

Article

Study on Energy-Saving Potential Based on Heat and Moisture Transfer Characteristics During Fresh Air Introduction in Deep Underground Engineering

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Abstract

The goal of this paper is to clarify the heat–moisture coupled regulation mechanism of deep-buried underground air tunnels and to address the research gaps in the heat–moisture coupled transfer between airflow and surrounding rock. This paper established a 560 m deep ventilation shaft with a diameter of 5 m focused on the heat–moisture coupled transfer of “surrounding rock—air tunnel—airflow” to investigate the airflow characteristics; analyze the heat and moisture changes of the tunnel surface and airflow, as well as the energy storage characteristics of the surrounding rock; and compare the induced airflow characteristics across four typical cities in China. The results show the following: there is an “inlet effect” in the deep-buried air tunnel; the wall temperature becomes basically stable after 200 m from the entrance, while a greater depth is required for the stable section of humidity; in summer, the airflow temperature decreases by more than 1 °C and the enthalpy decreases by 3.5 kJ/kg; in addition, the ground temperature in Guangzhou is relatively high, resulting in a limited effect on adjusting the intake airflow. This study aims to provide support for the energy-saving design of fresh air systems in deep-buried underground buildings.

Keywords: underground air tunnel; heat–moisture coupled transfer; fresh air regulation; air tunnel energy storage



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1. Introduction

As the urbanization process advances in-depth toward underground space, deep-buried underground buildings have become a crucial carrier for alleviating the shortage of urban land resources and expanding urban functions. They are widely applied in key fields such as underground transportation hubs, deep laboratories, and underground complexes [1]. As a core facility for ensuring indoor air quality and thermal comfort in deep-buried underground buildings, the fresh air system exhibits energy efficiency in its pretreatment stage that directly impacts the overall energy-saving performance of the system. Serving as a key channel for fresh air supply, underground air tunnels can be regarded as a type of earth–air tunnel heat exchanger, which regulates incoming fresh air by utilizing the heat–moisture storage properties of the surrounding soil: cooling the outdoor air in summer and warming it in winter to deliver fresh air at a suitable temperature to the underground building, thereby reducing the energy consumption of air

conditioning systems. Presently, this technology has been widely applied in applications including agricultural greenhouses, deep-buried workshops, and emerging nearly zero-energy buildings (nZEBs) [2–6].

In recent years, a large number of researchers have developed various numerical models to characterize the heat transfer performance of earth–air tunnel heat exchangers (EATHEs). For example, Al-Ajmi et al. [7] proposed a theoretical model that can predict the outlet air temperature in hot and arid climatic regions; Liu et al. [8] developed a numerical model for heat transfer calculation targeting underground vertical U-tubes with a length of less than 16.5 m. However, these models only consider the sensible heat transfer process and do not involve moisture-related heat transfer phenomena. Eduardo de la Rocha Camba and Fontina Petrakopoulou [9] introduced an idea for replacing water-based cooling systems in thermal power plants with earth-cooling air tunnels. The new system takes advantage of the low and relatively constant underground temperature for cooling ambient air before it is introduced in the air condenser of the plant.

Heat–moisture coupled transfer in deep-buried underground air tunnels exhibits distinct multiphysics coupling characteristics, with its regulatory effect on fresh air dependent on the dynamic heat–moisture coupled exchange mechanism among the surrounding rock, air tunnel wall, and airflow. Existing studies, through the establishment of mathematical models for the moisture and heat balance of the surrounding rock, have identified that this complex heat–moisture coupled transfer process is jointly driven by the following: (1) the seepage of liquid water in the surrounding rock under capillary force; (2) the diffusion of water vapor under a water vapor partial pressure gradient; (3) heat conduction through the solid skeleton of the surrounding rock; and (4) latent heat release and absorption during the moisture phase change [10,11].

Currently, studies on heat–moisture coupled transfer in surrounding rock primarily focus on the surrounding rock in engineering settings such as tunnels, underground hydropower stations, and roadways, encompassing two key research directions: surrounding rock heat transfer and its heat–moisture coupled transfer. Liu [12] investigated the thermal accumulation effect of tunnel surrounding rock induced by periodic variations in outdoor air temperature and its propagation law in the surrounding rock. The study found that the tunnel wall temperature changes periodically with outdoor air temperature, exhibiting amplitude attenuation and phase delay relative to the air temperature; additionally, the amplitude of temperature waves within the surrounding rock attenuates exponentially with increasing depth. Qin et al. [13,14] focused on the temperature field of roadway surrounding rock, established a one-dimensional unsteady heat conduction governing equation under periodic boundary conditions, introduced dimensionless criterion numbers to conduct dimensionless analysis of the mathematical model, and derived prediction formulas for roadway wall heat flux and surrounding rock temperature. Wang et al. [15] investigated the evolution characteristics of heat storage in subway tunnel surrounding rock under periodic dynamic variations in air temperature by constructing a scaled-down test bench.

Regarding research on heat–moisture coupled transfer in surrounding rock, Liu et al. [16,17] classified hydropower station underground caverns into two categories: narrow and long caverns, and large-space caverns. By adopting Whitaker’s volume-averaging theory, taking temperature and moisture content as the driving potentials, and accounting for wall condensation, they investigated the dynamic heat–moisture coupled adsorption–desorption characteristics of surrounding rock. Zhang [18] adopted relative humidity and temperature as the driving potentials, considered latent heat, established a mathematical model for heat–moisture coupled transfer in surrounding rock, proposed a method for calculating the far-boundary thickness of surrounding rock in underground space, and

calculated the hourly heat–moisture coupled adsorption–desorption of the wall as well as the temperature and humidity distribution of the surrounding rock via numerical methods. Xiang [19], building on the heat–moisture coupled transfer theoretical model for surrounding rock in hydropower station underground workshops, integrated numerical simulation, experimental research, and data regression analysis to investigate the factors influencing the heat–moisture coupled adsorption–desorption of the surrounding rock wall.

In summary, existing theories regarding heat–moisture coupled transfer in surrounding rock are relatively mature. However, a gap remains in targeted studies on heat–moisture coupled transfer between tunnel airflow and surrounding rock during the air induction process of underground air tunnels. Against this backdrop, this study focuses on the effects of deep-buried underground air tunnels on the heat–moisture state and enthalpy of intake fresh air, and conducts research in three key aspects: First, we analyze the dynamic variation characteristics of fresh air temperature and humidity along the tunnel, and quantify the intensity of heat–moisture exchange at different locations and in different seasons. Second, we reveal the mechanism by which the tunnel regulates the enthalpy of fresh air, and clarify the regulatory contributions of summer enthalpy reduction and winter enthalpy increase. Third, by incorporating the characteristics of typical climate zones, we evaluate the differences in the regulatory effects of underground air tunnels on fresh air heat, moisture, and enthalpy levels under different meteorological conditions.

2. Mathematical–Physical Model

2.1. Physical Model

Figure 1 illustrates an engineering case where the ventilation shaft of an underground building has a depth of approximately 560 m and a diameter of 5 m. This engineering project is located in Chengdu, Sichuan Province, China. This dimensional design balances fresh air supply volume and air tunnel resistance: it not only meets the fresh air requirements for both underground personnel's respiration and equipment heat dissipation, but also avoids unduly high airflow resistance from an unduly small shaft diameter and increased construction costs from an unduly large one. The shaft's fresh air supply is sourced from a ground-based air induction station. Notably, in typical engineering scenarios, the ground-based air station serves solely for "power-driven air transportation" and is not equipped with additional air treatment equipment (e.g., heating, cooling, humidification, or dehumidification devices). Thus, the state properties (e.g., temperature, humidity) of the fresh air entering the shaft are fully consistent with real-time outdoor meteorological conditions.

As shown in Figure 2, the geometric model of the underground building and the heat–moisture coupled transfer process are presented. Since the fresh air tunnel has a regular circular cross-section, its heat–moisture coupled transfer characteristics in the circumferential direction are uniform (that is, the heat transfer and mass transfer capabilities between the air tunnel wall and the surrounding rock are consistent at any circumferential position). Thus, there is no need to construct a complex 3D geometric model; instead, only a 2D longitudinal cross-sectional model along the air tunnel axis needs to be established. In this model, the fresh air flows stably inside the air tunnel, and at the same time, continuously undergoes heat–moisture coupled transfer with the surrounding underground rock through the air tunnel wall; this includes both heat exchange (e.g., high-temperature outdoor fresh air releases heat to low-temperature surrounding rock in summer, and low-temperature outdoor fresh air absorbs heat from high-temperature surrounding rock in winter) and moisture migration (e.g., soil moisture in the surrounding rock diffuses into dry fresh air, or water vapor in high-humidity fresh air permeates into dry surrounding rock). This coupling process directly determines the final state of the fresh air when it reaches the

entrance of the underground building, and it is not only a key consideration factor in the environmental control design of underground buildings, but also the core content of this study.

