL thermal conductivity.

3.3.3. Influence of Airflow Parameters

Figure 10 displays the variations of the temperature and thermal stress with changing heat convective coefficient (h) and inlet airflow temperature (T_{in}). Contrary to the influence of TIL factors, varying the airflow parameters has an unnoticeable effect on the temperature and stress distribution of the tunnel rock. Both the temperature and thermal stress remain nearly unchanged as the heat convection coefficient h increases from 50 W/(m²·K) to 200 W/(m²·K). Similarly, the inlet airflow temperature plays an unobvious role in the rock temperature and stress. The rock surface temperature T_r increases by 12.46 °C as the inlet airflow temperature T_{in} rises from −20 °C to 20 °C, while the associated thermal stress σ_T decreases by 5.50 MPa. This indicates that the heat convective coefficient and inlet airflow temperature have little influence on the temperature and thermal stress evolution in a ventilated high-temperature tunnel.



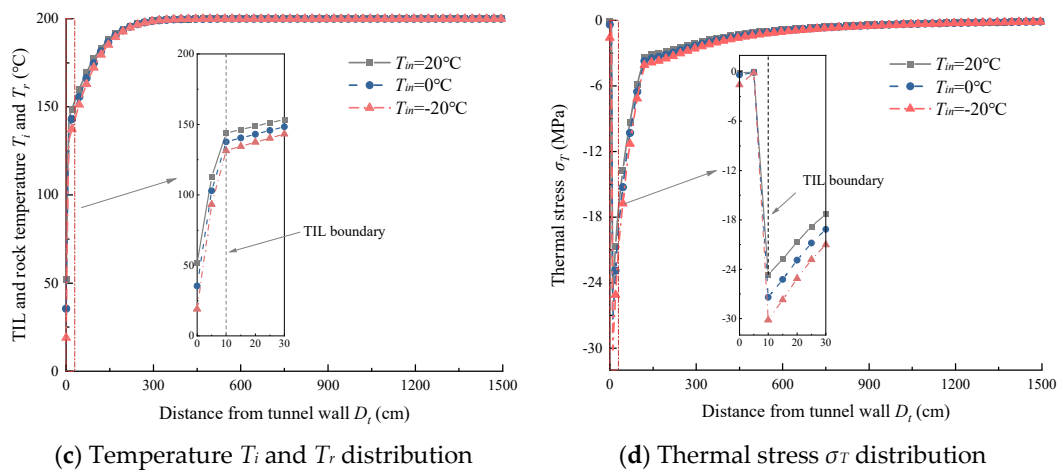


Figure 10. Temperature and stress variations with varying heat conductive coefficients and inlet airflow temperatures.

3.4. Thermal Cracks Evolution in Tunnels under Cold Ventilation

3.4.1. Cracks Propagation in Tunnels with and without TIL

The tunnel wall is quickly cooled once the tunnel is ventilated under the cold airflow, resulting in a sharp temperature drop and associated thermal stress. The stress induced by the temperature variation possibly leads to rock damage and crack initiation when it exceeds the tensile strength of the tunnel rock [29], weakening the tunnel stability. Figure 11 presents the crack evolution in tunnels with and without TIL through the heterogeneous model ($m = 6$) as the ventilation time increases. The thermal stress immediately exceeds the tensile strength of the tunnel rock once the airflow enters the high-temperature tunnel without TIL, causing damage elements observed around the tunnel wall (Figure 11a). Then, the thermal stress weakens, and the number of new damage element decreases (Figure 11b). However, the total number of damage element gradually increases as the ventilation time goes on, which coalesces and nucleates to visible cracks in the rock mass around the tunnel wall (Figure 11c). Those cracks become more pronounced when the ventilation time t reaches 10 h and 100 h (Figure 11d,e), during which some cracks gradually stop growing and others unstoppably propagate into the rock interior. This induces the long crack to alternate with short cracks around the tunnel wall with the same spacings. Such hierarchical cracks have been found by Tang et al. [29]. Note that the initial crack propagates in the direction perpendicular to the tunnel wall, slightly deflected at its tip with the increased ventilation time. The failure elements disturb the heat conduction of adjacent elements, which changes the temperature gradient and associated tensile stress, thus deflecting the following crack propagation.

