

Article

A Novel Earth-to-Air Heat Exchanger-Assisted Ventilated Double-Skin Facade for Low-Grade Renewable Energy Utilization in Transparent Building Envelopes

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Abstract

Transparent building envelopes significantly increase energy demands due to low thermal resistance and solar heat gain, while conventional double-skin facades may lead to overheating and high cooling loads in the summer. This study proposes a novel earth-to-air heat exchanger (EAHE)-assisted ventilated double-skin facade (VDSF) system utilizing low-grade shallow geothermal energy for year-round thermal regulation of transparent building envelopes. A numerical model of this coupled system was developed and validated to estimate the thermal performance of the EAHE-assisted VDSF system in a hot-summer-and-cold-winter climate. Parametric study was conducted to investigate the impact of some key design parameters on thermal performance of the EAHE-assisted VDSF system and further reveal recommended design parameters of this coupled system. The results indicate that the EAHE-VDSF system reduces annual accumulated cooling loads by 20.3% to 76.5% and heating loads by 19.6% to 47.1% in comparison to a conventional triple-glazed, non-ventilated facade. The cavity temperature of the VDSF decreases by 15 °C on average in the summer, effectively addressing the overheating issue in DSFs. The proposed coupled EAHE-VDSF system shows promising energy-saving potential and ensures stability and consistency in the thermal regulation of transparent building envelopes.

Keywords: earth-to-air heat exchanger; ventilated double skin facades; low-grade renewable energy; transparent building envelope; advanced building materials



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1. Introduction

Transparent building envelopes are an important part of buildings [1], such as windows, glass curtain walls, and glass roofs, which can provide the advantages of unobstructed views, daylighting, and passive solar gain [2,3]. It is estimated that building energy consumption accounts for 55% of global energy use [4], and a large portion of this energy consumption is associated with building envelopes [5]. However, according to statistics, 30–50% of the heat gain through building envelopes is caused by transparent building envelopes [6]. Although transparent building envelopes offer aesthetic appeal and daylight access, they have U-values which are approximately three to five times

higher (1.5 to 3.0 W/m²·K) than opaque walls (0.3 to 0.8 W/m²·K) [7,8], which results in disproportionate energy loss. The percentage of solar heat received via transparent building envelopes in peak cooling load is relatively high, especially in cooling-dominated climate regions. Increasing window-to-wall ratios in current architectural designs will also result in a 5–8% [9] increase in annual cooling energy for every 10% increase in window-to-wall ratios.

So far, some high-performance transparent building envelopes have been developed to improve thermal insulation, solar regulation, energy harvesting, and sustainability. In recent years, relative research on advanced transparent building envelopes has focused on the following aspects. For instance, the integration of phase change materials (PCMs) with transparent building envelopes has been widely explored. Studies have demonstrated that PCMs can reduce building cooling loads by approximately 20% by leveraging latent heat storage to dampen heat transfer fluctuations [10,11]. Furthermore, research by Cekon et al. [12] and Grynning et al. [13] highlighted the significant role of PCMs in enhancing indoor thermal comfort by modulating temperature swings. Advancements in this area include the development of adaptive PCM-glazing units [14] and investigations into their dynamic thermal performance at full scale [15]. Additionally, various solar film coatings are applied to transparent building envelopes, which can lower the U-value while selectively modulating optical properties including emissivity, absorptivity, and reflectivity based on occupancy requirements, thereby limiting indoor solar heat gain and reducing cooling load [16–19]. Moreover, glass panels coupled with photovoltaic (PV) laminates can be used to compose building-integrated photovoltaics (BIPVs). This approach not only enhances thermal performance by reducing the U-value of glazing systems but also harnesses solar energy for on-site power generation, thereby improving overall building energy efficiency [20–22]. Furthermore, ventilated double-skin facades (DSFs) employ specific operational strategies that vary by season. During the summer, the ventilation airflow driven by the stack effect can release the absorbed solar heat in ventilated DSFs and decrease indoor heat gain, while in the winter, the sealed cavity configuration improves thermal resistance by establishing an enclosed air layer. This dual-mode operation achieves effective heat dissipation in cooling seasons and enhanced thermal insulation in heating conditions [23].

Current research on DSF primarily focuses on dynamic shading systems, hybrid ventilation strategies, and integrations with photovoltaic (PV) panels. A recent study, which employed two-dimensional computational fluid dynamics (CFD) modeling of DSF with integrated shading devices, demonstrated significant potential for reducing building energy consumption while enhancing thermal comfort [24]. A further study has shown that incorporating dynamic shading with light shelves substantially improves indoor daylight quality and illuminance distribution uniformity [25]. Moreover, PV modules are adopted as in-between louvers of ventilated DSF for mitigating solar heat gain and generating electricity on-site [26]. Naturally ventilated airflow can cool the surface of PV modules by natural convection, which is able to enhance the power generation efficiency of PV modules [27]. This integrated system not only generates on-site electricity but also significantly mitigates heat gain and heat loss through the building envelope. Despite these advancements, cavity overheating in DSF remains a persistent challenge during summer operation in cooling-dominated climates [28–31].

The development of such integrated passive solutions is critical for enhancing building resilience under future climate scenarios [32]. The effectiveness of passive techniques, however, is highly dependent on their synergistic design and local climatic conditions [33]. Based on this rationale, this study leverages low-grade shallow geothermal energy to mitigate cavity overheating in DSF. To mitigate overheating in double-skin facades (DSF),

low-grade natural energy sources can be utilized. Pipe-embedded DSFs have been proposed, where circulating water within pipes integrated into shading layers directly releases absorbed solar heat. This system employs naturally cooled water sources to resolve cavity overheating issues in conventional DSF configurations [34–37]. A pipe-embedded DSF significantly reduced cavity temperatures, decreasing louver mean temperatures from approximately 57 °C to 25.4 °C and lowering overall cavity temperatures to roughly 29 °C, which was substantially below ambient air conditions [34,35]. Furthermore, the solar heat gain coefficient (SHGC) of the pipe-embedded DSF was reduced to 60% of that of conventional DSF values, which was attributed to the decreased solar heat gain through the pipe-embedded shading layer [37].

A water flow window (WFW) permits the circulation of low-grade water through the space between two glass panels [38]. During the cooling season, low-grade waterflow can be generated through evaporative cooling, ground heat exchangers, etc. Compared to conventional windows, WFW systems circulate cool water within the cavity to efficiently lower inner glazing surface temperatures and diminish heat transmission through fenestration [39]. This configuration achieves enhanced solar shading and cooling load reduction. During the heating season, warm water circulation generated by the solar heat collector can effectively reduce indoor heat loss through windows [40]. Moreover, WFW systems regulate the temperatures of inner glazing surfaces, substantially narrowing the temperature fluctuation and improving indoor thermal comfort [39].

The above-mentioned studies demonstrated that a cool airflow or waterflow generated by low-grade energy sources can be utilized to avoid overheating in DSF and reduce the cooling load in the summer. The earth-to-air heat exchanger (EAHE) is designed to exchange heat between the soil and air that flows through a buried pipe [41]. At a specific depth, the subterranean soil temperature remains relatively constant throughout the year, with only minor fluctuations. In the winter, the temperature of the soil underground is much higher than the temperature of the ambient air, and in the summer, it is much lower. The EAHE preheats intake air in the winter and precools it in the summer, utilizing shallow geothermal energy for space heating/cooling [42,43]. It is estimated that EAHE maintains stable outlet air temperatures after certain pipe lengths, generally around 30 m.

This study proposes a novel earth-to-air heat exchanger-assisted ventilated double-skin facade (EAHE-VDSF), which utilizes shallow geothermal energy to continuously provide cool/warm airflow for minimizing the heat gain/loss through DSF in the summer or winter. This integrated system offers an alternative method for utilizing low-grade shallow geothermal to achieve thermal regulation of DSF and energy saving in buildings. Compared with above-mentioned water-based thermal regulation DSF (e.g., pipe-embedded windows or water-flow glazing), the EAHE-VDSF eliminates the need for installing additional heating and cooling equipment and avoids freeze and corrosion risks. For the practical application of EAHE-VDSF, the thermal performance of this system should be quantitatively estimated in both cooling and heating seasons. It is essential to ascertain the influence of critical design factors on thermal performance of EAHE-VDSF and determine the recommended design parameter.

The main objectives of this paper are to (a) develop an integrated EAHE-VDSF system that utilize low-grade shallow geothermal energy to achieve thermal regulation of DSF, (b) establish a coupled simulation model to analyze the thermal performance of the EAHE-VDSF, (c) identify the influence of critical design factors on thermal performance and determine the optimal design parameter. The paper is structured as follows: Section 2 details system configuration, heat transfer processes, and numerical model development with validation. Section 3 presents the case study methodology. Results and comparative

analysis are discussed in Section 4, followed by discussion in Section 5. Finally, Conclusions are presented in Section 6.

2. System Descriptions and Principles

2.1. Configuration and Principle of EAHE-VDSF

The EAHE-VDSF integrated system is composed of an underground earth-to-air heat exchanger and a ventilated double-skin facade, as illustrated in Figure 1. The VDSF consists of an exterior double-glazed unit with a sealed air gap, an interior single-glazed panel, and an in-between ventilated cavity. The EAHE consists of a horizontally buried pipe that facilitates heat exchange between the soil and air, along with two vertical pipes for the intake of ambient air and the discharge of preheated/precooled air. The preheated/precooled air by EAHE is then delivered into the ventilated cavity of the VDSF, where it exchanges heat with the adjacent glazing surfaces before ultimately being released into the external environment. This configuration effectively utilizes soil thermal mass to minimize the cooling and heating loads of the VDSF.

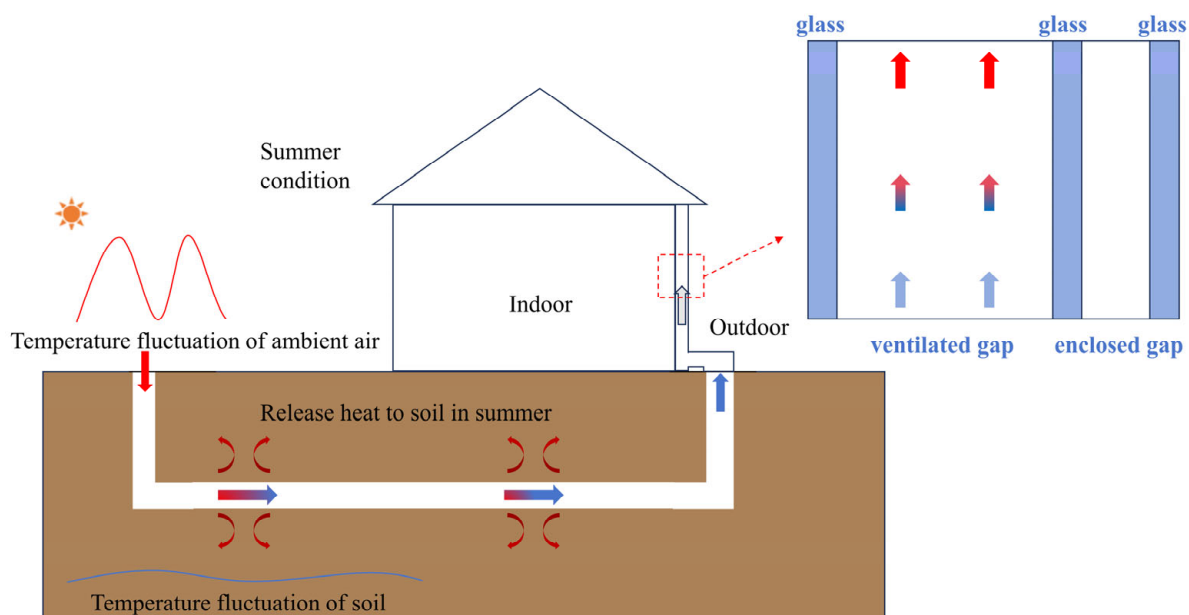


Figure 1. Schematic diagram of the coupled EAHE-VDSF system operating during the cooling season.

Subsurface soil temperature exhibits relative constancy throughout the year at a specified depth. The temperature of underground soil is significantly higher or lower than the outdoor air temperature during winter or summer, respectively. In the summer, as shown in Figure 1, the warm ambient air enters the EAHE, transferring heat to the surrounding soil through convection, and subsequently undergoes precooling prior to entering the ventilated cavity of the VDSF. The cooled ventilated airflow facilitates heat exchange with the adjacent glazing surface, effectively removing accumulated heat and thereby reducing the temperature of the interior glazing surface. This process prevents heat transfer from the outdoor environment to the indoor space. Similar phenomena can be found in the winter condition of the EAHE-VDSF. Cold outdoor air enters the EAHE and is preheated through heat absorption from the surrounding soil. The preheated air flowing through the cavity within the VDSF increases the temperature of the interior glazing surface, thereby reducing conductive heat loss.