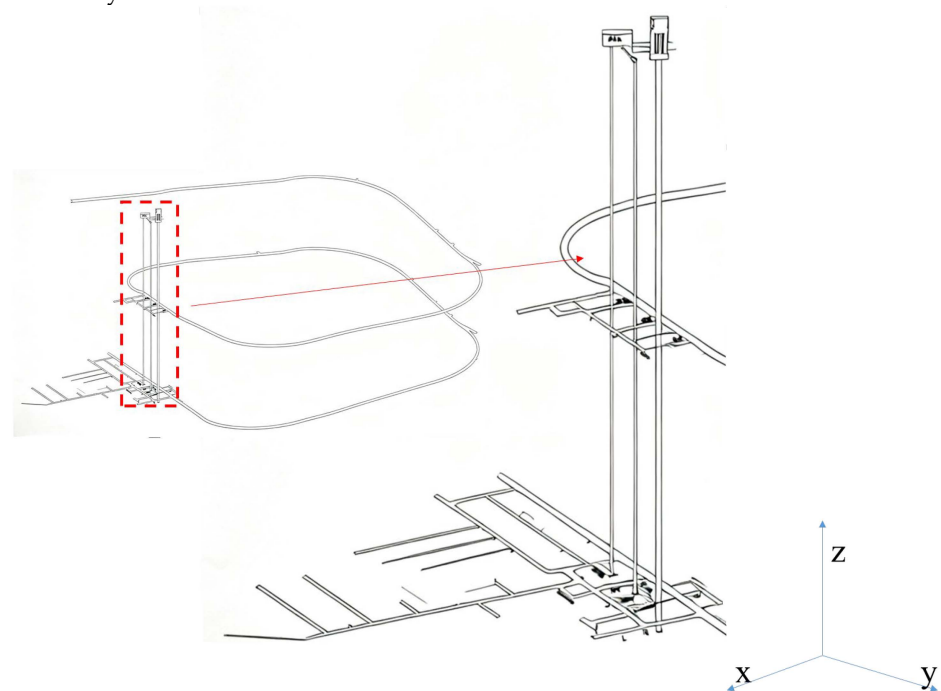


Figure 1. Case of underground building ventilation shaft project.

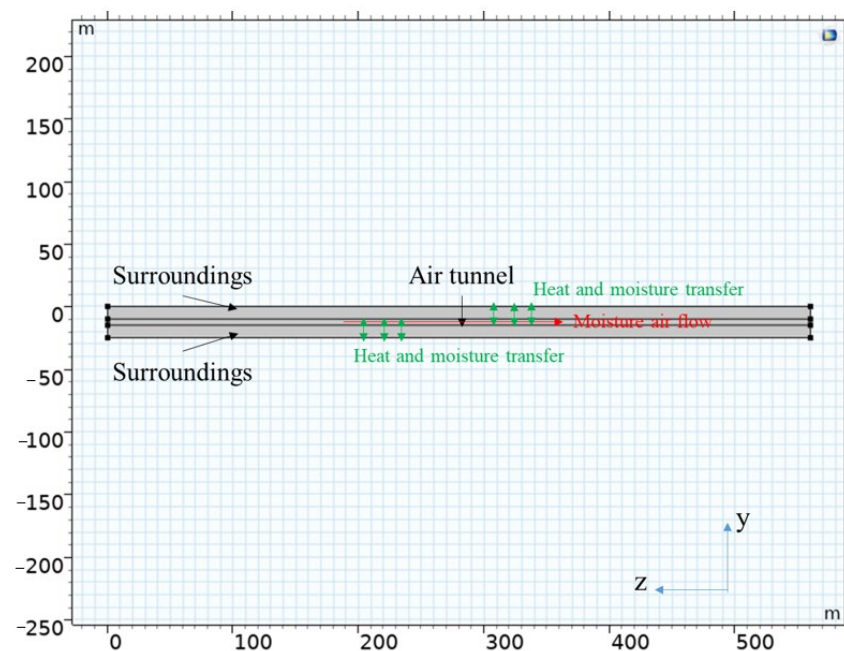


Figure 2. Geometric model of underground ventilation shaft and schematic diagram of heat–moisture coupled transfer.

2.2. Mathematic Model

The surrounding rock of the underground air tunnel focused on in this study is an unsaturated porous medium. Moisture in its internal pores mainly exists in two forms: liquid water and water vapor, and both forms undergo internal migration. Among them, the migration of liquid water is primarily driven by the dual forces of gravitational potential and matric potential: gravitational potential promotes the directional migration of moisture

along the gravitational field direction, while capillary potential (a component of matric potential) drives the seepage of liquid water from areas with lower capillary pressure to those with higher capillary pressure. However, considering the calculation context and accuracy requirements of this study, the effect of gravity on liquid water migration can be neglected.

From the perspective of moisture content thresholds, when the surrounding rock's moisture content exceeds its maximum hygroscopic moisture content, internal moisture primarily exists as free water. In this case, liquid water seeps and diffuses from areas of higher moisture content to those of lower content under capillary force; conversely, if the moisture content is below this threshold, moisture is mainly retained in the rock as adsorbed water. In this state, the dominant form of moisture migration is water vapor diffusion.

Notably, the heat–moisture coupled transfer process within the surrounding rock is highly complex. Its transfer behavior is governed not only by the rock's own thermo-hygroscopic properties (e.g., thermal conductivity, porosity, water-holding capacity, among others) but also significantly influenced by the indoor environmental parameters of the underground building (e.g., temperature, humidity, airflow conditions). To simplify subsequent mathematical model development and calculations, the following assumptions are made regarding the surrounding rock's characteristics prior to model establishment:

- (1) The surrounding rock medium is assumed to be uniform, continuous, and isotropic, with its physical properties (e.g., thermal conductivity, permeability) remaining consistent across all spatial positions and directions;
- (2) Moisture within the surrounding rock is restricted to two phases: gas (water vapor) and liquid (liquid water), with moisture freezing in low-temperature environments neglected for the present;
- (3) Water vapor is treated as an ideal gas, with its state changes adhering to the ideal gas law. Intermolecular forces and molecular volume of real gases are neglected;
- (4) Any micro-region (i.e., local point) within the surrounding rock is assumed to satisfy heat and moisture balance conditions, without instantaneous drastic fluctuations in temperature or humidity parameters;
- (5) Given the regular shape of the surrounding rock, its heat–moisture transfer is assumed to occur solely along its thickness direction (exhibiting one-dimensional transfer), with heat and moisture exchange in other directions neglected;
- (6) Under isothermal conditions, capillary hysteresis during moisture adsorption–desorption in the surrounding rock is neglected to simplify the computational complexity of moisture migration;
- (7) The surrounding rock is assumed to lie within the underground constant temperature zone, where seasonal atmospheric temperature fluctuations do not affect its initial temperature, ensuring stable initial temperature conditions for the model.

(1) Governing Equations of Surrounding Rock

(1.1). Moisture transfer

Moisture in the surrounding rock exists in two phases: liquid (liquid water) and vapor (water vapor). Liquid water undergoes mass transfer driven by capillary force, with its seepage and migration behavior characterized and solved using Darcy's law; water vapor, meanwhile, undergoes mass transfer driven by water vapor partial pressure, and its diffusion and migration behavior can be described via Fick's law. Based on the law of mass conservation, the moisture balance equation for the surrounding rock can be derived as follows:

$$\frac{\partial w}{\partial \tau} = -\nabla \cdot (\vec{J}_l + \vec{J}_v) \quad (1)$$

where w denotes the moisture content of the materials, kg/m^3 ; $\vec{J}_l$ is the liquid water transfer, $\text{kg}/(\text{m}^2 \cdot \text{s})$; $\vec{J}_v$ is the water vapor transfer, $\text{kg}/(\text{m}^2 \cdot \text{s})$.

According to Darcy's law, the calculation formula for the migration amount of liquid water is as follows:

$$\vec{J}_l = K_l \nabla S \quad (2)$$

where K_l denotes the permeability of liquid water, $\text{kg}/(\text{m} \cdot \text{s} \cdot \text{Pa})$; S is the capillary pressure, Pa.

The liquid water conductivity of the material is difficult to obtain directly. It can be calculated using the following formula:

$$K_l = \frac{\delta_v \varphi P_{sat}}{R_v \cdot (T - 273.15) \cdot \rho_w} \quad (3)$$

where R_v is the gas constant of water vapor, which is about $462 \text{ J}/(\text{kg} \cdot \text{K})$; T is the temperature, K; ρ_w is the density of liquid water, which is $1000 \text{ kg}/\text{m}^3$.