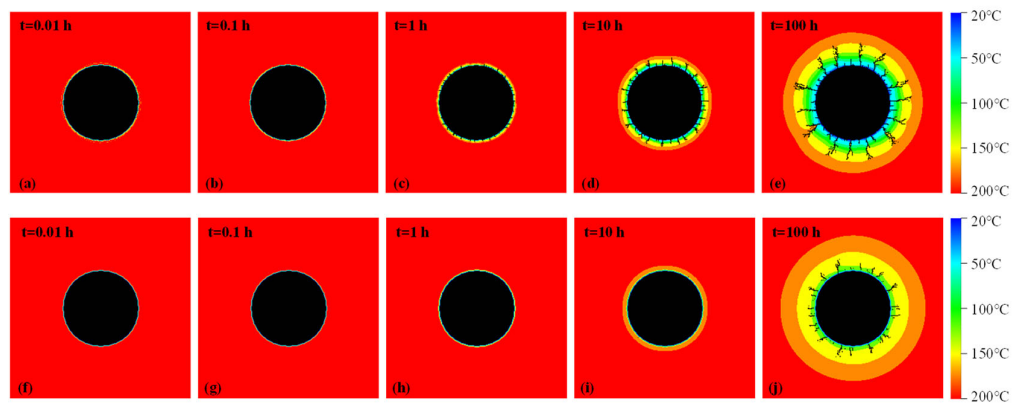


Figure 11. Crack evolution with increasing ventilation time in tunnels: (a)–(e) without TIL, (f)–(j) with TIL.

After paving a TIL with 0.1 m of thickness and 0.1 W/(m·K) of thermal conductivity, the crack initiation time is remarkably postponed. Few unnoticeable cracks are discovered around the tunnel rock surface until the ventilation time t grows to 10 h (Figure 11f–i). Although hierarchical cracks appear around the tunnel rock after 100 h of ventilation (Figure 11j), the number and length of cracks are remarkably less than those without TIL. Figure 12 shows the visual crack evolution in the tunnel rock with ventilation time. The total length of visible cracks in the tunnel without TIL is 791.93 cm at $t = 1$ h, which extends to 1721.48 cm and 3214.02 cm as the ventilation time t grows to 10 h and 100 h, respectively. However, the visible cracks in the tunnel with TIL are firstly found at $t = 10$ h, with a total length of 309.52 cm, then the total length increases to 1505.11 cm as the ventilation time grows to 100 h, which is only 47% of that in the tunnel without TIL.

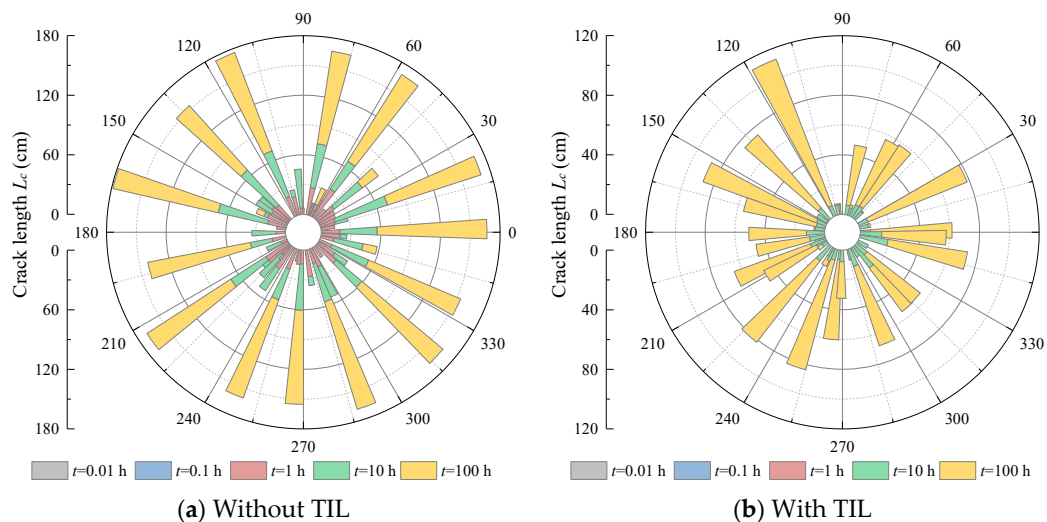


Figure 12. Cracks evolution with various ventilation time t : (a) without TIL and (b) with TIL.