2.2. Mathematical Model of EAHE-VDSF

2.2.1. Earth-to-Air Heat Exchanger

The soil temperature surrounding the buried pipe directly determines the pre-cooling/pre-heating capacity of the EAHE. In the calculation of soil temperature, the soil is assumed to be homogeneous and isotropic. The one-dimensional unsteady heat conduction process along the soil depth direction is governed by Equation (1):

$$\frac{\partial T_s}{\partial \tau} = \alpha_s \frac{\partial^2 T_s}{\partial z^2} \quad (1)$$

where T_s is the soil temperature (K) and z is the soil depth (m). The subsurface soil is modeled as a semi-infinite medium. By integrating Equation (1), an expression for the annual hourly soil temperature variation at depth z under periodic boundary conditions representing outdoor temperature fluctuations is obtained, as shown in Equation (2). This equation is validated by Al-Ajmi et al. [44] and commonly used to calculate the underground soil temperature in related studies [41,45].

$$T_s(z, t) = T_{s,mean} - A_s \exp\left(-z \sqrt{\frac{\pi}{8760\alpha_s}}\right) \cos\left(\frac{2\pi}{8760} \left(t - t_0 - \frac{z}{2} \sqrt{\frac{8760}{\pi\alpha_s}}\right)\right) \quad (2)$$

where α_s is soil thermal diffusivity (m^2/h); A_s is annual amplitude of the surface soil temperature (K); $T_{s,mean}$ is annual mean surface soil temperature (K); t_0 is the time of year corresponding to the minimum surface soil temperature. In Equation (2), the soil surface temperature (T_s at $z = 0$) is assumed to be equal to the outdoor air temperature. Given hourly outdoor air temperature data throughout the year and the soil thermal diffusivity, the annual variation in subsurface soil temperature can be calculated.

The heat transfer process within the EAHE contains three main parts: convective heat transfer between the flowing air and the pipe wall, conduction through the pipe wall itself, and conduction within the surrounding soil, as illustrated in Figure 2. Based on the principle of energy conservation, an energy balance equation for the flow of air within the pipe is established, expressed as Equation (3):

$$m_a C_a \frac{dT_a}{dx} = (T_s - T_a) \frac{1}{R_{total}} dx \quad (3)$$

where C_a is the specific heat capacity of air ($\text{kJ}/\text{kg}\cdot\text{K}$); m_a is the mass flow rate of air inside the pipe (kg/h); R_{total} is the total thermal resistance between the flowing air and the undisturbed soil in the EAHE ($\text{m}\cdot\text{K}/\text{W}$); T_s is the undisturbed soil temperature (K); and T_a is the temperature of the air inside the pipe (K).

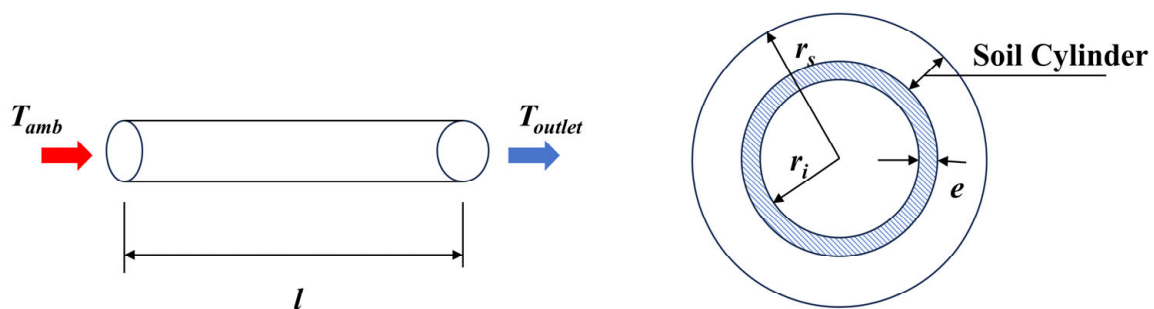


Figure 2. Schematic diagram and cross-sectional schematic of the EAHE.

Solving the governing Equation (3) yields Equation (4) for calculating the exhaust air outlet temperature of the EAHE system, which has been validated by the experimental data [46].

$$T_{outlet} = T_s + (T_{amb} - T_s) \exp\left(-\frac{l}{m_a C_a R_{total}}\right) \quad (4)$$

where T_{outlet} is the outlet air temperature of the EAHE (K); T_{amb} is the outdoor air temperature, equivalent to the inlet air temperature of the EAHE (K); and l is the length of the buried pipe within the EAHE (m).

The total thermal resistance (R_{total}) between the flowing air and the undisturbed soil, expressed by Equation (5), comprises three components: (1) the convective heat transfer resistance between the air and the pipe inner wall (R_{conv}), (2) the conductive resistance through the pipe wall (R_{pipe}), and (3) the conductive resistance through the surrounding soil (R_{soil}). The individual thermal resistances are calculated by Equations (6)–(8):

$$R_{total} = R_{conv} + R_{pipe} + R_{soil} \quad (5)$$

$$R_{conv} = \frac{1}{2\pi r_i h} \quad (6)$$

$$R_{pipe} = \frac{1}{2\pi k_p} \ln\left(\frac{r_i + e}{r_i}\right) \quad (7)$$

$$R_{soil} = \frac{1}{2\pi k_s} \ln\left(\frac{r_s + r_i + e}{r_i + e}\right) \quad (8)$$

where k_s is thermal conductivity of the soil (W/m·K); k_p is thermal conductivity of the pipe material (W/m·K); e is the thickness of the pipe wall (m); r_s is the radius of the thermally disturbed soil zone around the pipe (m); r_i is internal radius of the buried pipe (m); and h is the convective heat transfer coefficient between the flowing air and the pipe inner wall (W/m²·K). The calculation of h can refer to our previous work [41].

2.2.2. Ventilated Double-Skin Facade

This study employs a 2D simplification approach, neglecting heat transfer along the horizontal direction parallel to glazing panes. This simplification has been widely adopted in related VDSF research [47,48]. Figure 3 illustrates the numerical modeling schematic of the VDSF. The system comprises three glass panels and two air cavities, discretized vertically into N segments and horizontally into five layers: outer glazing (L_1), sealed air cavity (L_2), middle glazing (L_3), ventilated cavity (L_4), and inner glazing (L_5). Consequently, the entire fenestration system is divided into $5 \times N$ discrete zones. This study simplifies the numerical model by disregarding conductive heat transmission between adjacent zones inside each layer, neglecting thermal energy storage of air, and assuming uniform thermal characteristics throughout each zone [49]. The ventilation airflow that enters the ventilated cavity (L_4) of VDSF is assumed to be exclusively precooled or preheated via the EAHE. The governing equations for the five layers in the j segment based on energy and mass conservation are expressed as follows.

For the outer glazing (L_1):

$$h_{co}(T_{out} - T_{1j}) + \sigma \varepsilon_1 \left[(T_{sky}^4 - T_{1j}^4) F_{sky} + (T_{ground}^4 - T_{1j}^4) F_{ground} \right] + h_{c12}(T_{2j} - T_{1j}) + \frac{\sigma(T_{3j}^4 - T_{1j}^4)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_3} - 1} + I_{sol} \alpha_1 = D_g \rho_g C_g \frac{\partial T_{1j}}{\partial t} \quad (9)$$

For the sealed air cavity (L_2):

$$h_{c12}(T_{1j} - T_{2j}) + h_{c23}(T_{2j} - T_{3j}) = 0 \quad (10)$$

For the middle glazing (L_3):

$$h_{c23}(T_{2j} - T_{3j}) + \frac{\sigma(T_{1j}^4 - T_{3j}^4)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_3} - 1} + h_{c34}(T_{4j} - T_{3j}) + \frac{\sigma(T_{5j}^4 - T_{3j}^4)}{\frac{1}{\varepsilon_3} + \frac{1}{\varepsilon_5} - 1} + I_{sol}\alpha_3 = D_g\rho_g C_g \frac{\partial T_{3j}}{\partial t} \quad (11)$$

For the ventilated cavity (L_4):

$$h_{c34}(T_{3j} - T_{4j}) + h_{c45}(T_{5j} - T_{4j}) + C_a\rho_a V_a(T_{4,j-1} - T_{4j}) \frac{N}{HW} = 0 \quad (12)$$

For the inner glazing (L_5):

$$h_{c45}(T_{4j} - T_{5j}) + \frac{\sigma(T_{3j}^4 - T_{5j}^4)}{\frac{1}{\varepsilon_3} + \frac{1}{\varepsilon_5} - 1} + h_{ci}(T_{in} - T_{5j}) + \sigma\varepsilon_5(T_{in}^4 - T_{5j}^4) + I_{sol}\alpha_5 = D_g\rho_g C_g \frac{\partial T_{5j}}{\partial t} \quad (13)$$

where H , W , and D_g represent the height, width, and thickness of the glazing (m); C is the specific heat ($\text{J/kg}\cdot\text{K}$); V_a is the airflow rate through the VDSF (m^3/h); I_{sol} is the total normal incident solar irradiance (W/m^2); T_{sky} is the sky temperature (K) calculated via the Swinbank model [49]; T_{ground} is the outdoor ground surface temperature (K), which is equated to the ambient temperature; ε is the surface emissivity; F represents the view factor; σ is the Stefan–Boltzmann constant ($5.67 \times 10^{-8} \text{ W/m}^2\cdot\text{K}^4$); and α_1 , α_3 , and α_5 are the overall absorptance of the each glazing layer. h_c is the convective heat transfer coefficient ($\text{W/m}^2\cdot\text{K}$), as described in Table 1.

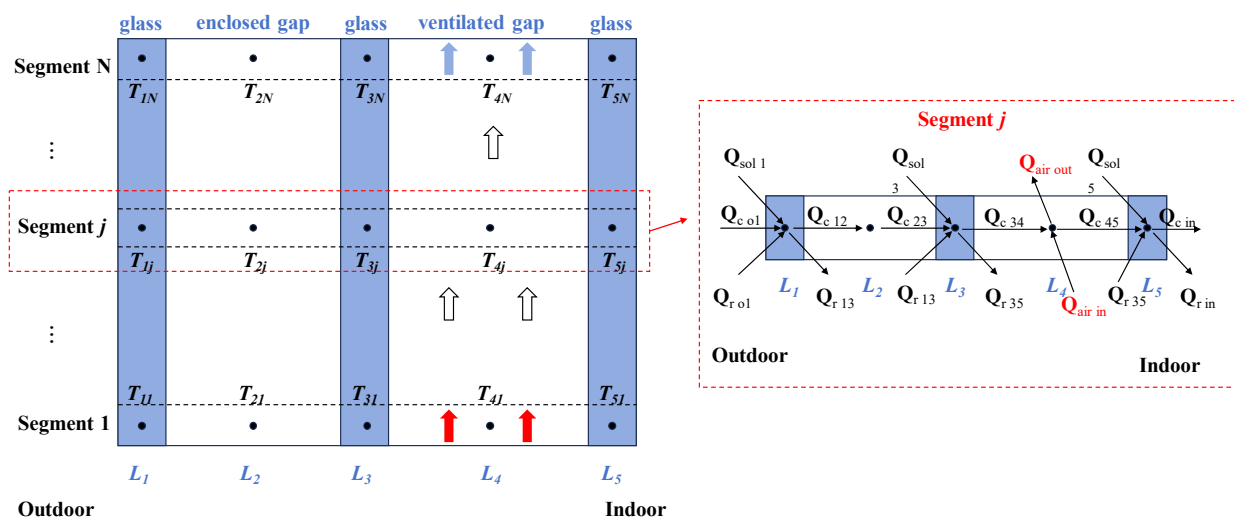


Figure 3. Discretization scheme for the VDSF under operating conditions.

Table 1. Expression of each convective heat transfer coefficient.