The capillary force can be converted into a more easily obtainable volumetric moisture content and relative humidity based on the isothermal moisture absorption equilibrium curve of the material. That is, the capillary force gradient is transformed into a relative humidity gradient. The formula is as follows:

$$\nabla S = \frac{dS}{dw} \cdot \frac{dw}{d\varphi} \nabla \varphi \quad (4)$$

where φ is the relative humidity; $\xi = \frac{dw}{d\varphi}$ represents the slope of the isothermal moisture absorption equilibrium curve of the material. Then, the formula for calculating the amount of liquid water migration is ultimately expressed as the following equation:

$$\vec{J}_l = K_l \frac{dS}{dw} \cdot \frac{dw}{d\varphi} \nabla \varphi = -D_w \xi \nabla \varphi \quad (5)$$

where $D_w = -K_l \frac{dS}{dw}$, which is the diffusion coefficient of liquid water, m^2/s .

According to Fick's law, the calculation formula for the migration amount of water vapor is as follows:

$$\vec{J}_v = -\delta_v \nabla P_v \quad (6)$$

where δ_v is the water vapor permeability coefficient, $\text{kg}/(\text{m} \cdot \text{s} \cdot \text{Pa})$; $P_v = \varphi P_{sat}$ is the vapor pressure, Pa; P_{sat} is the saturation vapor pressure, Pa.

Since the saturated vapor pressure is directly related only to temperature, it can be calculated using the following formula:

$$P_{sat} = 610.5 \exp\left(\frac{17.269(T - 273.15)}{T - 35.85}\right) \quad (7)$$

Convert the water vapor partial pressure gradient into the relative humidity gradient and temperature gradient. The formula is as follows:

$$\nabla P_v = P_{sat} \nabla \varphi + \varphi \nabla P_{sat} \quad (8)$$

$$\nabla P_{sat} = \frac{dP_{sat}}{dT} \nabla T \quad (9)$$

The formula for calculating the amount of water vapor migration is ultimately expressed as follows:

$$\vec{J}_v = -\delta_v (P_{sat} \nabla \varphi + \varphi \frac{dP_{sat}}{dT} \nabla T) \quad (10)$$

Therefore, the following can be obtained:

$$\begin{aligned}\xi \frac{\partial \varphi}{\partial \tau} &= \frac{\partial}{\partial x} \left[D_w \xi \nabla \varphi + \delta_v (P_{sat} \nabla \varphi + \varphi \frac{dP_{sat}}{dT} \nabla T) \right] \\ &= \frac{\partial}{\partial x} \left[(D_w \xi + \delta_v P_{sat}) \frac{\partial \varphi}{\partial x} + \delta_v \varphi \frac{dP_{sat}}{dT} \frac{\partial T}{\partial x} \right]\end{aligned}\quad (11)$$

The final moisture balance equation for the surrounding rock can be simplified as follows:

$$\xi \frac{\partial \varphi}{\partial \tau} = \frac{\partial}{\partial x} (D_\varphi \frac{\partial \varphi}{\partial x} + D_T \frac{\partial T}{\partial x}) \quad (12)$$

where $D_\varphi = D_w \xi + \delta_v P_{sat}$ is the mass transfer coefficient caused by the gradient of relative humidity, $\text{kg}/(\text{m} \cdot \text{s})$; $D_T = \delta_v \varphi \frac{dP_{sat}}{dT}$ is the mass transfer coefficient caused by the temperature gradient, $\text{m}^2/(\text{s} \cdot \text{K})$.

(1.2). Heat transfer

The heat transfer process of the surrounding rock not only involves the heat transfer during the migration of moisture, but also may include the latent heat generated during the phase change of moisture. Therefore, the heat transfer of the surrounding rock mainly includes heat conduction of the surroundings, the energy carried during the migration of moisture, and the heat generated by the phase change of moisture. Thus, the total heat flow formula is as follows:

$$q = -\lambda \nabla T + c_v T \vec{J}_v + c_w T \vec{J}_l + L(T) \vec{J}_v \quad (13)$$

where q is the heat flow, W/m^2 ; λ is the effective thermal conductivity of the material, $\text{W}/(\text{m} \cdot \text{K})$; c_v is the specific heat capacity of water vapor, $\text{J}/(\text{kg} \cdot \text{K})$; c_w is the specific heat capacity of liquid water, which is approximately $4200 \text{ J}/(\text{kg} \cdot \text{K})$; $L(T)$ is the latent heat of evaporation.

Since the latent heat of evaporation is directly related only to temperature, the calculation formula is as follows:

$$L(T) = [2500 - 2.4(T - 273.15)] \times 10^3 \quad (14)$$

Since the sensible heat component of moisture is much smaller than the latent heat component, when calculating the heat flow of the surrounding rock, the heat migration caused by the migration of liquid water and water vapor can be ignored. Thus, the formula can be simplified to the following form.

$$q = -\lambda \nabla T + L(T) \vec{J}_v \quad (15)$$

According to the law of conservation of energy, the thermal equilibrium equation of the surrounding rock is as follows:

$$(c_s \rho_s + c_w w) \frac{\partial T}{\partial \tau} = -\nabla q \quad (16)$$

where ρ_s is the density of surrounding rock, kg/m^3 ; c_s is the constant-pressure specific heat capacity of the rock in a dry state, $\text{J}/(\text{kg} \cdot \text{K})$.

Therefore, the following can be obtained:

$$(c_s \rho_s + c_w w) \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x} \left[(\lambda + L(T) \delta_v \varphi \frac{dP_{sat}}{dT}) \nabla T + L(T) \delta_v P_{sat} \nabla \varphi \right] \quad (17)$$

The final thermal balance equation of the surrounding rock can be simplified as follows:

$$(c_s \rho_s + c_w w) \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x} \left(\lambda_{eff} \frac{\partial T}{\partial x} + J_\varphi \frac{\partial \varphi}{\partial x} \right) \quad (18)$$

where the equation $\lambda_{eff} = \lambda + L(T) \delta_v \varphi \frac{dP_{sat}}{dT}$ is the effective thermal conductivity of the surrounding rock, $W/(m \cdot K)$; $J_\varphi = L(T) \delta_v P_{sat}$ is the heat transfer coefficient caused by the gradient of relative humidity.

(2) Governing equations of moisture air

The equation for describing the transfer of moisture in humid air is as follows:

$$M_g \left(\frac{\partial c_g}{\partial \tau} + \nabla \cdot (-D \nabla c_g) + v \cdot \nabla c_g \right) = G_0 \quad (19)$$

where c_g is the concentration of water vapor in the airflow, kg/m^3 ; M_g is the relative molecular mass; D is the diffusion coefficient, m^2/s ; G_0 is the moisture source, $kg/(m^3 \cdot s)$. The calculation formula is as follows:

$$G_0 = \frac{2}{R} \cdot h_m \cdot (P_{g,wall} - P_g) \quad (20)$$

The heat balance equation is as follows:

$$\rho c \frac{\partial T}{\partial \tau} + \nabla \cdot (-\lambda \nabla T) + \rho_l c_l v \cdot \nabla T = Q_0 \quad (21)$$

where v is the airflow velocity, m/s ; λ is the heat conductivity coefficient, $W/(m \cdot K)$; Q_0 is the heat source, W/m^3 . The calculation formula is as follows:

$$Q_0 = \frac{2}{R'} \cdot h_r \cdot (T_{wall} - T) \quad (22)$$

where R' is the diameter, m ; T_{wall} is the wall temperature, K ; T is the air temperature, K ; h_r is the convective heat transfer coefficient, $W/(m^2 \cdot K)$.

2.3. Material Properties

By consulting the relevant literature, the thermal and moisture physical parameters of the materials studied in this paper are obtained as shown in Table 1:

Table 1. Material properties.

Volumetric Moisture Content (kg/m^3)	Thermal Conductivity ($W/(m \cdot K)$)	Water Vapor Permeability Coefficient ($kg/(m \cdot s \cdot Pa)$)	Liquid Water Transfer Coefficient ($kg/(m \cdot s \cdot Pa)$)
$38.4\varnothing^{15.2} + 60\varnothing^{0.45}$	$0.79 + \frac{1.98}{1000} w$	$\frac{2.13 \times 10^{-6}}{R_v T}$	$\frac{\delta_v \varphi P_{sat}}{R_v \cdot (T - 273.15) \cdot \rho_w}$

3. Model Implementation and Validation

3.1. The Implementation of the Numerical Model

COMSOL Multiphysics 6.2 software excels at solving coupled solutions in multiphysics scenarios and is a finite-element-based computational tool. In this study, three basic physical fields were adopted: “Laminar Flow”, which is used to describe the airflow status; “Heat Transfer in Moist Air”, which is adopted to predict the heat transfer process in moist air and its surroundings; furthermore, the “Porous Media Module” integrated into “Heat Transfer in Moist Air” provides a convenient method to couple the solution of the heat transfer

process in the solid domain; and “Moisture Transfer in Moist Air”, which is adopted to describe the permeation of wet components.