In summary, the cold airflow decreases the tunnel temperature, forming a noticeable temperature variation and associated tensile stress-dominated area. The crack initiates and propagates in this area, damaging tunnel rock and endangering tunnel safety. Paving a TIL is of help to decrease the heat exchange between the cold airflow and the tunnel rock, which reduces the decreasing velocity of the tunnel temperature. It weakens the thermal damage in tunnel rock, postponing the crack initiation and decreasing the crack density.

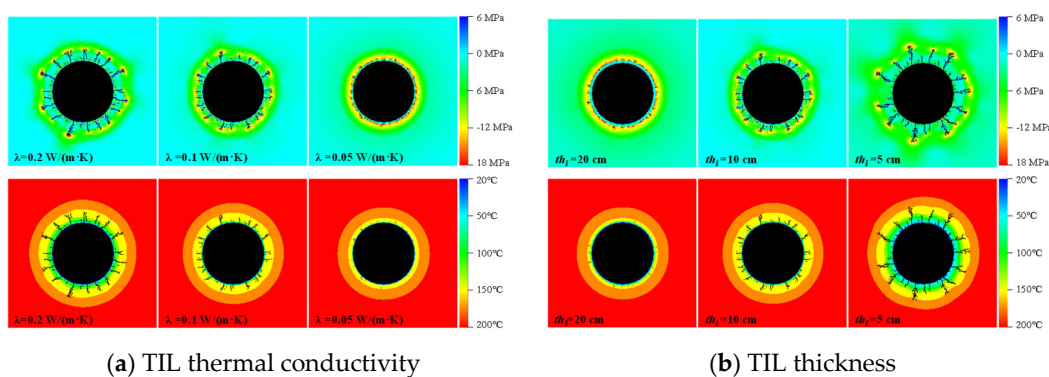
3.4.2. Influences of TIL and Airflow Parameters on Crack Propagation

TIL and airflow parameters play different roles in the variation of the temperature and stress field discussed in Section 3.3. In this section, we discussed their influence on the crack evolution in tunnel rock. Figure 13 exhibits the crack variation when the tunnel is ventilated by 100 h under different TIL thicknesses, TIL thermal conductivities, inlet airflow temperatures, and heat convection coefficients, respectively.

The thermal cracks grow with the increased TIL thermal conductivity and reduce with the thickened TIL. The crack is unnoticeable (Figure 13a) with a few AE events (Figure 14a) and a small AE energy (Figure 15a) when TIL thermal conductivity λ_i is 0.05 W/(m·K). It becomes obvious with increasing thermal conductivity λ_i to 0.1 W/(m·K) and more significant with the larger thermal conductivity, followed by more AE events and larger AE energy. However, those cracks reduce as TIL thickness increases and become invisible when TIL thickness grows to 20 cm (Figure 13b), during which both the AE event and energy decrease (Figures 14b and 15b). Figure 16 illustrates the length and number of visible cracks within every 30° from 0° to 360°. The total length of visible cracks grows from 351.42 cm to 2492.13 cm as the TIL thermal conductivity λ_i increases from 0.05 W/(m·K) to 0.2 W/(m·K), whereas it reduces from 2854.81 cm to 423.53 cm as the TIL thickness th_i grows from 5 cm to 20 cm.