Convection Heat Transfer	Expression or Value ($\text{W/m}^2\text{K}$)
h_{c12}, h_{c23} between enclosed air and window [50]	$\begin{cases} Nu = 0.067383Ra^{0.73} & Ra > 5 \times 10^4 \\ Nu = 0.028154Ra^{0.4134} & 10^4 < Ra \leq 5 \times 10^4 \\ Nu = 1.75967 \times 10^{-10}Ra^{2.298075} & Ra \leq 10^4 \\ Ra = \frac{\rho^2 d^3 g \beta c_p \Delta T}{\mu \lambda} \end{cases}$
h_{c34}, h_{c45} between ventilated air and window [51]	$h_c = 5.62 + 3.9V_{air} \quad (V_{air} < 5\text{m/s})$
h_{co} between outdoor air and glazing [52]	$h_c = 2.8 + 3V_{out}$
h_{ci} between indoor air and glazing [53]	$h_c = 8.3$

In this study, the VDSF is discretized into 10 vertical segments along its height. A compromise between computational efficiency and simulation accuracy is reached by this discretization. Input parameters for the numerical model include normal solar irradiance; outdoor/indoor air temperatures, VDSF inlet air temperature (equivalent to EAHE outlet temperature), and exhaust airflow rate within the VDSF cavity. The governing equations are solved using an iterative algorithm implemented in the platform MATLAB R2017a, generating simulated temperature values at each nodal point throughout the VDSF system.

2.3. Model Validation

It is necessary to ensure the mathematical model and simulation procedure have enough reliability and accuracy. The mathematical model was initially validated against experimental data from Bansal et al. [54], who experimentally investigated the performance of EAHE under varying inlet air velocities. To validate the developed model of EAHE, the design parameters and boundary conditions of experimental investigation were used as the input of analytical model of the EAHE to calculate the outlet air temperature of EAHE. The calculated outlet air temperatures were compared with experimental data [53] for more validation.

The input parameters used for this validation are detailed in Table 2, with comparative results summarized in Table 3. The absolute error between the experimental data and the model predictions ranges from $-1.1\text{ }^{\circ}\text{C}$ to $0.9\text{ }^{\circ}\text{C}$, indicating very close agreement. Specifically, for the boundary condition of 2 m/s inlet air velocity, the maximum discrepancy between the predicted and measured outlet air temperatures is $1.1\text{ }^{\circ}\text{C}$. Furthermore, at an air velocity of 3 m/s within the buried pipe, the relative deviation is only 0.6% . These results demonstrate that the developed mathematical model effectively calculates the thermal performance of the EAHE with reasonable accuracy.

Table 2. Input parameters for EAHE model validation.

Parameter	Reference Values
pipe length (m)	23.42
pipe diameter (m)	0.15
soil density (kg/m^3)	2050
soil specific heat capacity ($\text{J/kg}\cdot\text{K}$)	1840
soil thermal conductivity ($\text{W/m}\cdot\text{K}$)	0.52
soil temperature ($^{\circ}\text{C}$)	26.7
air velocity (m/s)	2, 3, 4 and 5

Table 3. Results of model validation against the experimental data of Bansal et al. [54].

Boundary Conditions		Outlet Air Temperature of EAHE ($^{\circ}\text{C}$)			
Inlet Velocity (m/s)	Inlet Air Temperature ($^{\circ}\text{C}$)	Experimental [54]	Calculated	Absolute Error	Relative Deviation
2	43.3	33.1	32.0	-1.1	3.2%
3	42.5	33.1	33.3	0.2	0.6%
4	42.3	33.5	34.3	0.8	2.4%
5	42.2	34.2	35.1	0.9	2.7%

Subsequently, the experimental data from our previous work [49] was used to validate this simulation methodology and computational results. Detailed information regarding the experimental setup dimensions and boundary conditions is provided in the aforementioned reference [49]. Figure 4 compares the simulated and experimentally measured temperatures of the interior glazing surface and outlet air. As shown in the figure, the simulated temperatures closely follow the temporal trends observed in the experimental

data. The root means square error (RMSE) between the simulated and measured values was 0.11 °C for the interior glazing surface temperature and 0.38 °C for the outlet air temperature. This validation results by comparing the simulation data with measured results published in our prior work [49] demonstrate that the proposed zonal model possesses sufficient accuracy for predicting glass surface temperatures within the VDSF. A more comprehensive explanation of the model development, experimental setup, and accuracy of the validation results can be found in our previous work [49].

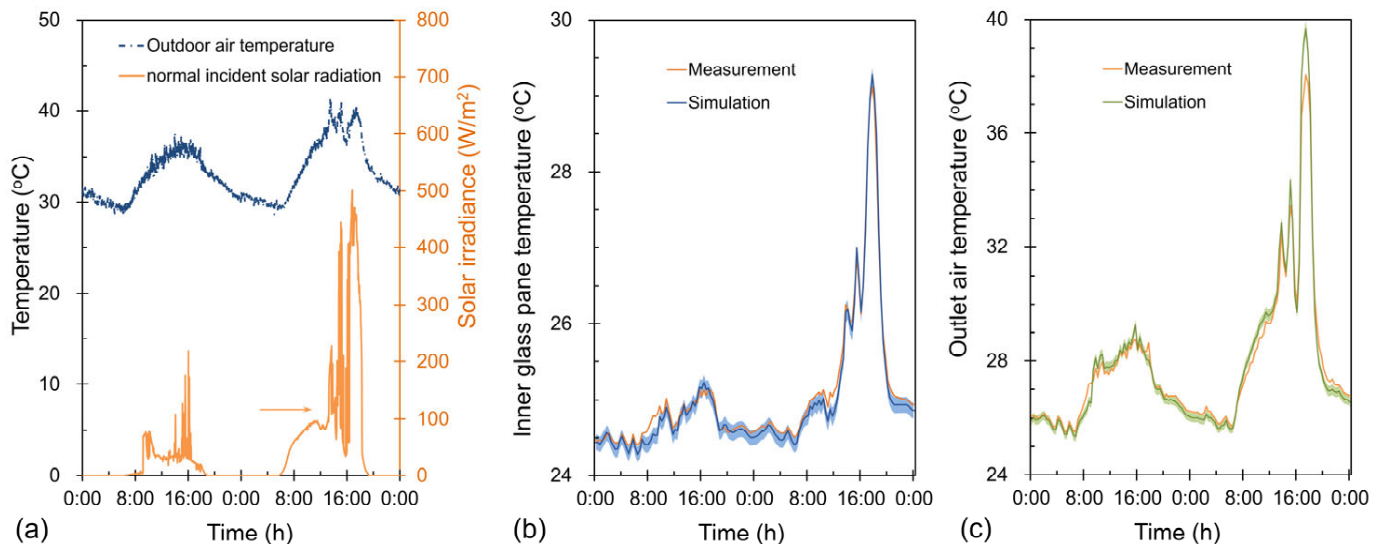


Figure 4. Computational results versus measured results [49]: (a) boundary conditions; (b) interior glazing surface temperature; (c) outlet air temperature.

3. Boundary Conditions of Case Study

This study employs a representative case study under a typical hot-summer-and-cold-winter climate condition to evaluate the thermal performance of the EAHE-VDSF coupled system. The typical meteorological year data of Wuhan city (typical hot-summer-and-cold-winter climate zone) was used for the simulation. Typical meteorological year data is a commonly used type of data for building energy simulation as it represents long-term climatic patterns. The system is installed within a reference office room (4 m × 4 m × 3 m) and consists of an EAHE subsystem and a south-oriented VDSF. The basic EAHE system features a buried pipe at a depth of 10 m, with a length of 100 m and an internal diameter of 0.1 m. The VDSF has dimensions of 4 m in width and 3 m in height, featuring three glazing panes, each with a thickness of 6 mm, a sealed cavity measuring 9 mm, and a ventilated cavity that is 30 mm thick. The key design parameters of the EAHE system used in this study are provided in Table 4. Figures 5 and 6 present the outdoor weather parameters of the typical summer and winter design day in Wuhan, respectively. The setpoint of indoor temperature was maintained at 25 °C and 18 °C throughout the cooling and heating season, respectively.

The thermal performance of the coupled EAHE-VDSF system was evaluated for typical summer and winter design days. Primary performance metrics including the outlet air temperature of the EAHE, the inner surface temperature of the VDSF glazing, the VDSF exhaust air outlet temperature, and the cooling/heating load of the VDSF were comprehensively investigated. The hourly cooling and heating load of the window can be calculated by Equations (14) and (15).

$$Q_{cool} = (T_5 - T_{in}) \times (h_{ri} + h_{ci}) + I_{sol} \times \tau \quad (14)$$

$$Q_{heat} = (T_{in} - T_5) \times (h_{ri} + h_{ci}) - I_{sol} \times \tau \quad (15)$$

where Q_{cool} and Q_{heat} are the hourly cooling and heating load of the VDSF, W/m^2 ; T_5 is the internal surface temperature of the room-side glazing (K). τ represents the total solar transmittance of the entire VDSF system. The value of τ for the baseline case (clear float glass) was calculated to be 0.5761 using WINDOW 8.0 software, as detailed in Section 4.3.3.

To quantify the absolute energy-saving potential of the proposed EAHE-VDSF system, a conventional triple-glazed, non-ventilated facade with identical dimensions and glazing properties was adopted as the baseline case. All the performance metrics (e.g., temperatures and energy loads) of the conventional triple-glazed, non-ventilated facade were compared with that of the proposed EAHE-VDSF system. Furthermore, a comprehensive parametric analysis was conducted to assess the influence of key design parameters on system performance. This study analyzes the design parameters of EAHE, focusing on buried pipe depth, length, and diameter, as well as the design parameters of VDSF, which include airflow rate in the ventilated cavity, cavity size, and glazing optical properties such as solar transmittance and absorptivity.

Table 4. Key parameters for EAHE thermal performance calculation.

Parameter	Values	Unit
buried pipe depth	10	m
buried pipe length	100	m
pipe inner diameter	0.1	m
pipe wall thickness	0.02	m
pipe thermal conductivity	0.16	W/(m·K)
soil density	2050	kg/m ³
soil specific heat	1840	J/(kg·K)
soil thermal conductivity	0.52	W/(m·K)
air density	1.205	kg/m ³
air specific heat	1013	J/(kg·K)
air thermal conductivity	0.02593	W/(m·K)
air kinematic viscosity	15.06×10^{-6}	m ² /s

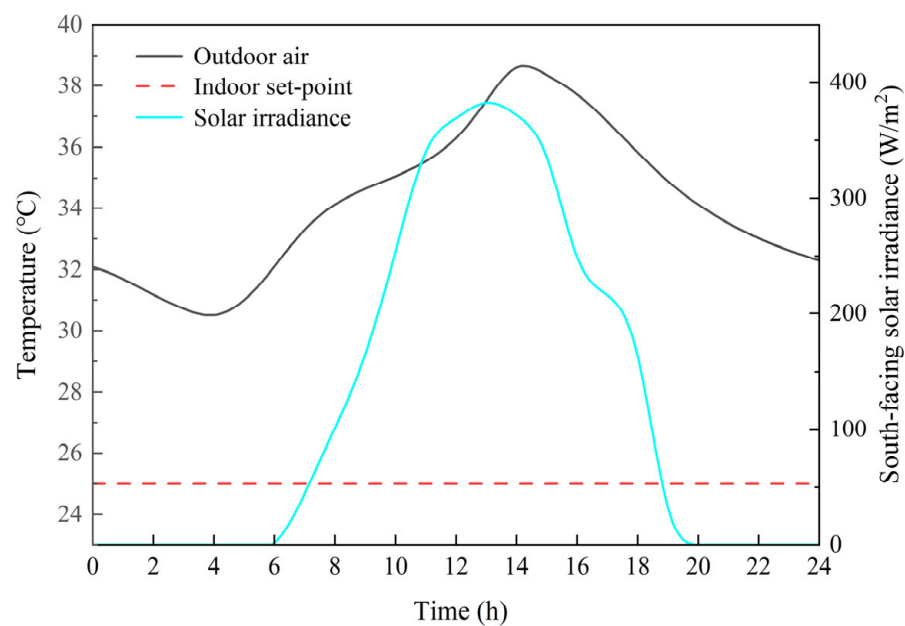


Figure 5. Meteorological parameters of a typical summer design day.