At the inlet, moist air flows into the air tunnel, and its thermal status varies with actual meteorological data. It should be noted that the actual meteorological parameters used in this paper were selected based on the ASHRAE 2021 meteorological data test set, and COMSOL contains integrated and easily retrievable data packages. The velocity is determined by the flowrate. At the boundaries, the Dirichlet condition is adopted to constrain the state of the invariant boundary. Moreover, the ground temperature for each of the four cities is set to their respective annual average temperatures. Details are shown in Figure 3.

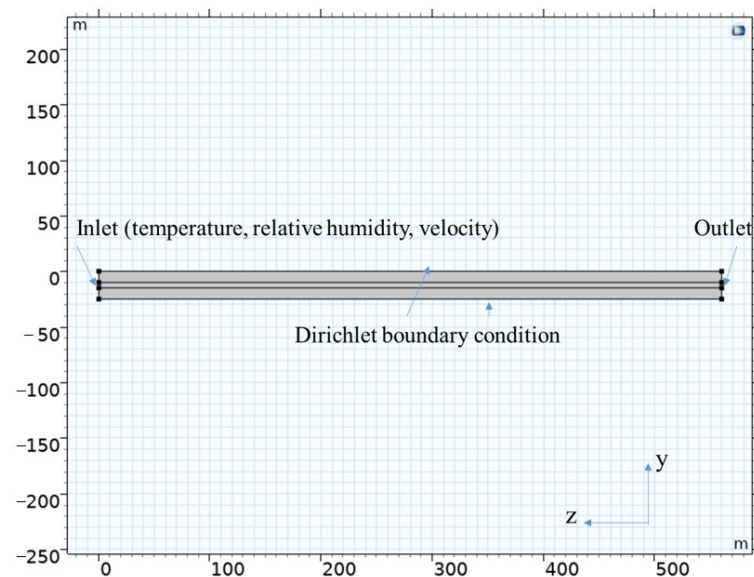


Figure 3. Schematic of the boundaries.

When conducting the solution calculation, a transient solver is employed to obtain time-varying information, with the convergence accuracy requirement set to less than 0.001. Moreover, the conventional grid division method is adopted, and the total number of grid elements is approximately 11,500. The validation of grid and time step independence is described in Section 3.3.

3.2. The Validation of the Numerical Model

To verify the reliability of the numerical model’s calculation results, this study selected field test data from Liu et al. [20], which were obtained from a 305 m long hydropower air tunnel near Xi’chang City, Sichuan Province, China, and compared them with the model’s predictions. The field test period was from 0:00 on 17 July to 23:00 on 20 July with a 1 h test interval. The inlet airflow velocity was approximately 1.93 m/s. The annual mean outdoor air temperature of Xi’chang is 16.9 °C, and the annual mean air relative humidity is 62%, which were considered as the initial conditions.

As shown in Figure 4, there is good agreement between the numerical calculation results and the field test results, with a maximum temperature difference of 0.4 °C and a maximum relative humidity difference of 6%. The maximum relative error in temperature prediction is within 4% and in relative humidity is within 6%. Thus, it can be concluded that the calculation results of the numerical model established in this study are reliable, and its errors fall within an acceptable range.

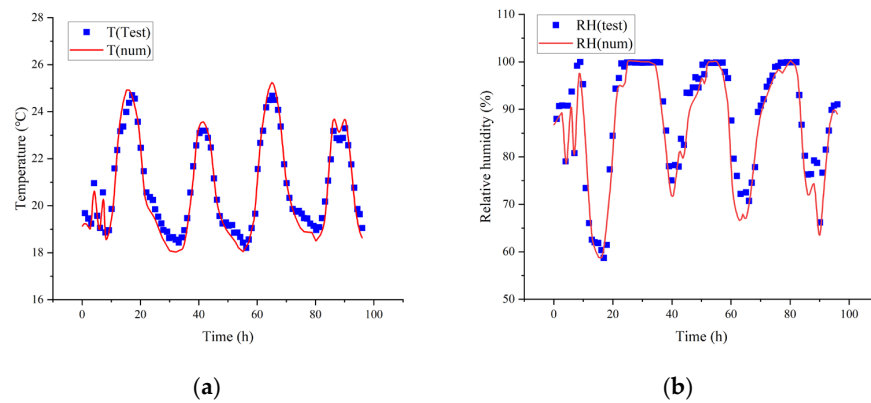


Figure 4. At a distance of 180 m from the entrance, the numerical results are compared with the field test results: (a) air temperature; (b) air relative humidity.

3.3. The Validation of the Grid and Time Step Independence

To illustrate the influence of grid size and time step on numerical calculation results, the validation of grid and time step independence was conducted.

As shown in Figure 5, the results under coarse grid, normal grid, and fine grid conditions were calculated, respectively. The results indicate that the differences between these three cases are negligible. To balance computational efficiency and sufficient calculation accuracy, this paper adopts the conventional grid division method for calculations.

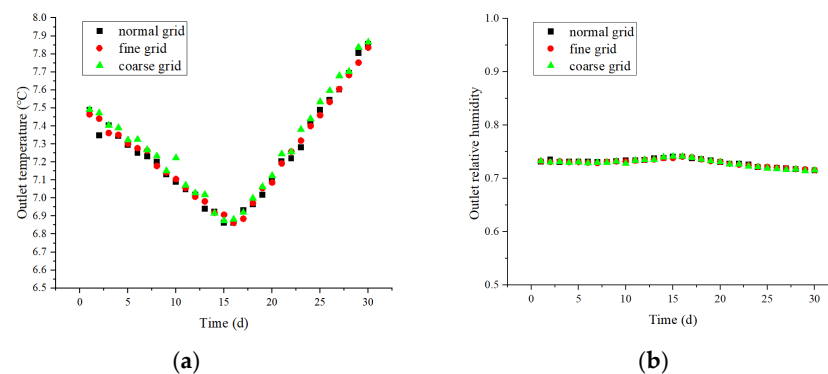


Figure 5. Validation of the grid independence: (a) outlet temperature; (b) outlet relative humidity.

In addition, the validation of time step independence is shown in Figure 6. Results under time step sizes of 0.5 d, 1 d, and 2 d were calculated, respectively. It can be seen that the results remain stable when the time step size is 1 d or 2 d. Considering computational cost and the density of result information, a time step size of 1 d was selected in this paper.

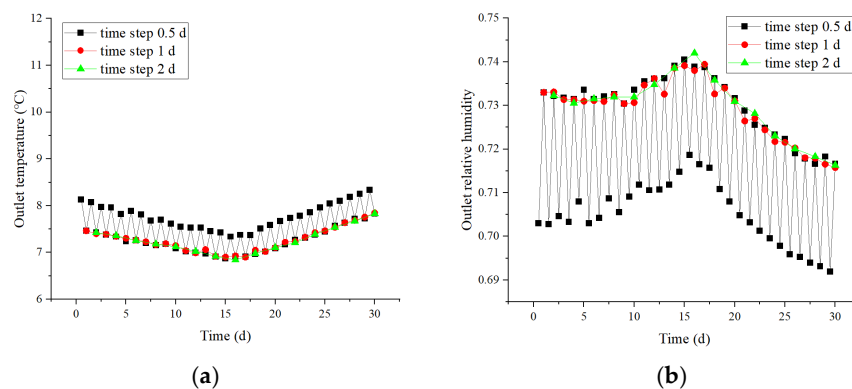


Figure 6. Validation of the time step independence: (a) outlet temperature; (b) outlet relative humidity.

4. Results and Discussion

4.1. Heat–Moisture Coupled Transfer Characteristics of Underground Air Tunnels

To analyze the fundamental characteristics of heat–moisture coupled transfer behavior in deep-buried underground air tunnels, this section examines multiple aspects: changes in the heat–moisture state of the air tunnel wall, variations in wall heat–moisture flux, and shifts in the heat–moisture state of airflow. It also conducts statistical analysis on the annual heat storage characteristics of the tunnel’s surrounding rock. For the analyses in this section, the following parameters are set: the fresh air supply rate of the underground air tunnel is 12,000 m³/h; the tunnel’s initial relative humidity is 80%, and its initial temperature is 11.2 °C. Outdoor fresh air meteorological parameters adopt the 2016 test data from Chengdu Shuangliu Meteorological Station (Sichuan Province, China), with a one-year numerical simulation conducted starting from 1 January 2016.