In constant, changing the inlet airflow temperature and heat convective coefficient have little effect on the crack propagation. The crack remains nearly unchanged as the heat convective coefficient h increases from 50 W/(m²·K) to 200 W/(m²·K) (Figure 13c), as well as the AE event and accumulated AE energy (Figures 14c and 15c). The total crack length is 1504.60 cm, 1505.11 cm, and 1493.72 cm when the heat convective coefficient h is 50 W/(m²·K), 100 W/(m²·K), and 200 W/(m²·K), respectively (Figure 16c). Similarly, the thermal crack increases slightly (Figure 13d) when the airflow temperature T_{in} decreases from 20 °C to −20 °C, during which the AE event and accumulated AE energy increase insignificantly (Figures 14d and 15d), and the total crack length increases from 1505.11 cm to 1654.39 cm (Figure 16d).

As a result, increasing TIL thickness and decreasing TIL thermal conductivity efficiently weakens the crack initiation and propagation, reducing the thermal shock damage of tunnels in the HDR and similar high-temperature conditions. On the contrary, the influence of varying inlet temperature and heat convective coefficient (such as varying the airflow velocity) is unnoticeable. Therefore, the critical key for weakening thermal damage in high-temperature tunnels is how to optimize TIL parameters.



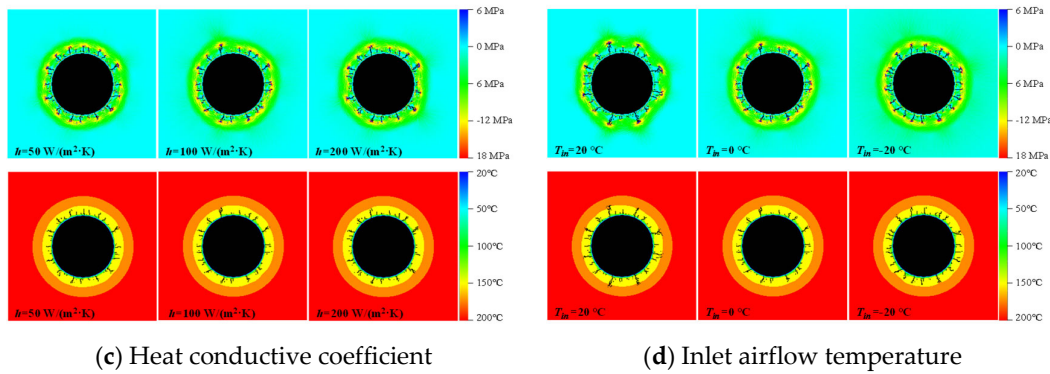


Figure 13. Crack evolution with various TIL and airflow parameters (the blue diagram is minimal stress distribution, and the red one is temperature distribution).