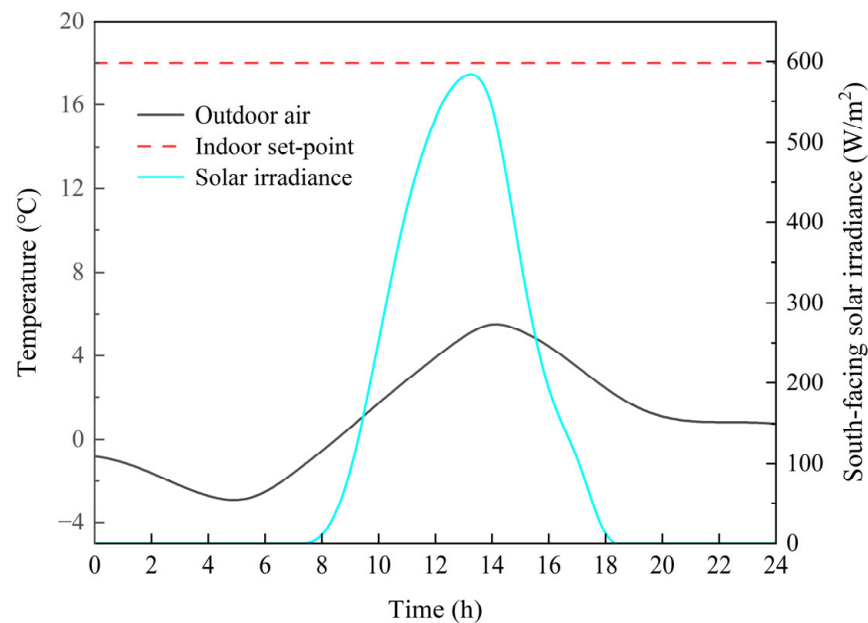


Figure 6. Meteorological parameters of a typical winter design day.

4. Performance Evaluation of EAHE-VDSF System

The thermal performance evaluation of the EAHE-VDSF coupled system and its influencing factors are systematically investigated and discussed. Section 4.1 presents the thermal performance assessment of the integrated system under typical summer and winter design-day conditions. Section 4.2 analyzes the impact of EAHE design parameters on the coupled system's performance. Section 4.3 examines the influence of VDSF design parameters on the system's behavior.

4.1. Thermal Performance Evaluation

4.1.1. Performance on Typical Summer Day

Figure 7 demonstrates the thermal performance of the EAHE-VDSF coupled system operating at 0.1 m/s exhaust cavity velocity under summer design-day conditions. The results indicate that the EAHE could effectively precool the flowing air in the buried pipe, reducing outdoor air temperatures by an average of 15 °C and lowering peak temperatures from 38.7 °C to 19.8 °C. Subsequently, air temperatures increased by approximately 4 °C after traversing the VDSF due to absorbing heat from the adjacent glazing surface. The room-side interior glazing surface (T_5) exhibited parallel variations, maintaining a mean temperature of 24.8 °C with a peak of 26.7 °C, consistently exceeding the indoor air temperature between 09:30 and 18:30. Cooling load analysis indicates a peak of 312.6 W/m² at 13:30, with negative loads observed from 00:00 to 07:30 and 18:00 to 24:00, indicating reverse heat flow and highlighting substantial potential for cooling demand reduction. The reverse heat flow means that the internal surface temperature of the VDSF was lower than the indoor air temperature in the summer.

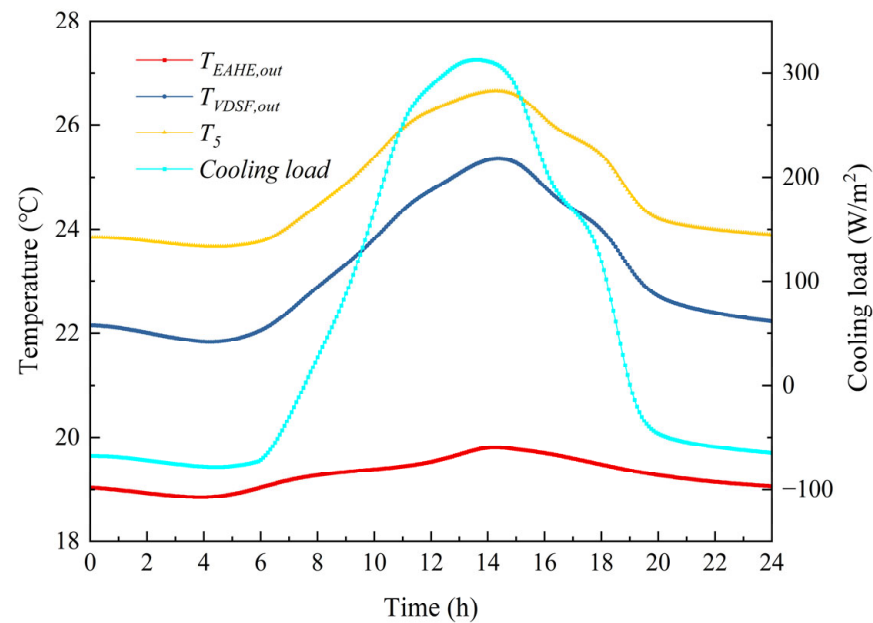


Figure 7. Thermal performance of the EAHE-VDSF on a typical summer design day.

4.1.2. Performance in Typical Winter Day

Figure 8 presents the thermal performance of the EAHE-VDSF coupled system operating at 0.1 m/s cavity velocity on a typical winter design day. It can be found that the EAHE shows significant preheating potential by increasing outdoor air temperatures by 14.3 °C on average. The ventilated airflow within VDSF decreases by 0.7 °C on average; however, a temperature increase occurs during the daytime due to high incident solar radiation. The average temperature of the interior glazing surface of the VDSF is 16.5 °C, which is slightly lower than indoor air temperature, resulting in a reduction in heat loss through the VDSF. The maximum temperature of the interior glazing surface of the VDSF reaches 19.4 °C, exceeding the indoor temperature due to the high incident solar radiation in the daytime. Heating load analysis indicates notable heat gain periods from 09:30 to 17:00, with a maximum heat flow of 412.3 W/m² occurring at 13:30.

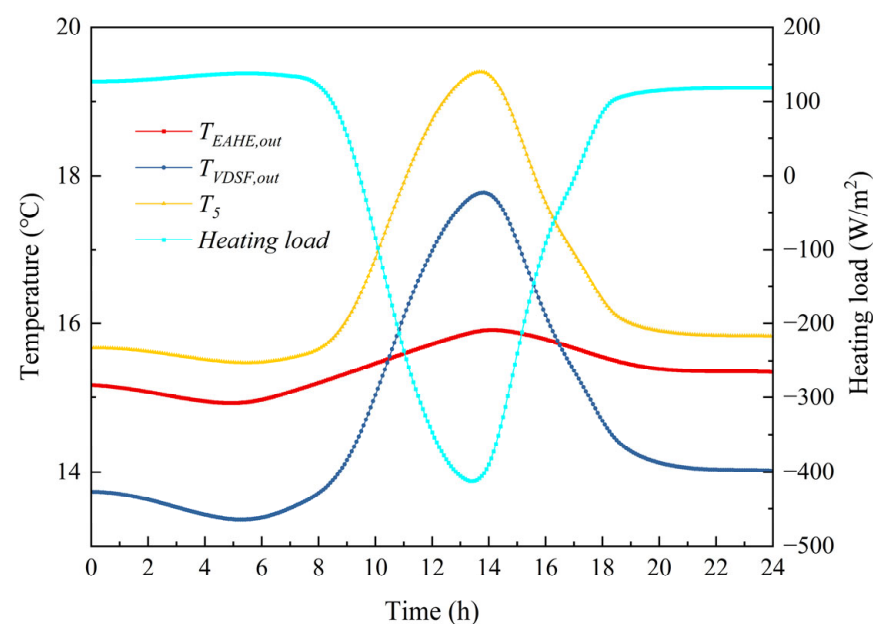


Figure 8. Thermal performance of EAHE-VDSF on a typical winter design day.

4.2. Effects of the Design Parameters of EAHE

In this section, the influence of the depth, length, and diameter of the buried pipe on the outlet air temperature of EAHE, interior surface temperature of VDSF, outlet air temperature of VDSF, and accumulated cooling/heating loads of the VDSF were comprehensively investigated. This parametric study considered buried pipes at depths ranging from 1 m to 10 m, lengths from 10 m to 150 m, and diameters from 100 mm to 300 mm.

4.2.1. Depth of Buried Pipe

To evaluate the thermal performance improvement of the EAHE-VDSF system, the interior glazing surface temperature of the baseline case is compared with that of the EAHE-VDSF system on typical summer and winter days, as shown in Figures 9 and 10. The annual accumulated cooling and heating loads of the baseline case and the EAHE-VDSF system with different burial depths are summarized in Table 5. As shown in Figure 9, the interior glazing surface temperature of the baseline case exhibits significantly higher fluctuations and peak value during the cooling season compared to all EAHE-VDSF configurations. With an increase in burial depth from 1 m to 4 m, the average outlet air temperature of the EAHE decreases from 22.5 °C to 18.0 °C, while the interquartile range (IQR) contracts from 3.8 °C to 1.2 °C, improving the stability and consistency in the precooling capacity of the EAHE. At depths exceeding 4 m, diminishing returns are evident, characterized by minimal temperature variation of less than 0.5 °C at depths of 8 m to 10 m. This phenomenon arises from increased sensitivity to ambient thermal disturbances in shallow soils, leading to notable fluctuations in soil temperature that affect the heat exchange between flowing air and the soil within the EAHE. At depths greater than 8 m, annual soil temperatures remain nearly constant, resulting in stable conditions for the outlet air temperature of the EAHE. Variations in VDSF exhaust temperatures and room-side glazing surface temperatures consistently align with EAHE outlet temperature trends across different burial depths. Table 5 displays the total accumulated seasonal cooling loads for the VDSF at various EAHE burial depths. The findings indicate a notable decrease in accumulated cooling load as burial depth increases. As the depth increases from 1 m to 10 m, the accumulated cooling load significantly decreases from 132.3 kWh/m² to 68.8 kWh/m², indicating a reduction rate of 48.0%. And in contrast with the baseline case, the EAHE-VDSF system with a 4 m burial depth reduces cooling loads by 69.8%.

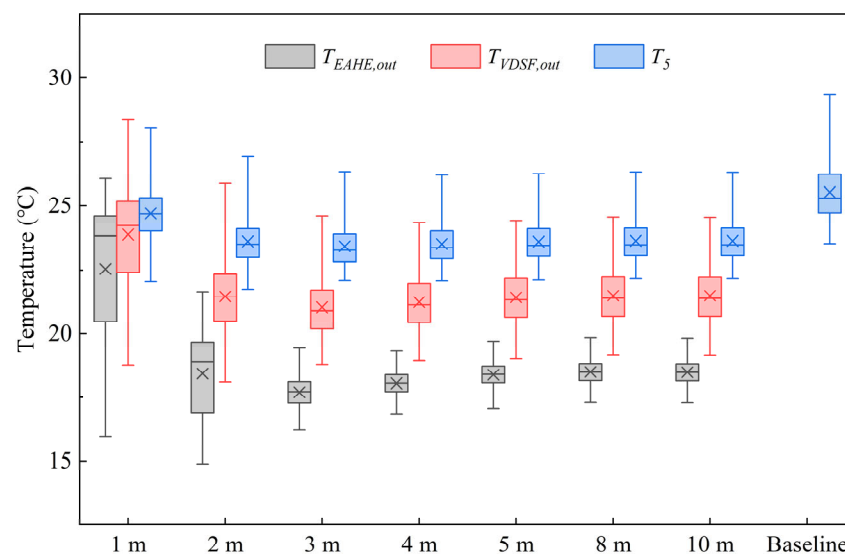


Figure 9. Impact of EAHE burial depth on thermal performance of coupled EAHE-VDSF system during cooling season.

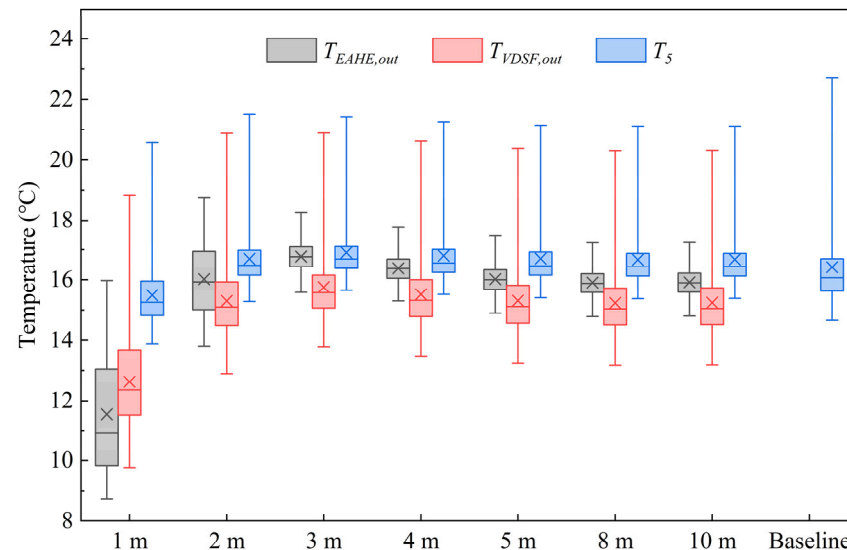


Figure 10. Impact of EAHE burial depth on thermal performance of coupled EAHE-VDSF system during heating season.