4.1.1. Variation in Heat and Humid Characteristics of the Tunnel Surface

When a deep-buried underground air tunnel delivers outdoor fresh air to underground buildings, the heat–moisture state of the airflow within the tunnel varies along the tunnel length. As shown in Figure 7, five time points across the year are selected to illustrate the temperature distribution along the tunnel. It can be observed that the air entering from the left inlet exerts a slight heating effect on the tunnel’s inlet section; however, as the airflow travels further along the tunnel, the airflow temperature change becomes minimal. This is because as the airflow travels further, its temperature gradually approaches equilibrium with the temperature of the tunnel wall’s boundary layer, thereby minimizing heat transfer between the airflow and the wall.

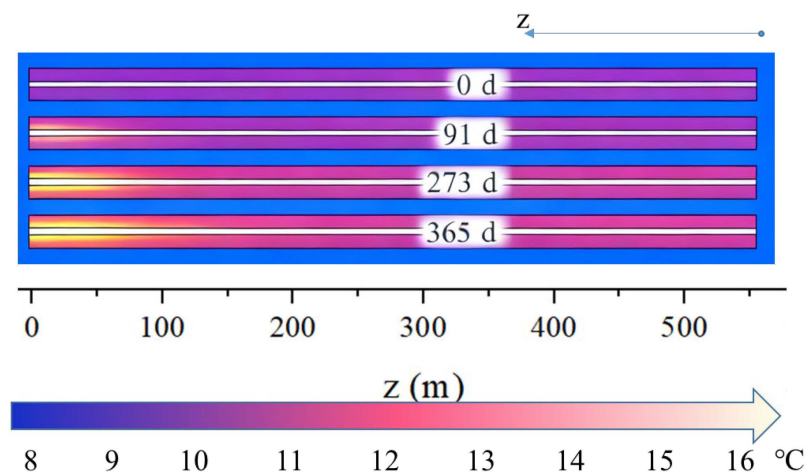


Figure 7. Temperature distribution map along the underground air tunnel.

Figure 8 illustrates the trend of temperature variation on the tunnel wall. It can be observed that the wall temperature in the tunnel’s rear section remains relatively stable, while the temperature in the front section fluctuates notably due to changes in outdoor meteorological temperature. The front section is hereafter referred to as the “inlet effect section.” Similarly, Figure 9 illustrates the trend of relative humidity variation on the tunnel wall. Here, it is observed that the variation trend of relative humidity along the tunnel length is consistent with that of temperature: it remains relatively stable in the tunnel’s rear section and fluctuates notably in the front section. Notably, the transition point for relative humidity stabilization is located further along the tunnel than that for temperature stabilization.

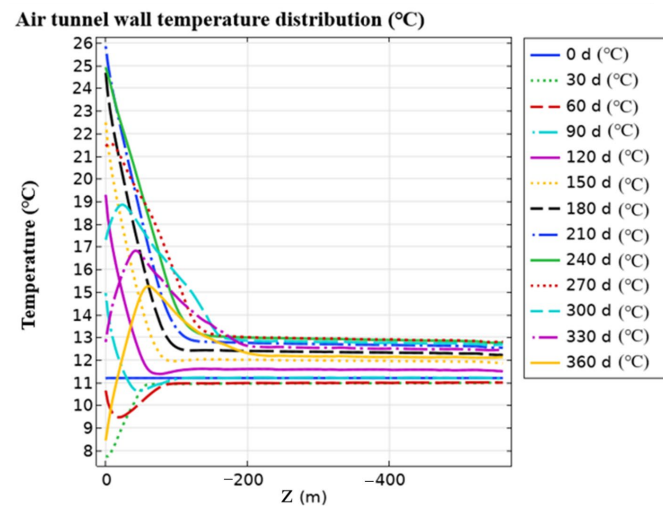


Figure 8. Temperature distribution along the underground air tunnel.

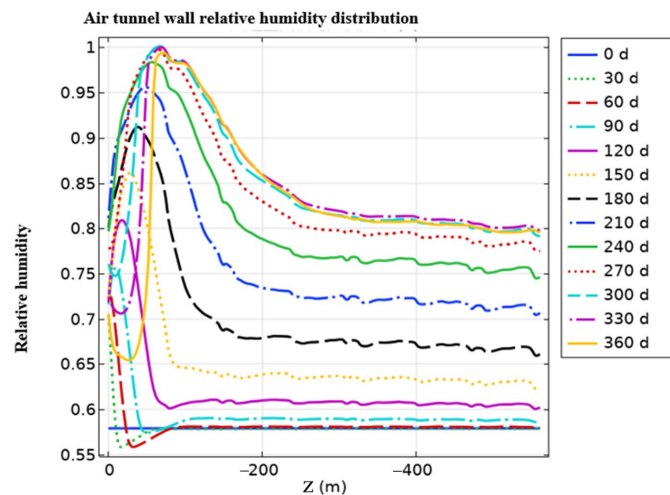


Figure 9. Distribution of relative humidity along the underground air tunnel.

As observed from the figures, after the airflow travels approximately 200 m from the inlet, the tunnel wall temperature remains stable across all operating time points; in contrast, the relative humidity continues to decrease slowly even beyond 200 m and only stabilizes at a greater distance along the tunnel. This phenomenon can be attributed to the fact that while the wall temperature tends toward stabilization, moisture transfer between the tunnel wall and the deeper regions of the surrounding rock persists: moisture in the airflow is transferred to the tunnel wall, and moisture on the wall is further transported to the deeper regions of the surrounding rock. The energy variations caused by these two moisture transfer processes reach equilibrium at the wall, resulting in no observable change in wall temperature; only changes in relative humidity are observed.

4.1.2. Variation in Heat and Moisture Flux of the Tunnel Wall Surface

The heat–moisture state of the air tunnel wall directly influences the variation in heat–moisture flux. As shown in Figure 10, the variation trend of heat flux along the tunnel wall is consistent with that of the wall’s heat–moisture state. Within the inlet effect section, the wall boundary heat flux can reach up to $\pm 4 \text{ W/m}^2$, indicating a significant temperature difference between the airflow and the tunnel wall in this region, with the heat exchange process being particularly pronounced.

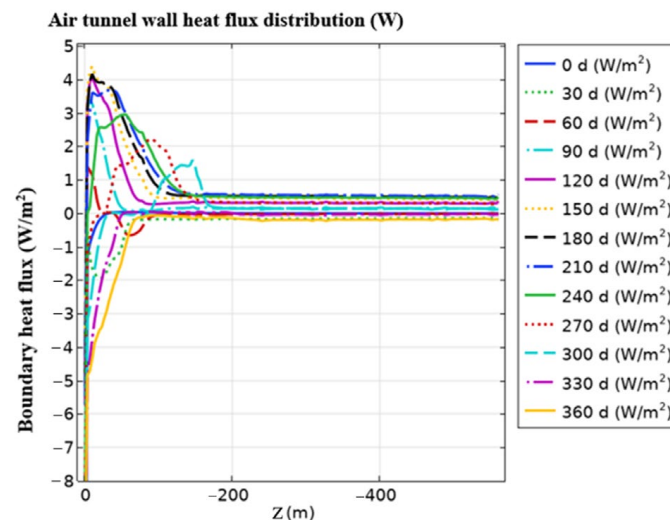


Figure 10. Variation in heat flux along the underground air tunnel.

Figure 11 illustrates the variation in the boundary moisture transfer flux. In terms of temporal variation, the maximum boundary moisture transfer mass flux reaches a value of $-4.5 \times 10^{-6} \text{ kg}/(\text{m}^2 \cdot \text{s})$ in winter, while in summer, this maximum value is approximately $3 \times 10^{-6} \text{ kg}/(\text{m}^2 \cdot \text{s})$. Specifically, the negative flux in winter indicates that moisture in the tunnel's surrounding rock is transferred to the airflow, whereas the positive flux in summer means that the tunnel's surrounding rock absorbs some of the moisture from the airflow.