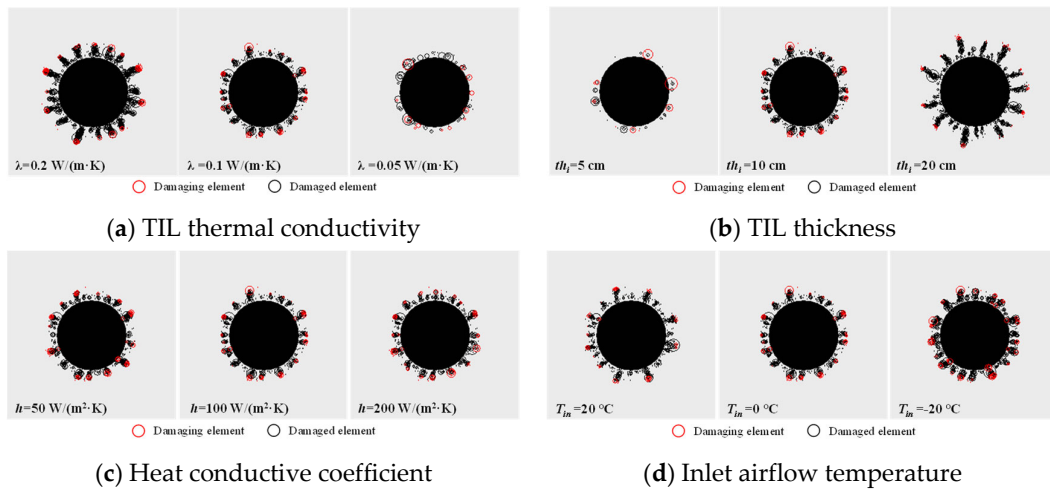
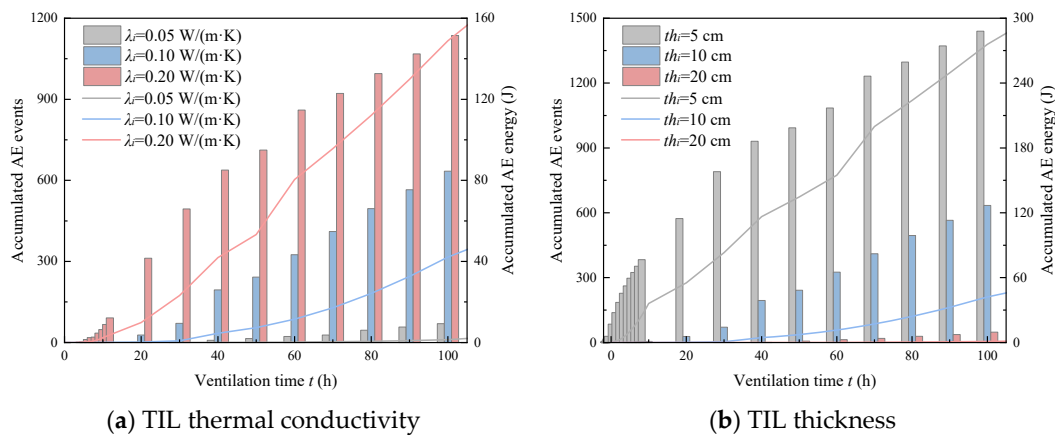


Figure 14. Damage elements with various TIL and airflow parameters (the red circle denotes the damaging elements in the current step, and the black circles denotes the damaged ones in the previous steps).



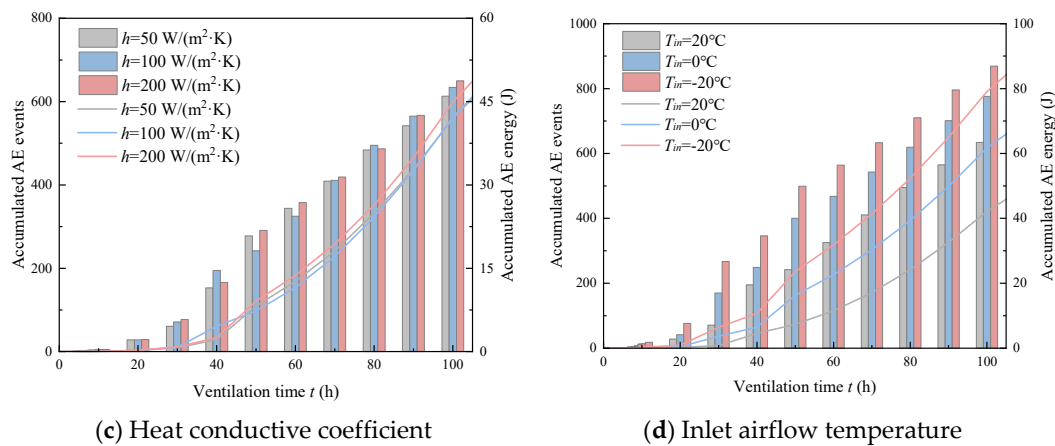


Figure 15. Variations of accumulated AE events and AE energy under different TIL and airflow parameters.