Table 5. Accumulated cooling and heating loads of the baseline case and VDSF under different EAHE burial depths.

Depth of Buried Pipe	Accumulated Cooling Load (kWh/m ²)	Accumulated Heating Load (kWh/m ²)
Baseline case	210.7	68.2
1 m	132.3	111.6
2 m	70.2	54.6
3 m	59.9	45.4
4 m	63.6	49.5
5 m	67.6	53.6
8 m	69.0	55.0
10 m	68.8	54.8

This enhancement in thermal performance is primarily attributed to the lower and more stable soil temperatures found at greater depths during the cooling season, which lead to a decrease in the outlet air temperature of the EAHE. Consequently, increasing the burial depth effectively enhances the overall thermal performance of the EAHE-VDSF coupled system.

In the heating season, the influence of EAHE burial depth demonstrated a trend similar to that observed in the cooling season. Figure 10 presents the influence of pipe depth on thermal performance of the EAHE-VDSF coupled system during the heating season. With an increase in burial depth from 1 m to 4 m, the average outlet air temperature of the EAHE increases from 11.8 °C to 16.0 °C, while the IQR decreases from 4.2 °C to 0.9 °C. The outlet air temperature of VDSF increases from 12.5 °C to 15.5 °C, and its inner surface temperature ranges from 15.5 °C to 16.5 °C. This means that increasing the burial depth of pipe can significantly improve the preheating potential of the EAHE and reduce the heat loss of the VDSF in the heating season. Beyond a depth of 5 m, these temperatures stabilize and exhibit relative constancy.

The results on seasonal accumulated heating load presented in Table 5 indicate a consistent trend of reduction as burial depth increases. As the depth increases from 1 m to 10 m, the accumulated heating load decreases from 111.6 kWh/m² to 54.8 kWh/m², reflecting a reduction rate of 50.9%. Compared with the baseline case, the EAHE-VDSF system with a 4 m burial depth reduces the heating loads by 27.4%. This improvement can

be attributed to higher and more consistent soil temperatures at greater depths during the heating season, leading to an increase in the outlet air temperature of the EAHE.

4.2.2. Length of Buried Pipe

Figure 11 illustrates the impact of EAHE pipe length on the thermal performance of the EAHE-VDSF coupled system during the cooling season. Increasing the pipe length significantly reduced the outlet air temperature of EAHE. As a result, the outlet temperature and interior glazing surface temperature of the VDSF decrease, resulting in a significant reduction in the cooling load produced by the VDSF. With an increase in pipe length from 10 m to 100 m, the seasonal average outlet air temperature of EAHE decreases from 25.3 °C to 18.5 °C, while the IQR is reduced from 5.0 °C to 1.0 °C. The average interior glazing surface temperature of VDSF decreases from 25.4 °C to 23.6 °C. The decrease in the temperature differential between the interior glazing surface and the indoor environment significantly facilitates a reduction in heat gain through the VDSF. Increasing the pipe length beyond 100 m results in only marginal changes in these temperatures, indicating negligible additional improvements in system thermal performance.

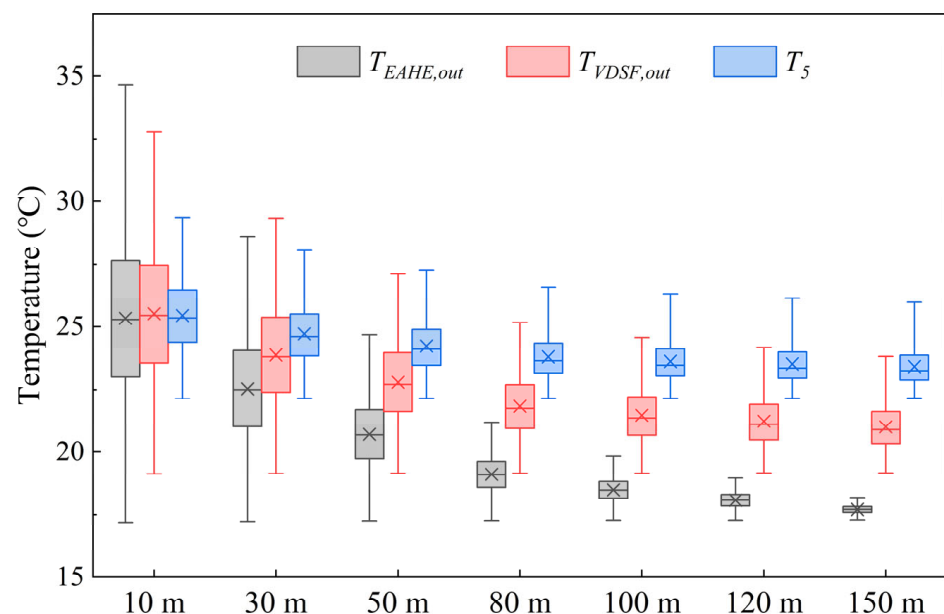


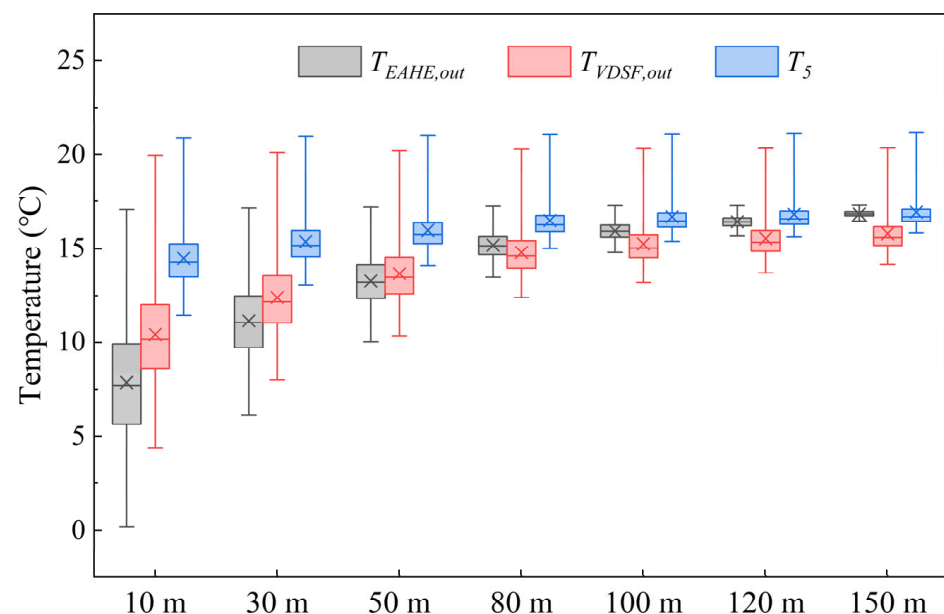
Figure 11. Impact of EAHE pipe length on the thermal performance of the coupled EAHE-VDSF system during the cooling season.

Table 6 presents the seasonal accumulated cooling loads for the VDSF across different EAHE pipe lengths. The results indicate a substantial reduction in accumulated cooling load with increasing pipe length. As the length increased from 10 m to 150 m, the accumulated cooling load decreased significantly from 217.6 kWh/m² to 57.0 kWh/m², representing a substantial reduction rate of 73.8%. Compared with the baseline case, the EAHE-VDSF system with a 150 m burial length reduces the cooling loads by 72.9%. This marked improvement in thermal performance is primarily attributed to the extended air residence time within the longer EAHE pipes, allowing for more complete heat exchange with the surrounding soil. This results in a lower outlet air temperature of EAHE during the cooling season. Consequently, increasing the EAHE pipe length significantly enhances the thermal performance of the EAHE-VDSF coupled system.

Table 6. Accumulated cooling and heating loads of the VDSF for different EAHE pipe lengths.

Length of Buried Pipe	Accumulated Cooling Load (kWh/m ²)	Accumulated Heating Load (kWh/m ²)
Baseline case	210.7	68.2
10 m	217.6	154.6
30 m	148.9	112.2
50 m	109.6	85.6
80 m	79.4	63.1
100 m	68.8	54.8
120 m	62.4	49.5
150 m	57.0	45.0

Figure 12 depicts the influence of EAHE pipe length on the system's thermal performance during the heating season. Increasing the pipe length enhances the preheating of outdoor air by the EAHE, significantly raising the outlet air temperature of EAHE. This subsequently increases both the outlet air temperature and interior glazing surface temperature of the VDSF, resulting in a decrease in the heat loss transmitted through the VDSF. Increasing the pipe length from 10 m to 100 m results in a significant rise in the seasonal average outlet air temperature of EAHE from 7.8 °C to 15.9 °C, along with a reduction in the IQR from 4.4 °C to 0.8 °C, enhancing the stability in preheating potential of EAHE. Furthermore, the average interior glazing surface temperature of VDSF increases from 14.5 °C to 16.7 °C. The subsequent decrease in the temperature differential between the inner glazing surface and the indoor environment significantly contributes to a reduction in the heating load. Extending the pipe length beyond 100 m results in negligible changes in temperatures, leading to correspondingly minor enhancements in the thermal performance of the EAHE-VDSF coupled system.

**Figure 12.** Impact of EAHE pipe length on the thermal performance of the coupled EAHE-VDSF system during the heating season.

The seasonal accumulated heating load in Table 6 indicates a notable reduction correlated with increasing pipe length. Specifically, as the length increases from 10 m to 150 m, the accumulated heating load decreases from 154.6 kWh/m² to 45.0 kWh/m², corresponding to a substantial reduction rate of 70.9%. Compared with the non-ventilated DSF, the EAHE-VDSF system with a 150 m burial length reduces the heating load by 34.0%. Simi-

larly, this improvement stems from the extended residence time within the longer pipes, which facilitates more effective heat exchange and results in a higher outlet air temperature of EAHE during the heating season.

4.2.3. Pipe Diameter of Buried Pipe

Figure 13 illustrates the influence of EAHE pipe diameter on the thermal performance of the EAHE-VDSF coupled system during the cooling season. As the pipe diameter increases from 100 mm to 300 mm, the seasonal average outlet air temperature of the EAHE exhibits a slight rise from 18.5 °C to 19.0 °C. Correspondingly, the average interior glazing surface temperature of the VDSF also shows an insignificant increase, from 23.6 °C to 23.8 °C, resulting in a minor decrease in the cooling load. Therefore, it can be concluded that increasing the pipe diameter results in a negligible improvement in the overall thermal performance of the EAHE-VDSF coupled system.