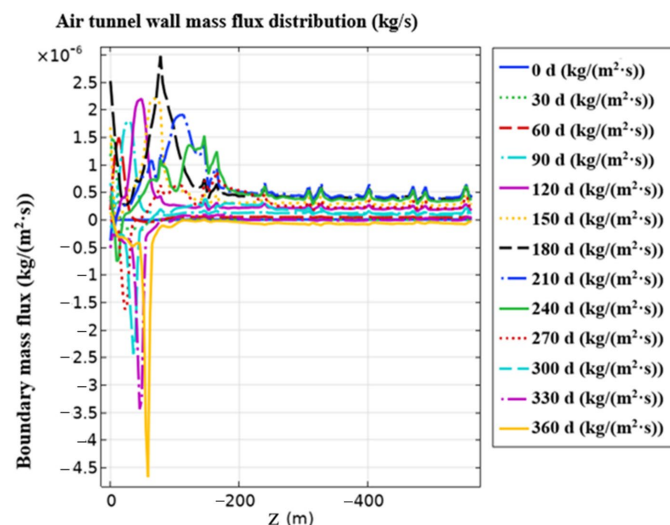


Figure 11. Variation in moisture flux along the underground air tunnel.

Figures 12 and 13 illustrate the variations in the average heat–moisture flux on the air tunnel wall. It can be observed that in summer, the maximum average heat flux exceeds $0.9 \text{ W}/\text{m}^2$, while in winter, that maximum is approximately $-0.5 \text{ W}/\text{m}^2$. From this, it can be inferred that the heat absorbed by the underground air tunnel in summer is greater than the heat released in winter. Similarly, in summer, the maximum average moisture transfer flux exceeds $6.5 \times 10^{-7} \text{ kg}/(\text{m}^2 \cdot \text{s})$, whereas in winter, that maximum is approximately $-1.8 \times 10^{-7} \text{ kg}/(\text{m}^2 \cdot \text{s})$. On an annual basis, the amount of moisture absorbed by the underground air tunnel from the airflow exceeds that released.

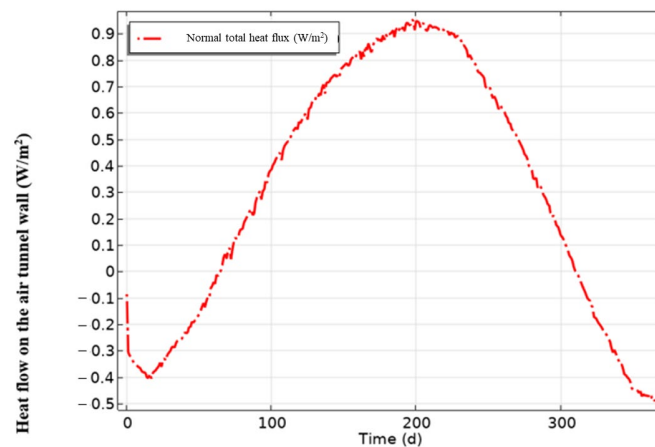


Figure 12. Interannual variation in the average heat flux on the underground air tunnel wall surface.

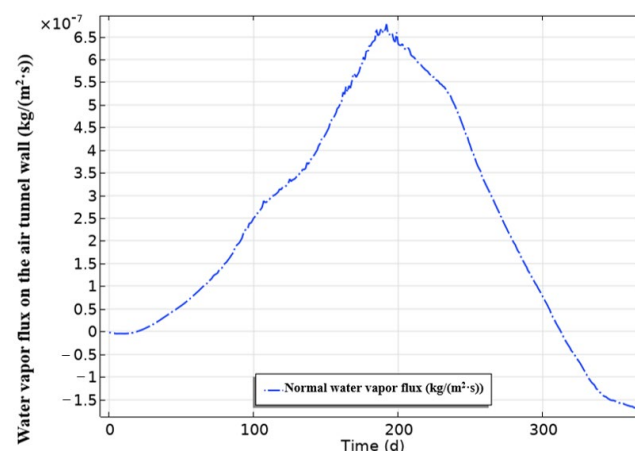


Figure 13. Interannual variation in the average water vapor flux on the underground air tunnel wall surface.

4.1.3. Heat–Moisture Coupled Transfer Characteristics of Airflow

From the above research, it is evident that underground air tunnels exert a heat–moisture regulation effect on moist airflow, with heat–moisture changes on the air–flow side primarily reflected in variations in temperature and humidity. As shown in Figures 14 and 15, under the current calculation conditions, the tunnel’s maximum cooling effect on airflow in summer exceeds 1 °C, while its heating effect on airflow in winter is relatively weak—with a maximum value of approximately −0.6 °C (note: the negative value here indicates a temperature rise trend, consistent with the “heating effect” described). Notably, the air inlet–outlet relative humidity difference exhibits a decreasing trend throughout the year. Only during the initial operation stage does this inlet–outlet relative humidity difference exceed approximately 2.5%; however, it gradually decreases to 0 as the operation period extends.

This phenomenon can be attributed to two primary factors: First, the tunnel’s surrounding rock gradually absorbs moisture until it approaches saturation, rendering it incapable of absorbing additional moisture from the airflow in the later operation stage. Second, the change in airflow relative humidity is influenced not only by moisture content but also by airflow temperature. The mechanism by which temperature and moisture content interact to alter air relative humidity is relatively complex—it is not a monotonic “one increases as the other decreases” relationship. For instance, this leads to phenomena such as increased relative humidity occurring when both moisture content and temper-

ature decrease simultaneously. Ultimately, this results in a minimal inlet–outlet relative humidity difference.

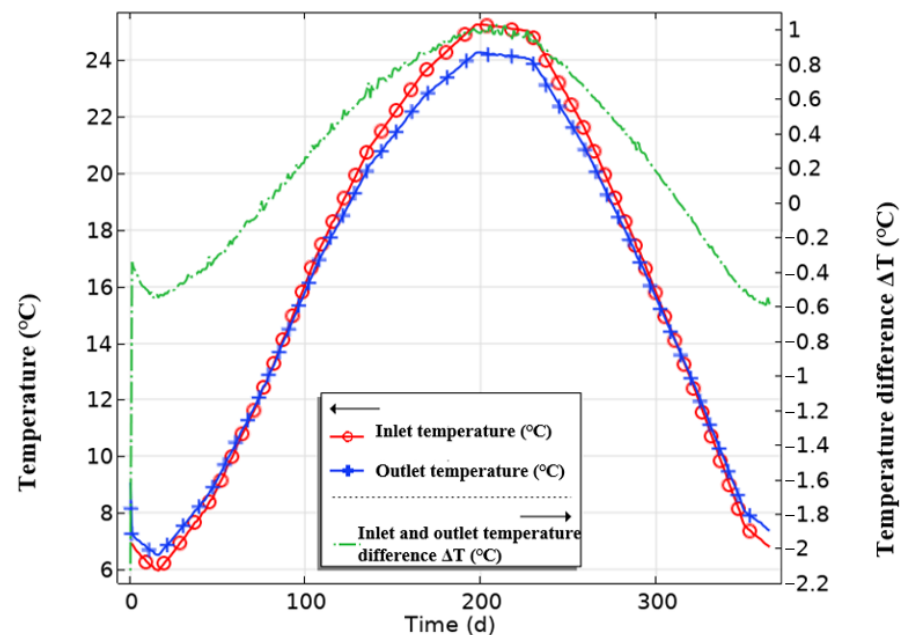


Figure 14. Annual variation in inlet and outlet air temperature and temperature difference.

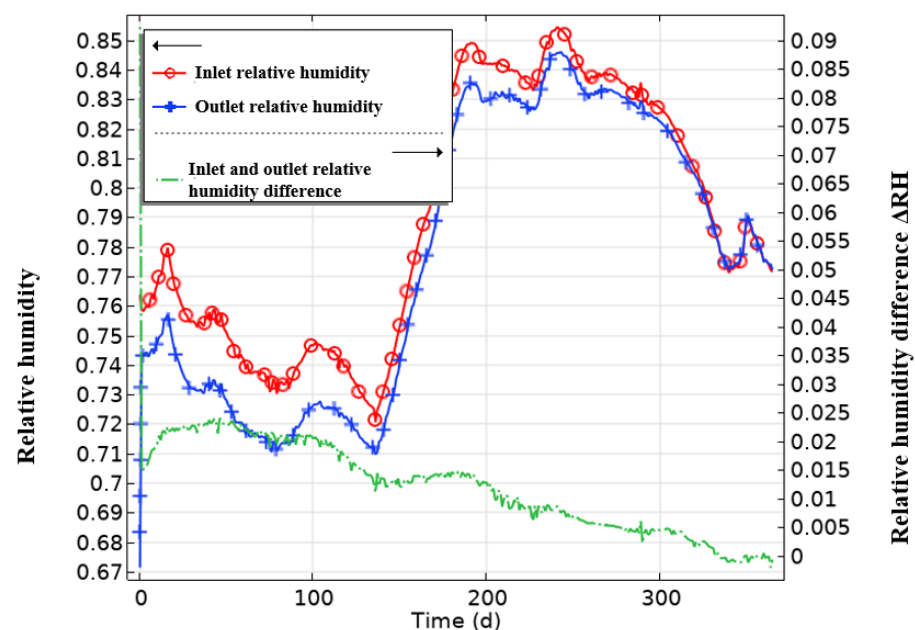


Figure 15. Interannual variation in relative humidity and humidity difference of inlet and outlet.