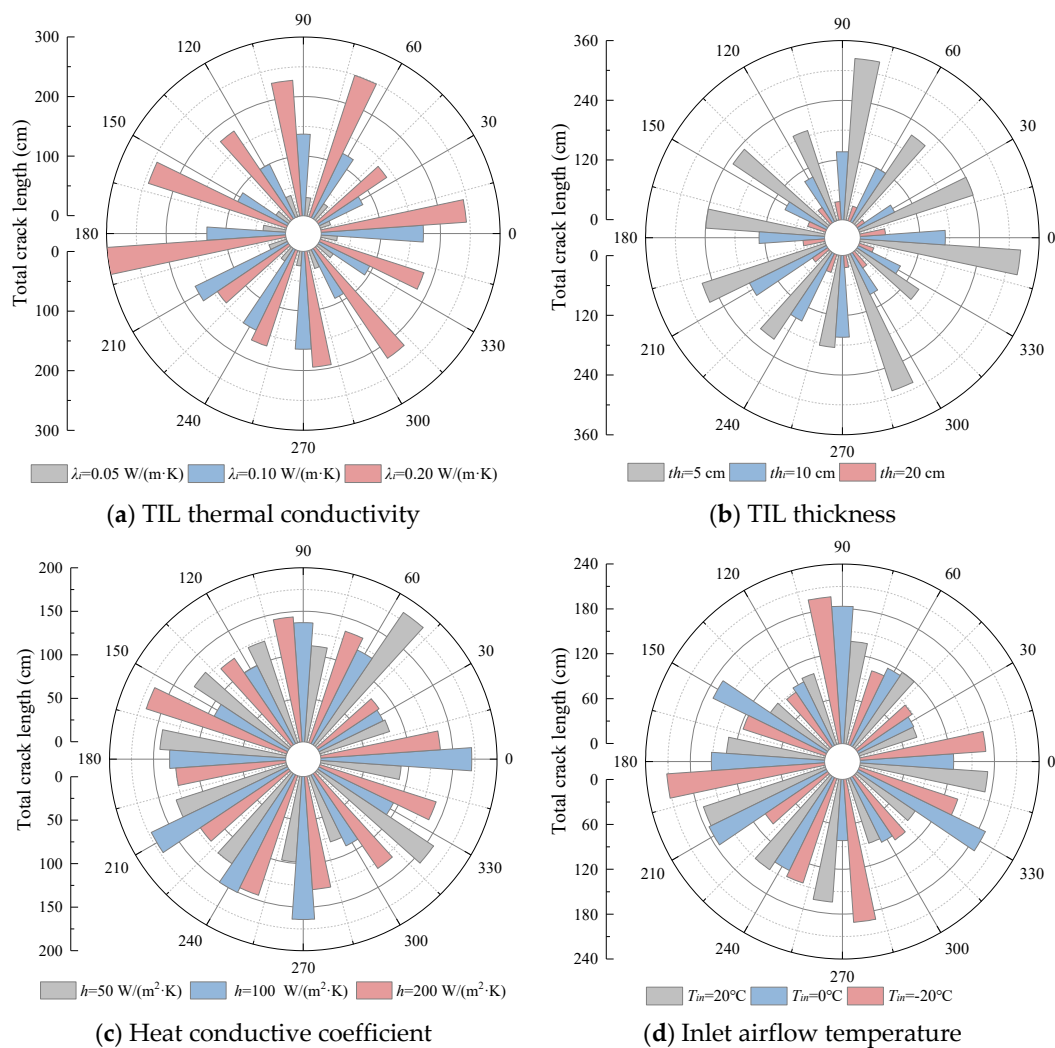


Figure 16. Total crack lengths under different TIL and airflow parameters.

4. Discussion

The temperature variation between the tunnel rock and airflow induces thermal stress, which is unnoticeable in most tunnel projects with small temperature differences

[29,37]. Previous studies paid attention to the temperature evolution around the tunnel rock, preventing tunnels in the cold region from freezing–thawing damage [2,16] and reducing the airflow temperatures in high-temperature tunnels to improve production efficiency and equipment safety [3,4]. However, thermal stress gradually becomes significant as the tunnel rock temperature increases, resulting in rock damage and crack initiation [29] that threatens tunnel construction safety. Unfortunately, the existence of only few studies in this field results in a knowledge gap. Our research successfully fills this gap and lays the foundation for subsequent research.