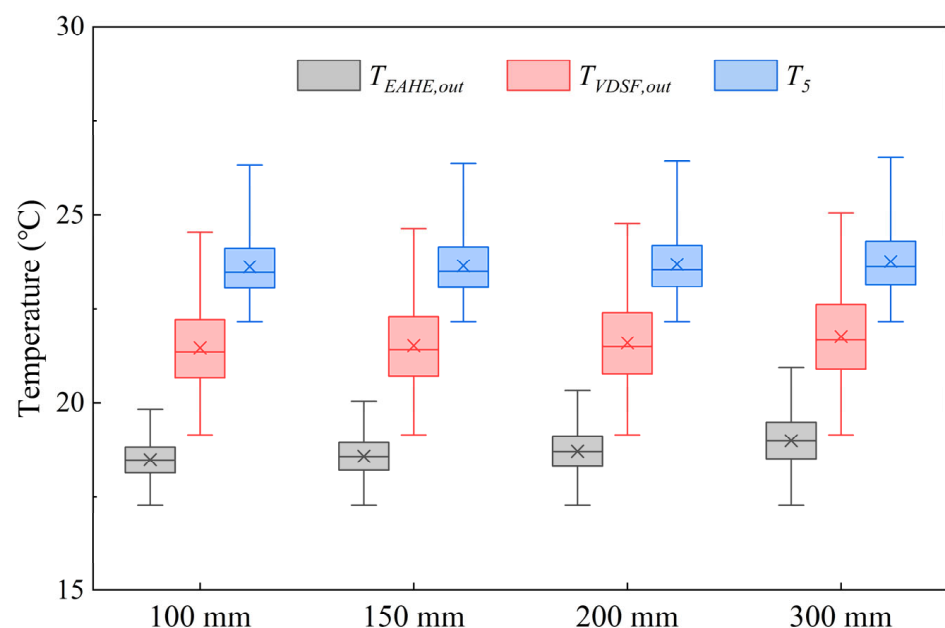


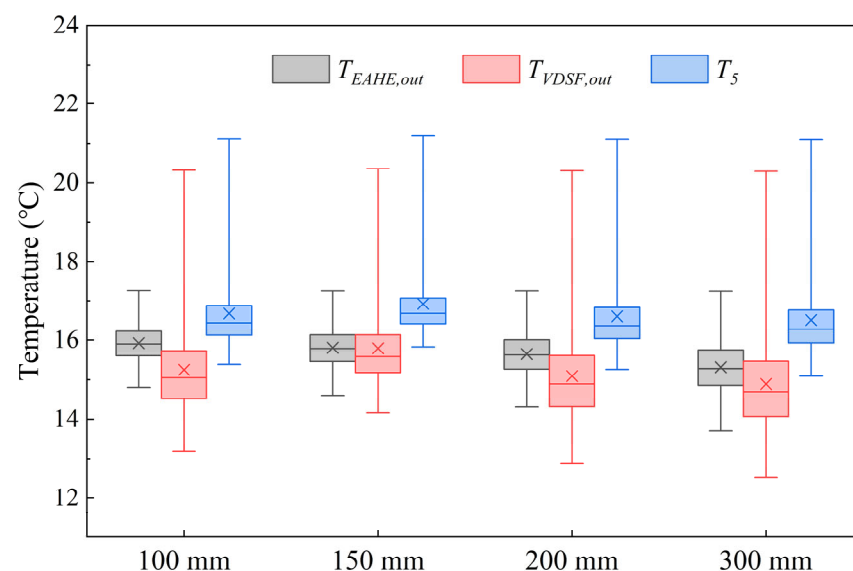
Figure 13. Impact of EAHE pipe diameter on the thermal performance of the coupled EAHE-VDSF system during the cooling season.

Table 7 presents the seasonal accumulated cooling loads for the VDSF under different diameters of buried pipes. The findings demonstrate a slight rise in accumulated cooling load as pipe diameter increases. With an increase in diameter from 100 mm to 300 mm, the accumulated cooling load increases from 68.8 kWh/m² to 77.5 kWh/m², indicating a rise of 12.6%. The EAHE-VDSF system with a 100 mm pipe diameter reduces the cooling load by 67.3% compared with the baseline case of non-ventilated DSFs. The observed decrease in thermal performance is primarily due to the diminished airflow velocity in the larger-diameter pipes. At a constant flow rate, a lower velocity results in a decreased convective heat transfer coefficient between the air and the pipe wall. This reduction leads to less effective heat exchange with the surrounding soil, causing a slight increase in the outlet air temperature of EAHE during the cooling season. Therefore, increasing the pipe diameter results in negligible improvement, or even a slight reduction, to the thermal performance of the EAHE-VDSF coupled system in the summer.

Table 7. Accumulated cooling and heating loads of the VDSF under varied EAHE pipe diameters.

Pipe Diameter of Buried Pipe	Accumulated Cooling Load (kWh/m ²)	Accumulated Heating Load (kWh/m ²)
Baseline case	210.7	68.2
100 mm	68.8	54.8
150 mm	70.4	45.0
200 mm	72.7	57.8
300 mm	77.5	61.6

Figure 14 depicts the impact of EAHE pipe diameter on system thermal performance during the heating season. Increasing the diameter from 100 mm to 300 mm results in a decrease in the seasonal average outlet air temperature of the EAHE from 15.9 °C to 15.3 °C. The average interior glazing surface temperature of the VDSF decreases from 16.7 °C to 16.5 °C, correspondingly, resulting in a slightly higher heating load of the VDSF.

**Figure 14.** Impact of EAHE pipe diameter on the thermal performance of the coupled EAHE-VDSF system during the heating season.

The seasonal accumulated heating load presented in Table 7 reveals a slight increase as the pipe diameter increases. As the diameter varies from 100 mm to 300 mm, the accumulated heating load increases from 54.8 kWh/m² to 61.6 kWh/m², corresponding to a rise of 13.0%. Additionally, the EAHE-VDSF system with a 100 mm pipe diameter lowers the heating loads by 19.6% compared to the baseline case. Similarly, this minor degradation arises from the decreased airflow velocity, which reduces the convective heat transfer coefficient. This results in reduced heat exchange efficiency during the heating season, leading to a minor decline in the preheating capacity of EAHE. Consequently, consistent with the results in the cooling season, increasing the pipe diameter yields negligible improvements in the thermal performance of the EAHE-VDSF coupled system in the winter.

4.3. Effects of the Design Parameters of VDSF

In this section, the influence of the airflow rate, ventilated cavity size, and optical parameter of glazing on the thermal performance of the coupled EAHE-VDSF system were comprehensively investigated. This parametric study considered airflow rate in ventilated cavity from 0.01 m/s to 0.5 m/s and thickness of ventilated cavity from 0.1 m to

0.4 m. Three different glazing types were evaluated to investigate the influence of glazing optical properties.

4.3.1. Airflow Rate in Ventilated Cavity

The airflow rate in the exhaust cavity significantly affects the thermal performance of the EAHE-VDSF coupled system by influencing the heat exchange efficiency of the VDSF and modifying the outlet air temperature of the EAHE through variations in airflow rate. This section investigates nine different airflow rates varied from 0.01 m/s to 0.5 m/s, corresponding to volumetric flow rates of 43.2 m³/h to 2160 m³/h, respectively.

Figure 15 illustrates the impact of ventilated airflow rate on the thermal performance of the coupled EAHE-VDSF system during the cooling season. As the airflow rate increases from 0.01 m/s to 0.5 m/s, the seasonal average outlet air temperature of EAHE shows a consistent rise from 17.3 °C to 23.3 °C. This trend can be attributed to the reduced air residence time within the EAHE at higher flow rates, diminishing the temperature differential between the inlet and outlet of EAHE. The outlet air temperature and interior glazing surface temperature of the VDSF initially decrease as the flow rate increases from 0.01 m/s to 0.1 m/s. Specifically, the average outlet air temperature decreases from 27.5 °C to 21.5 °C, while the interior glazing surface temperature drops from 25.0 °C to 23.6 °C. However, as the airflow rate further increases from 0.1 m/s to 0.5 m/s, a reversed variation trend can be observed, resulting in an increase in both temperatures. The outlet air temperature of VDSF varies from 21.5 °C to 23.6 °C, while the interior glazing surface temperature increases from 23.6 °C to 24.6 °C. This result indicates the existence of an optimal ventilated airflow rate that achieves the lowest seasonal average interior glazing surface temperature while minimizing the cooling load of the VDSF during summer. In this parametric study, the airflow rate of 0.1 m/s represents the optimal operating point for maximizing the thermal performance of the EAHE-VDSF coupled system during the cooling season.

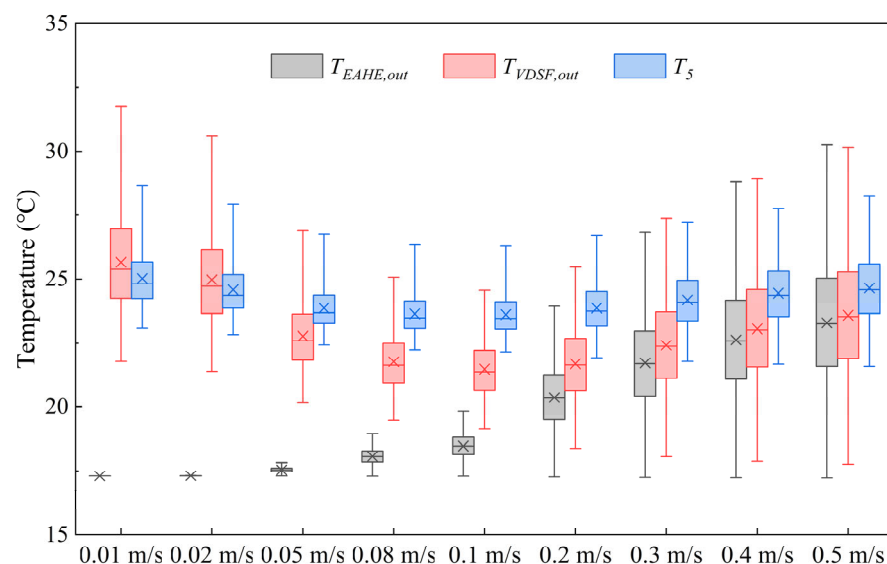


Figure 15. Impact of airflow rate within the exhaust cavity on the thermal performance of the coupled EAHE-VDSF system during the cooling season.

Table 8 presents the seasonal total accumulated cooling loads for the VDSF across different exhaust cavity airflow rates. The results demonstrate a significant non-monotonic relationship. As the airflow rate increases from 0.01 m/s to 0.1 m/s, the accumulated cooling load decreases substantially from 168.0 kWh/m² to 68.8 kWh/m², representing a reduction of 59.0%. In comparison to the baseline case, the EAHE-VDSF system with

an airflow rate of 0.08 m/s decreases the cooling loads by 66.7%. However, a further increase in airflow rate from 0.1 m/s to 0.5 m/s leads to a significant rise in the cooling load, which rises from 68.8 kWh/m² to 151.0 kWh/m². This pronounced variation in thermal performance is primarily driven by corresponding changes in the outlet air temperature of the EAHE. The accumulated cooling load data indicates an optimal operating airflow rate of 0.1 m/s for the EAHE-VDSF coupled system during the cooling season.

Table 8. Accumulated cooling and heating loads of the VDSF under different exhaust airflow rates.

Airflow Rate in Ventilated Cavity	Accumulated Cooling Load (kWh/m ²)	Accumulated Heating Load (kWh/m ²)
Baseline case	210.7	68.2
0.01 m/s	168.0	67.2
0.02 m/s	132.0	59.8
0.05 m/s	83.1	50.0
0.08 m/s	70.2	51.1
0.1 m/s	68.8	54.8
0.2 m/s	86.4	82.5
0.3 m/s	110.7	109.1
0.4 m/s	132.5	130.9
0.5 m/s	151.0	144.7

Figure 16 depicts the impact of ventilated airflow rate on the thermal performance of the system during the heating season, revealing a similar optimal velocity. Increasing the velocity from 0.01 m/s to 0.5 m/s consistently decreases the average outlet air temperature of EAHE from 17.3 °C to 10.2 °C due to reduced residence time and heat exchange effectiveness. As airflow velocity increases from 0.01 m/s to 0.1 m/s, the average interior glazing surface temperature of VDSF increases from 16.4 °C to 16.7 °C. However, as the airflow rate further varies from 0.1 m/s to 0.5 m/s, the interior glazing surface temperature declines from 16.7 °C to 14.7 °C, enlarging the heating load of the VDSF. It can be found that there exists an optimal ventilated airflow rate that achieves the highest seasonal average interior glazing surface temperature while minimizing the heating load of the VDSF during winter.

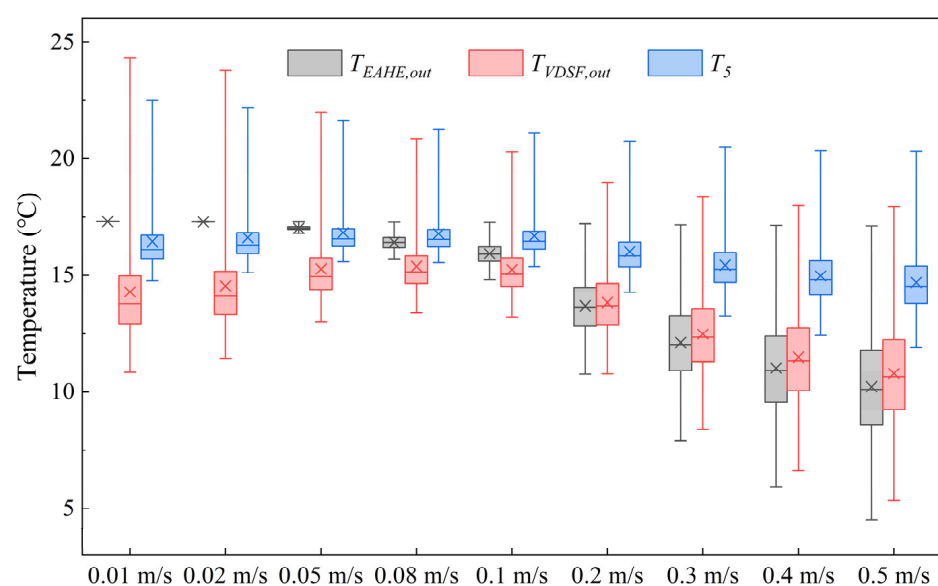


Figure 16. Impact of airflow rate within the exhaust cavity on the thermal performance of the coupled EAHE-VDSF system during the heating season.