To further illustrate the underground air tunnel's regulation effect on airflow, enthalpy—a parameter that simultaneously reflects the combined effects of air moisture content and temperature—was used for analysis, as shown in Figure 16. It can be observed that in summer, the tunnel achieves the greatest enthalpy reduction for the airflow, with a maximum reduction of approximately 3.5 kJ/kg. In winter, the tunnel exerts an enthalpy-increasing effect on the airflow, with a maximum enthalpy rise of around 1 kJ/kg. This finding indicates that the tunnel's precooling effect on fresh air in summer can reduce the fresh air heat gain load of underground buildings, while its enthalpy-increasing effect in

winter can enhance the airflow's energy content—also reducing the fresh air heat loss load of underground buildings. Both effects offer potential benefits for underground buildings.

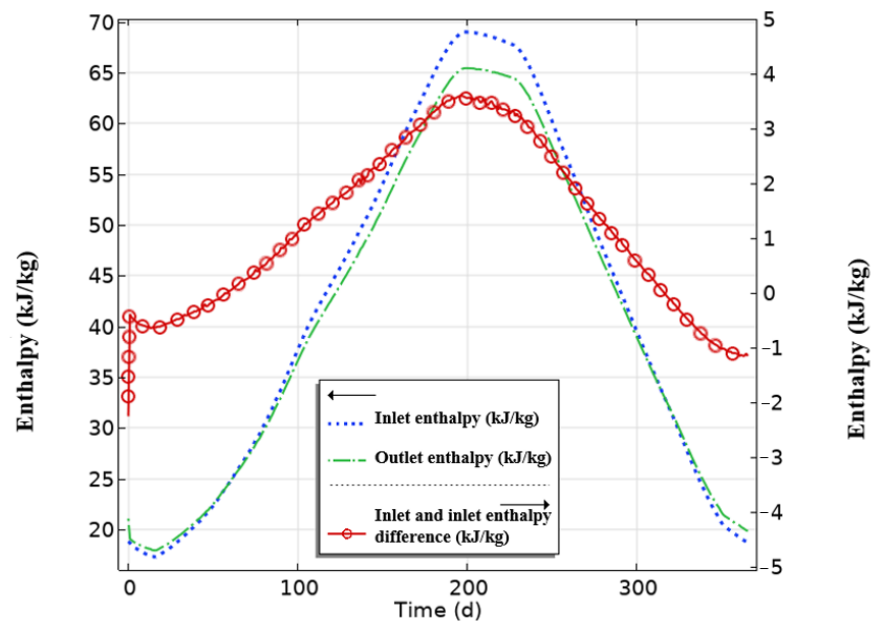


Figure 16. Interannual variations in inlet and outlet air enthalpy and enthalpy difference.

4.1.4. Energy Storage of the Air Tunnel Surroundings

The energy storage characteristics of underground air tunnel surrounding rock under winter and summer conditions can be used to evaluate its annual energy performance. As shown in Figure 17, over the annual operation period, the energy variation in the surrounding rock exhibits a sine wave pattern that correlates with changes in outdoor meteorological parameters. In winter, the maximum energy variation does not exceed -800 W (the negative value indicates the surrounding rock releases energy to the airflow); in summer, the maximum energy variation exceeds 800 W (indicating the surrounding rock absorbs energy from the airflow).

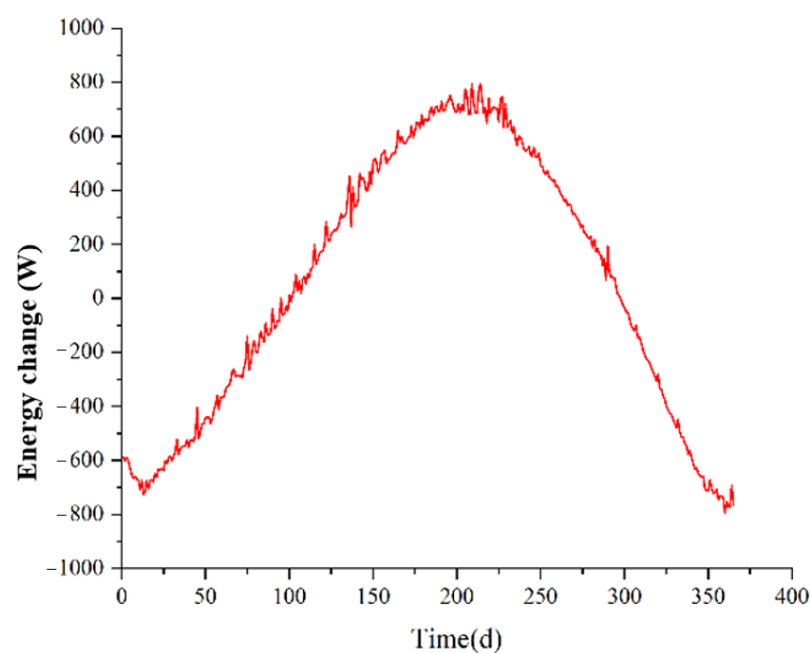


Figure 17. Energy changes in the surrounding rock in underground air tunnel surroundings.

This energy variation directly reflects the preconditioning effect of the tunnel surrounding rock on the incoming fresh air—and to a certain extent, this preconditioning effect benefits underground buildings. Figure 18 illustrates statistics on the surrounding rock's energy variation during winter and summer operating periods. It can be observed that the surrounding rock's heat storage capacity in summer is greater than its heat release capacity in winter. The total annual energy regulation capacities are approximately as follows: the summer heat storage capacity is around 2.25×10^3 (kW·h), and the winter heat release capacity is around 1.75×10^3 (kW·h). Notably, this result is based solely on the performance characteristics under the current calculation parameters.

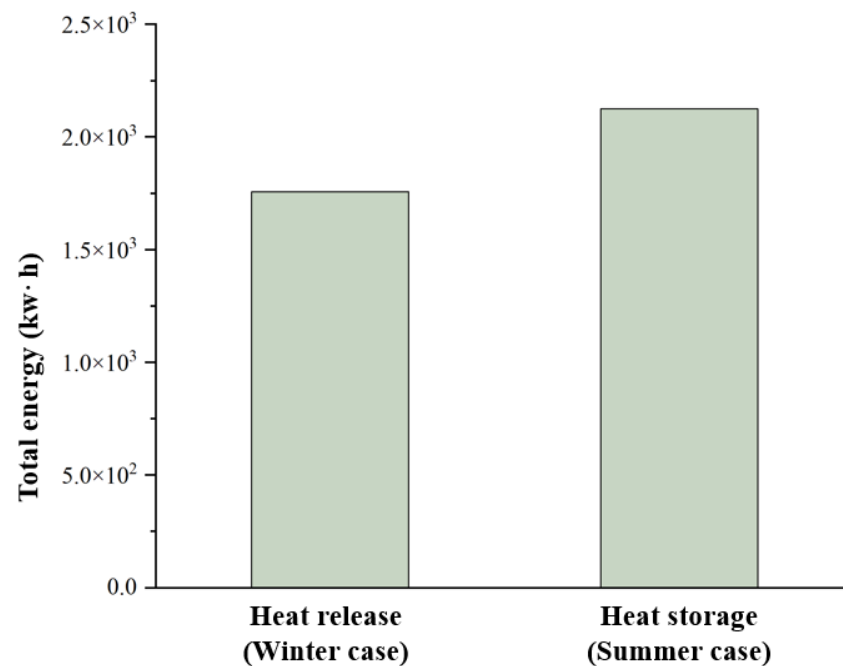


Figure 18. Cumulative energy changes in the surrounding rock in the underground air tunnel under winter and summer cases.

4.2. The Ventilation Characteristics of Underground Air Tunnels in Cities of Different Climate Zones of China

From the above research, it is established that the preconditioning effect of underground air tunnels on fresh air varies with operating conditions. Given China's extensive geographical area, to examine the operating characteristics of deep-buried underground air tunnels during the air supply process across different climate zones, this section selects four typical cities (Harbin, Nanjing, Beijing, and Guangzhou) for comparative analysis. In the calculations, the ground temperature for each of the four cities is set to their respective annual average temperatures, with values of approximately 5.38 °C, 21.4 °C, 13.7 °C, and 24.6 °C [21].