The tunnel rock temperature sharply decreases after tunnel excavation due to the heat transfer between the tunnel rock and airflow [22], inducing thermal stress and possible thermal damage in the rock mass [37]. That thermal stress is significantly weakened after paving a TIL on the tunnel wall that reduces the heat transfer flux and the temperature gradient between the tunnel rock and airflow. As a result, it postpones crack initiation and decreases the ultimate crack density, providing efficient time to adopt engineering measures for tunnel supporting. The insulation capacity is significantly enhanced via increasing the TIL thickness and decreasing the TIL thermal conductivity, which agrees with previous studies in cold region tunnels [10,45,46]. However, with thickening TIL and decreasing TIL thermal conductivity, the enhancement of the thermal insulation capacity remarkably decreases [25,47], but the TIL cost rapidly increases [43,44]. Therefore, how to balance the TIL insulation capacity and economy is necessary to be considered in the design of high-temperature tunnels.

Airflow parameters, such as inlet temperature and airflow speed, play vital roles in preventing the cold tunnels from freeze–thaw damage in tunnels [20,42,48], but their impact on thermal damage is unnoticeable. This disagrees with the stimulation results of Tang et al. [29], who suggested that a more significant heat conductive coefficient leads to earlier and more cracks in the rock mass. The reason for this difference includes two aspects. Firstly, the heat convective coefficient adopted in our study is from 20 W/(m²·K) to 300 W/(m²·K), which is small compared to Tang et al. [29], from 300 W/(m²·K) to 30,000 W/(m²·K). Secondly, we discussed the long-term effect of cold shock in this paper, not the short-term effect studied by Tang et al. [29]. The tunnel rock temperature rapidly decreases in a short time when ventilated by the cold airflow, during which increasing the heat conductive coefficient can enhance the temperature reduction [29,49]. However, the tunnel wall temperature rapidly decreases as the ventilation time grows and immediately equals the inlet temperature. Then, the Robin condition between the tunnel rock and the airflow swifts to the Dirichlet condition with a constant boundary temperature, where changing the convection heat transfer coefficient is meaningless for heat exchange. Thus, varying the heat convection coefficient has an unobvious effect on thermal stress and rock damage in long-term ventilation. Meanwhile, the inlet temperature reduces the average temperature in high-temperature tunnels, extending the valid ventilation distance where the temperature is acceptable for workers [3]. However, the temperature difference via varying inlet temperature is very small in our study, which is not enough to change the thermal stress and crack evolutions significantly.

In actual tunnels, in situ stress plays a crucial role in tunnel rock damage and associated cracks' evolution [29], and rocks experience plastic deformations in tension [40], which should be considered in the further simulation. Adopting a fixed heat convective coefficient in the simulation induces slight deviations, so investigating it by laboratory experiment will improve the accuracy of related numerical simulations. Moreover, converting a 2D model to a 3D one, one of our further research focuses, also can improve the simulation results. Additionally, ventilation machines and machinery equipment working in tunnels affect the airflow temperature distribution [50]; in turn, their mechanical behavior and operating status are affected by the airflow temperature [51,52], which should receive more attention in future research.

5. Conclusions

In this paper, we established a 2D model by RFP-thermal^{2D}, by which the temperature and stress field in a high-temperature tunnel with or without TIL were investigated, followed by the associated thermal damage and cracks evolution. The main conclusions are drawn:

- (1) The thermal stress is induced in the high-temperature tunnel rock ventilated by the cold airflow, damaging the rock unit when it exceeds the tensile strength of the tunnel rock. Such damaged units increase as the ventilation time grows and coalesces to visible cracks in the tunnel rock, reducing the tunnel stability.
- (2) Paving a TIL on the tunnel wall weakens the cold shock from the airflow, postponing crack initiation and reducing the total crack number and length. Visual cracks are discovered in the tunnel without TIL after ventilation for 1 h; however, the initiation time grows to 10 h in the tunnel with TIL. The total crack length under 100 h of ventilation decreases from 3214.02 cm to 1505.11 cm, a reduction of 53.17%.
- (3) Thickening TIL and decreasing TIL thermal conductivity remarkably enhanced the insulation effect on thermal damage, whereas descending the inlet temperature and ascending the heat transfer conductive coefficient has little insulation effect. This sensitivity analysis is helpful in designs to prevent thermal damage in high-temperature tunnels.

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