The seasonal accumulated heating load of the VDSF under different exhaust airflow rates are listed in Table 8. The findings indicate that elevating the airflow rate from 0.01 m/s to 0.1 m/s leads to a reduction in the accumulated heating load from 67.2 kWh/m² to 54.8 kWh/m², reflecting an 18.5% decrease. In contrast to the baseline case, the EAHE-VDSF system reduces the heating loads by 25.1% with a 0.1 m/s airflow rate. In contrast, further increasing the airflow rate from 0.1 m/s to 0.5 m/s results in a significant increase in the heating load from 54.8 kWh/m² to 144.7 kWh/m². This variation primarily arises from alterations in the outlet air temperature of the EAHE.

4.3.2. Size of Ventilated Cavity

The dimensions of the ventilated cavity directly affect the heat exchange performance within the VDSF. A single-variable study was conducted, maintaining a constant volumetric airflow rate of 432 m³/h. The exhaust cavity thickness was varied from 0.1 m to 0.4 m in the parametric study.

Figure 17 depicts the influence of exhaust cavity thickness on the thermal performance of the EAHE-VDSF coupled system during the cooling season. As the cavity thickness increases from 0.1 m to 0.4 m, the average outlet air temperature of EAHE remains unchanged due to the fixed airflow rate in buried pipe. The average outlet air temperature of the VDSF demonstrates a slight reduction of 0.2 °C (from 21.6 °C to 21.4 °C), whereas the interior glazing surface temperature indicates a minimal increase of 0.1 °C (from 23.5 °C to 23.6 °C). The minimal impact is due to the simultaneous decrease in airflow velocity within the cavity, decreasing from 0.3 m/s at a thickness of 0.1 m to 0.075 m/s at a thickness of 0.4 m. A lower velocity results in a decreased convective heat transfer coefficient (h_c) within the VDSF cavity, consequently diminishing the effectiveness of convective heat transfer. In this velocity range, the magnitude of h_c is primarily determined by its constant term (as shown in Table 1), leading to minimal variations in the thermal performance of the VDSF.

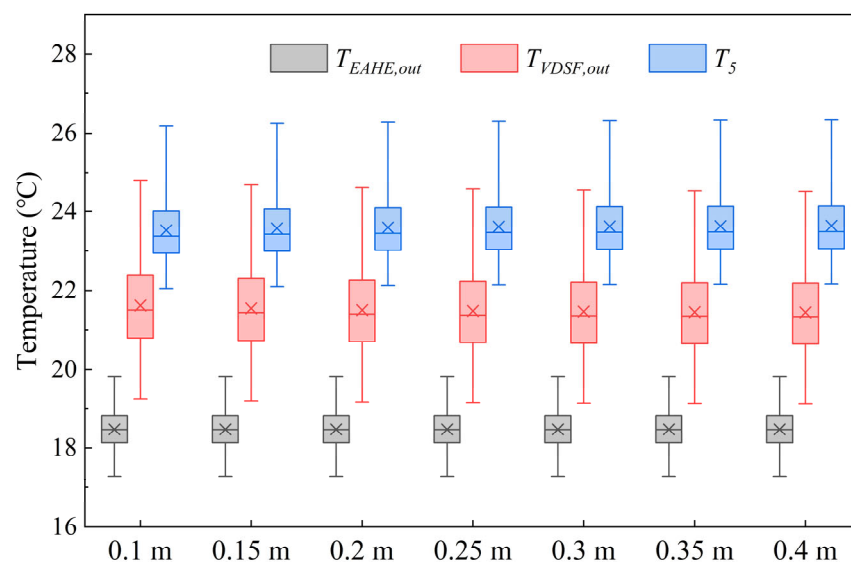


Figure 17. Impact of size of the ventilated cavity on the thermal performance of the coupled EAHE-VDSF system during the cooling season.

Table 9 presents the seasonal total accumulated cooling loads for the VDSF under different thickness of ventilated cavity. The results indicate a slight rise in accumulated cooling load as ventilated cavity thickness increases. With an increase in cavity thickness from 0.1 m to 0.4 m, the accumulated cooling load exhibits a slight rise from 63.7 kWh/m² to 69.5 kWh/m², indicating an increase of 8.3%. The slight difference in thermal performance is mainly due to minor alterations in the interior glazing surface temperature of VDSF

caused by the decreased airflow velocity in the larger cavity. Thus, ventilated cavity size shows a limited influence on the thermal performance of the EAHE-VDSF coupled system in the summer.

Table 9. Accumulated cooling and heating loads of the VDSF for different ventilated cavity dimensions.

Size of the Ventilated Cavity	Accumulated Cooling Load (kWh/m ²)	Accumulated Heating Load (kWh/m ²)
Baseline case	210.7	68.2
0.1 m	63.7	55.6
0.15 m	66.1	55.2
0.2 m	67.4	55.0
0.25 m	68.3	54.9
0.3 m	68.8	54.8
0.35 m	69.2	54.8
0.4 m	69.5	54.7

Figure 18 illustrates the influence of exhaust cavity thickness on the thermal performance of the EAHE-VDSF coupled system during the heating season. The results in the heating season are similar to those in the cooling season. Increasing the thickness from 0.1 m to 0.4 m leads to a minuscule increase of 0.01 °C in the average outlet air temperature (from 15.24 °C to 15.25 °C) and a negligible rise of 0.02 °C in the interior glazing surface temperature of the VDSF (from 16.65 °C to 16.67 °C). The seasonal accumulated heating load presented in Table 9 indicates that increasing the cavity thickness from 0.1 m to 0.4 m results in a negligible decrease in the heating load from 55.6 kWh/m² to 54.7 kWh/m², corresponding to a reduction of 1.6%. Therefore, it can be concluded that the size of the ventilated cavity has a negligible impact on the overall thermal performance of the coupled system in both seasons.

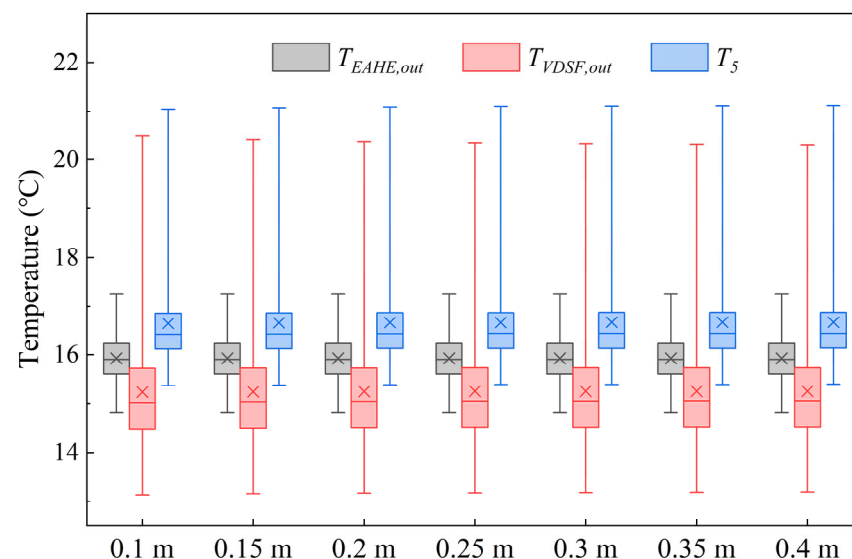


Figure 18. Impact of size of the ventilated cavity on the thermal performance of the coupled EAHE-VDSF system during the heating season.

4.3.3. Optical Parameter of Glazing

The optical properties of the glazing significantly influence radiative heat transfer within the VDSF. To identify the influence of the glazing optical parameter, the adoption of three different glazing types was considered for the intermediate glazing layer of the VDSF, including clear float glass, low-E glass (low-E on clear glass), and solar control glass (solar

coating on clear glass). In coated glazing units (low-E on clear and solar coating on clear), the coated surface was oriented towards the sealed air cavity. The overall optical properties of the VDSF using each intermediate glazing type were calculated using the WINDOW software, with results summarized in Table 10.

Table 10. Optical properties of the VDSF using different glazing types.

Mid Glazing	Absorptance			Transmittance	Reflectance
	Outer Glazing	Mid Glazing	Inner Glazing		
clear float glass	0.1134	0.0853	0.0638	0.5761	0.1614
low-E on clear	0.13	0.2941	0.0288	0.3166	0.2305
solar on clear	0.1254	0.4022	0.0226	0.2077	0.242

Figure 19 illustrates the impact of intermediate glazing optical properties on the thermal performance of the EAHE-VDSF coupled system during the cooling season. The thermal performance of the EAHE remains unchanged, as only the glazing properties were modified. In comparison to the baseline clear float glass, the average outlet air temperature of the VDSF increases by 0.2 °C for low-E on clear glass and 0.8 °C for solar coating on clear glass, while the interior glazing surface temperature of the VDSF rises by 0.1 °C and 0.3 °C, respectively. Table 11 lists the seasonal total accumulated cooling loads for the VDSF, considering various optical properties of the intermediate glazing layer. Low-E on clear glazing significantly decreases the accumulated cooling load of the VDSF by 28.1%, reducing it from 68.8 kWh/m² to 49.5 kWh/m² compared to standard clear glazing. Solar coating on clear glazing results in a 20.9% reduction, decreasing the cooling load from 68.8 kWh/m² to 54.4 kWh/m². Compared with the non-ventilated DSF, the use of clear float glass, low-E on clear glass, and solar coating on clear glass result in cooling load reductions of 67.3%, 76.5%, and 74.2% for the EAHE-VDSF coupled system, respectively. The results mean that optical parameter of glazing would help to decrease the cooling load of the EAHE-VDSF coupled system.

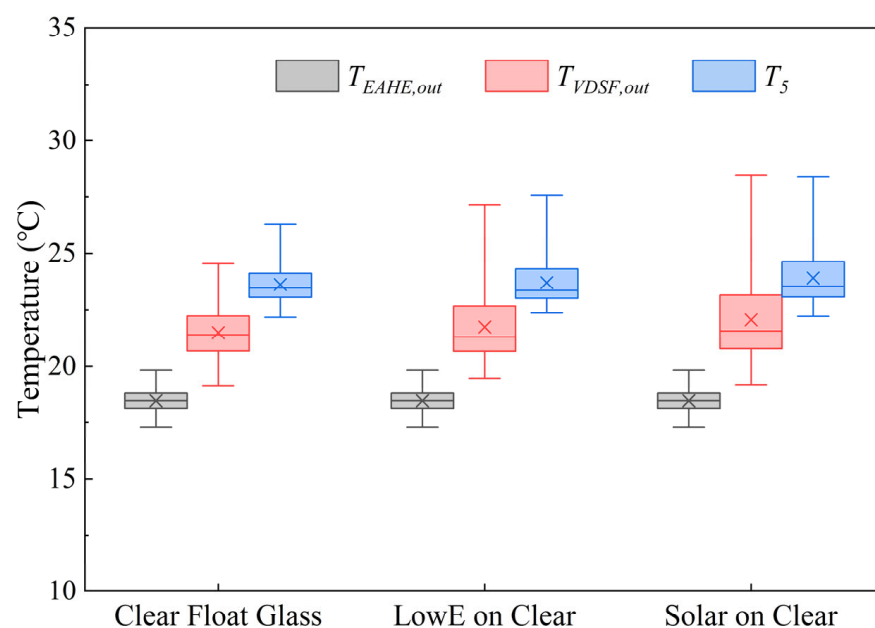
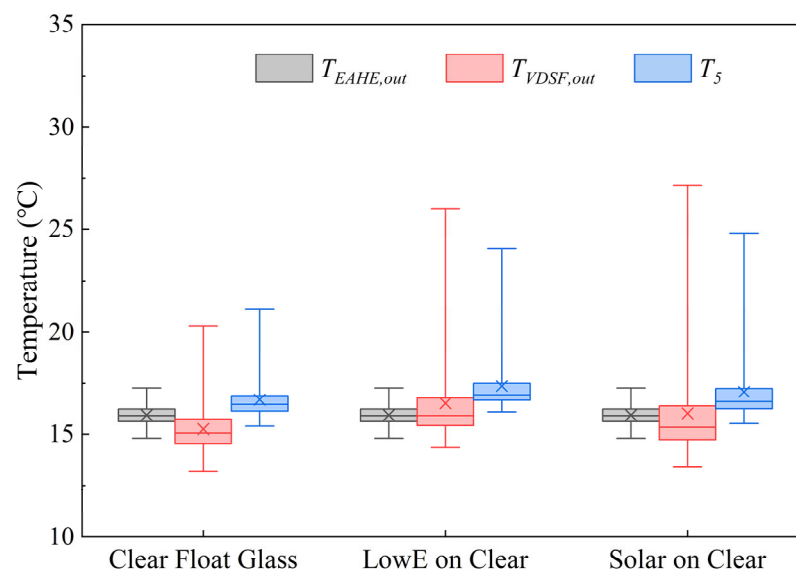


Figure 19. Impact of intermediate glazing optical properties on the thermal performance of the coupled EAHE-VDSF system during the cooling season.