Figure 19 illustrates the calculation results of the fresh air inlet–outlet enthalpy difference. It can be observed that the preconditioning effect of underground air tunnels in Guangzhou is significantly weaker than that in the other three cities: the maximum summer inlet–outlet enthalpy difference does not exceed 6 kJ/kg, and the maximum winter inlet–outlet enthalpy difference does not exceed 4 kJ/kg. In contrast, for the other three cities under summer conditions, the maximum inlet–outlet enthalpy difference exceeds 8 kJ/kg.

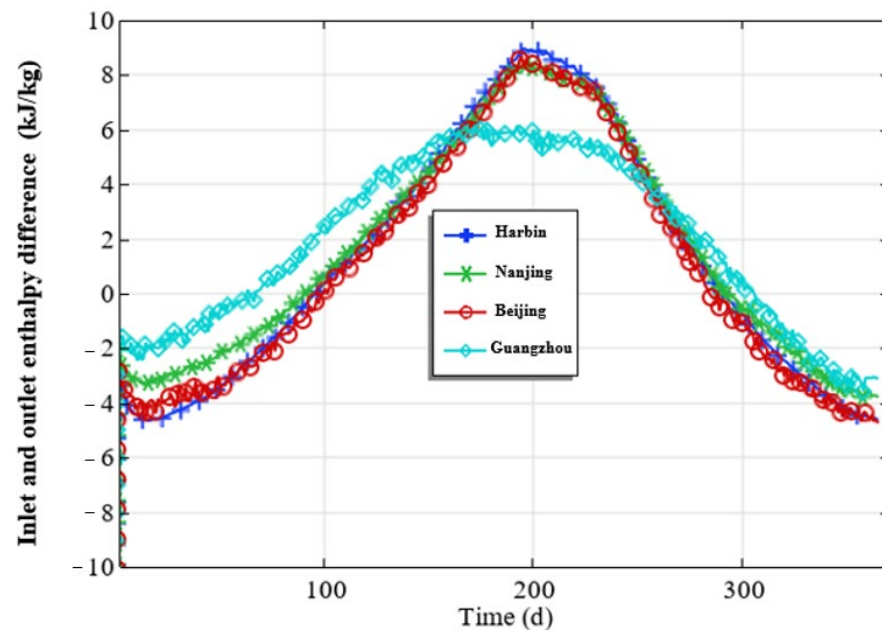


Figure 19. Enthalpy difference between the inlet and outlet in typical cities in China.

This phenomenon can be primarily attributed to Guangzhou's relatively high ground temperature, which results in weak heat interaction between the ground and fresh air—thus limiting the tunnel's preconditioning effect on fresh air. Furthermore, for the other three cities, their preconditioning effects exhibit minimal differences in the later stage of annual operation, particularly between Beijing and Harbin. This is because the heat–moisture interaction between the tunnel's surrounding rock and fresh air depends not only on temperature but also on the air's moisture content. Although the annual average ground temperatures of these two cities differ by approximately 8.32 °C, the difference in outdoor air humidity may offset the impact of this temperature difference—resulting in minimal differences in their preconditioning effects.

5. Conclusions

Based on the research on heat–moisture coupled transfer in deep-buried underground air tunnels, this paper draws the following conclusions:

Deep-buried underground air tunnels exhibit a significant “inlet effect” in heat–moisture transfer: Within the first 200 m along the tunnel length, the wall temperature and humidity fluctuate notably under the influence of outdoor meteorological parameters. Beyond 200 m, the wall temperature stabilizes, while the relative humidity only stabilizes at a greater distance along the tunnel. Under the calculation conditions of this study, the heat–moisture exchange intensity in the inlet effect section is the highest, with the boundary heat flux reaching $\pm 4 \text{ W/m}^2$. Specifically, the surrounding rock releases moisture to the airflow in winter (with a maximum moisture transfer flux of $-4.5 \times 10^{-6} \text{ kg/(m}^2 \cdot \text{s)}$) and absorbs moisture from the airflow in summer (with a maximum moisture transfer flux of $3 \times 10^{-6} \text{ kg/(m}^2 \cdot \text{s)}$).

Underground air tunnels show seasonal differences in regulating the heat, moisture, and enthalpy of fresh air: Under the current calculation conditions, the tunnel achieves airflow cooling (with a maximum cooling effect exceeding 1 °C) and enthalpy reduction (with a maximum reduction of 3.5 kJ/kg) in summer, thereby reducing the fresh air heat gain load of underground buildings. In winter, it realizes airflow heating (with a maximum heating effect of approximately −0.6 °C, where negative values indicate temperature rise) and enthalpy increase (with a maximum increase of 1 kJ/kg). Furthermore, the annual

energy storage of the surrounding rock exhibits a “summer storage and winter release” characteristic: the heat storage capacity in summer is about 2.25×10^3 (kW·h), and the heat release capacity in winter is about 1.75×10^3 (kW·h), reflecting the tunnel’s advantage in passive fresh air preconditioning.

Climate zone differences significantly impact the tunnel’s fresh air preconditioning effect. Among the four selected cities, Guangzhou has the highest annual average ground temperature (24.6 °C), leading to the weakest heat interaction with fresh air. Its maximum inlet–outlet enthalpy difference is only approximately 6 kJ/kg in summer and 4 kJ/kg in winter, resulting in a preconditioning capacity much lower than that of the other three cities. Although the annual average ground temperature difference between Harbin and Beijing reaches 8.32 °C, the difference in outdoor air moisture content between the two cities may offset the impact of this temperature difference, leading to similar fresh air preconditioning effects in the later stage of annual operation. Nanjing’s preconditioning effect falls between the above-mentioned cities, which further confirms that ground temperature and outdoor air moisture content jointly dominate the heat–moisture regulation capacity of underground air tunnels.

However, this study has certain limitations: it ignores the impact of gravity on liquid water migration, only selects four typical Chinese cities (resulting in insufficient climate zone coverage), and does not consider the influence of different lithologies on heat–moisture coupled transfer, which may restrict the generalizability of its results.

Future work will optimize the model by incorporating gravity effects, expand meteorological data to more climate zones, conduct research combining various surrounding rock lithologies, and verify the model with more actual engineering cases to improve the application accuracy of the findings in deep underground engineering designs.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author, the data are not publicly available due to the requirement for a confidentiality period for the project.

Conflicts of Interest: Authors Jiangyan Ma, Lin Huang, Baoshun Deng and Lei He were employed by the company China Railway First Survey and Design Institute Group Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interests.

Nomenclature

c_v	The specific heat capacity of water vapor, J/(kg·K)
c_w	The specific heat capacity of liquid water, J/(kg·K)
c_s	The specific heat capacity of solid materials, J/(kg·K)
c_g	The concentration of water vapor in the airflow, kg/m ³
D	The diffusion coefficient, m ² /s
D_w	The diffusion coefficient of liquid water, m ² /s
D_φ	The mass transfer coefficient caused by the relative humidity gradient, kg/(m·s)

D_T	The mass transfer coefficient caused by temperature gradient, $\text{m}^2/(\text{s} \cdot \text{K})$
G_0	The moisture source, $\text{kg}/(\text{m}^3 \cdot \text{s})$
h_r	The convective heat transfer coefficient, $\text{W}/(\text{m}^2 \cdot \text{K})$
$\vec{J}_l$	The liquid water transfer, $\text{kg}/(\text{m}^2 \cdot \text{s})$
$\vec{J}_v$	The water vapor transfer, $\text{kg}/(\text{m}^2 \cdot \text{s})$
K_l	The permeability of liquid water, $\text{kg}/(\text{m} \cdot \text{s} \cdot \text{Pa})$
$L(T)$	The latent heat of evaporation, J/kg
M_g	The relative molecular mass, g/mol
P_{sat}	The saturation vapor pressure, Pa
P_v	The vapor pressure, Pa
q	The heat flow, W/m^2
Q_0	The heat source, W/m^3
R'	The diameter, m
R_v	Gas constant of water vapor, $\text{J}/(\text{kg} \cdot \text{K})$
S	The capillary pressure, Pa
T	The temperature, K
T_{wall}	The wall temperature, K
ρ_s	The density of surrounding rock, kg/m^3
ρ_w	The density of liquid water, kg/m^3
φ	The relative humidity
δ_v	The water vapor permeability coefficient, $\text{kg}/(\text{m} \cdot \text{s} \cdot \text{Pa})$
λ	The effective thermal conductivity, $\text{W}/(\text{m} \cdot \text{K})$
v	Airflow velocity, m/s
w	Moisture content, kg/m^3
τ	Time, s

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