Table 11. Accumulated cooling and heating loads of the VDSF with different glazing optical properties.

Mid Glazing of VDSF	Accumulated Cooling Load (kWh/m ²)	Accumulated Heating Load (kWh/m ²)
Baseline case	210.7	68.2
clear float glass	68.8	54.8
low-E on clear	49.5	36.1
solar on clear	54.4	51.3

Figure 20 depicts the thermal performance of the EAHE-VDSF system under varying intermediate glazing in the heating season. Compared to clear float glass, the average outlet air temperature of the VDSF rises by 1.2 °C for low-E on clear glass and 0.7 °C for solar coating on clear glass, which also increase the interior glazing surface temperature by 0.7 °C and 0.4 °C, respectively. The seasonal accumulated heating load presented in Table 11 indicates that the application of low-E on clear glazing results in a significant reduction in the heating load by 34.1%, decreasing from 54.8 kWh/m² to 36.1 kWh/m². The application of solar on clear glazing leads to a reduction of 6.4%, with the heating load varying from 54.8 kWh/m² to 51.3 kWh/m². The utilization of clear float glass, low-E on clear glass, and solar on clear glass for EAHE-VDSF systems can decrease 19.6%, 47.1%, and 24.8% of heating load, respectively, when compared with the baseline case of non-ventilated DSF. Low-E on clear glazing exhibits superior thermal performance compared to standard clear glazing in both seasons. The system demonstrates notable decreases in the accumulated cooling load (76.5%) and heating load (47.1%), thereby significantly improving the overall energy efficiency of the coupled system. Solar coating on clear glazing demonstrates favorable thermal performance for the VDSF in the cooling season, resulting in a 20.9% reduction in the accumulated cooling load. Despite this, its effect during the heating season is limited.

**Figure 20.** Impact of intermediate glazing optical properties on the thermal performance of the coupled EAHE-VDSF system during the heating season.

5. Discussion

5.1. Assumptions and Uncertainties of Numerical Modeling

The model is built upon several assumptions commonly adopted in related research to balance computational cost and accuracy: The 2D simplification for the VDSF neglects

heat transfer along the horizontal direction, which is justified given the dominant vertical temperature stratification in tall facades [47,48]. The soil surrounding the EAHE is assumed to be homogeneous and isotropic, a standard assumption for preliminary design and analysis [41,44]. Thermal energy storage of air within the cavities is neglected. In this study, the uncertainties of simulation results may be derived from parameter uncertainty (e.g., soil thermal properties), input uncertainty (e.g., TMY weather data), and model-structure uncertainty (e.g., the 2D simplification).

A comprehensive sensitivity analysis of the key design parameters has, in fact, been presented in Sections 4.2 and 4.3. The parametric studies on pipe depth, length, diameter, and airflow rate effectively serve as a detailed sensitivity check, quantifying the impact of these key inputs on the system's thermal performance (e.g., cooling load varied from 57.0 to 217.6 kWh/m² with pipe length). The results indicate that the system output is most sensitive to pipe length and ventilated airflow rate, while being less sensitive to pipe diameter and cavity thickness.

The findings are most reliable for buildings in climates similar to hot-summer-cold-winter zones. The identified strong sensitivity to pipe length and airflow rate provides clear guidance for practitioners: these parameters should be prioritized in design optimization. The relatively low sensitivity to pipe diameter suggests that cost and practical installation constraints can guide pipe diameter selection without significantly compromising performance. Engineers should be aware that soil property variability is a key source of uncertainty and site-specific geotechnical surveys are recommended for detailed design.

5.2. Performance of This Coupled System

The EAHE coupled with the VDSF creates an effective solution for low-grade geothermal energy utilization in transparent building envelopes. The above results indicate that the preconditioning of ambient air through the EAHE can effectively reduce overheating issues inherent to summer associated with conventional VDSFs and significantly reduce the cooling and heating load of VDSFs throughout the whole year. During the cooling season, the EAHE lowers ambient air temperature by an average of 15 °C, with a maximum reduction from 38.7 °C to 19.8 °C, utilizing the high thermal inertia of shallow soil layers, which are approximately 18 °C at a depth of 10 m. The average interior glazing surface temperature of the VDSF is 24.8 °C and very close to the indoor temperature. This results in a 48% reduction in annual cooling load at optimal burial depth. In the heating season, the EAHE preheats the flowing ambient air within a buried pipe and raises its temperature by 14.3 °C, facilitating net heat gain through the facade during the daytime and reducing the heating load of the VDSF by 50.9%. Based on the above discussion, it can be concluded that the coupled EAHE-VDSF system can provide an alternative approach to effectively precool/preheat ventilation air and achieve promising energy-saving potential for building ventilation in hot-summer-and-cold-winter climates.

5.3. Recommended Design Parameters

In this study, the influence of critical design factors on thermal performance of EAHE-VDSF systems was systemically investigated. Regarding the depth of the horizontal buried pipe in EAHEs, the underground soil temperature at different depths exhibits high thermal variability due to the impact of the ambient environment. As the depth of the buried pipe exceeds 4 m, stability and consistency in the precooling and preheating capacities of an EAHE can be achieved. Although deeper burial (>8 m) further stabilizes outputs, diminishing returns are evident, characterized by minimal variation (less than 0.5 °C) of outlet air temperature. Thus, 4 m to 5 m represents a cost-effective optimum for cooling/heating load reductions exceeding 48%. The recommended length for buried

pipes in EAHEs is between 80 m and 100 m, as extending the pipe length beyond 100 m yields only marginal improvements in the thermal performance of the coupled system. Increasing the diameter of the buried pipe slightly decreases the cooling and heating load of EAHE-VDSF coupled systems and its impact is very limited. Concerning the ventilated airflow rate in the VDSF, there exists an optimal ventilated airflow rate that achieves the minimum cooling and heating loads of VDSFs in the summer and winter, respectively. This optimal value of the ventilated airflow rate may be influenced by local climate conditions and various design parameters of the EAHE-VDSF coupled system, highlighting the necessity for variable-speed fan control in practical applications of this system. Regarding glazing selection, further employing low-E glazing in VDSFs is recommended, which can further reduce the cooling and heating loads by 28.1% and 34.1% compared to the use of clear glass.

5.4. Practical Implications, Limitations, and Future Research

This study shows the EAHE-VDSF system's considerable thermal performance and energy-saving potential, but in order to appropriately assess its feasibility and generalizability, several crucial practical issues and implications for future studies need to be discussed.

Firstly, this study is subject to limitations inherent to its simulation-based approach. Although the EAHE and VDSF sub-models were individually validated with satisfactory accuracy, the fully coupled EAHE-VDSF system has not been tested against integrated experimental data. The potential for interactive effects or error accumulation between the subsystems thus remains unquantified. Furthermore, the analysis relies on typical meteorological year (TMY) data. As highlighted in prior research [55,56], such data may not capture urban microclimatic effects like the urban heat island (UHI) effect, potentially leading to an underestimation of cooling loads in real urban settings. Consequently, the present findings are most directly applicable for comparative analysis and concept validation.

Secondly, although the main focus of this work was energy load reduction, the system's impact on indoor environmental quality is crucial. The stabilization of the interior glazing surface temperature (T_5) significantly contributes to improved thermal comfort by reducing radiant temperature asymmetry. Future experimental studies should incorporate detailed comfort assessments, including metrics such as Predicted Mean Vote (PMV) and operative temperature, to quantitatively evaluate the overall comfort benefits. Additionally, the potential for draught and noise generated by the ventilation system should be systematically evaluated in real-world applications.

Thirdly, a comprehensive evaluation of the system's net energy benefit requires accounting for additional energy consumption. The energy input for the fan or blower to overcome pressure drops in the EAHE pipe and the VDSF cavity was not included in the current energy balance. Preliminary estimates suggest that fan energy consumption would be substantially lower than the achieved heating and cooling savings, indicating a high seasonal Coefficient of Performance (COP). However, a detailed analysis quantifying pressure drops, optimizing fan selection and control strategies, and calculating the net energy saving and seasonal COP will be fully addressed in future research.

Additionally, the long-term practical feasibility of the system involves considerations beyond the scope of this simulation-based study. Issues such as soil pipe fouling, moisture management, and maintenance access for the buried EAHE components are critical for real-world deployment. These challenges can be addressed through engineering solutions, such as using smooth-walled pipes (e.g., HDPE), installing sediment traps, and designing inspection points.

Furthermore, a simplified economic analysis was conducted to preliminarily estimate the payback period of installing an additional EAHE system to the conventional non-ventilated DSF. Economic analysis was conducted using the recommended design parameters of 10 m depth, 100 m length, and 100 mm pipe diameter. Table 12 lists the initial cost based on the local price of installing an EAHE system. Based on the previously mentioned simulation results, it is estimated that the EAHE-VDSF system will reduce 38.8 kWh/m² annual electricity consumption compared with conventional DSFs, assuming an average 4.0 COP for typical heat pump operation. Considering the local electricity price of 0.608 CNY/kWh, the payback periods of installing an additional EAHE system are 2.8 years, 5.5 years, and 13.8 years for integration with a 100 m², 50 m², and 20 m² glass curtain, respectively. This indicates that a larger glazing area shows better economic attractiveness for this EAHE-VDSF coupled system.

Table 12. Initial investment of EAHE-VDSF system.

Component	Cost (CNY)	
Buried pipes	2760	Each for diameter 0.1 m and length 120 m
Blower	750	Single phase, 3200 rpm
Construction	3000	/

Finally, the findings of this study are based on a specific climatic context (Wuhan, hot-summer-and-cold-winter climate). To evaluate the general applicability of the system, future research will encompass annual simulations, investigations into various facade orientations, and performance evaluations across a diverse range of climate zones.

6. Conclusions

This study proposes a novel earth-to-air heat exchanger-assisted ventilated double-skin facade (EAHE-VDSF) system to utilize low-grade geothermal energy for thermal regulation of transparent building envelopes. The thermal performance and parameters of this coupled system were systemically investigated in both cooling and heating seasons. The main results can be concluded as follows:

- (1) The EAHE-VDSF system reduces annual accumulated cooling loads by 20.3–76.5% and heating loads by 19.6–47.1% in comparison to a conventional triple-glazed, non-ventilated facade, primarily by leveraging soil thermal inertia for preconditioning the ambient air. The cavity temperature of the VDSF decreases 15 °C in the summer on average, effectively addressing the issue of overheating in the DSF.
- (2) For the design parameters of the EAHE part, a burial depth of 4 m to 5 m and pipe length of 80 m to 100 m are recommended as a compromise between the construction cost, thermal stability, and energy-saving potential of the EAHE-VDSF system. For the design parameters of the VDSF part, an airflow rate of 0.1 m/s in the ventilated cavity optimizes shallow geothermal utilization in the EAHE and dynamic insulation in the VDSF, which achieves the minimum seasonal accumulated cooling and heating load of the coupled system in both seasons. Low-E coating is recommended for employment in the VDSF for enhancing control of heat gains and losses through transparent building envelopes. Moreover, the diameter of the buried pipe in the EAHE and thickness of the ventilated cavity in the VDSF show very limited influence on the performance of the coupled system.
- (3) Compared with the water-based thermal regulation DSF (e.g., pipe-embedded windows or water-flow glazing), the EAHE-VDSF eliminates the need for installing additional heating and cooling equipment, avoids freeze and corrosion risks, and provides a novel approach to utilize low-grade natural energy sources for dynamic

thermal regulation of transparent building envelopes. The synergy between the pre-conditioning potential in the EAHE and dynamic insulation by ventilated airflow in the VDSF enables net energy savings exceeding 50% in both seasons.

These findings demonstrate the significant potential of the integrated EAHE-VDSF system as a high-performance sustainable building envelope solution. By synergistically combining low-grade geothermal energy utilization with the dynamic insulation of VDSFs, the coupled system can ensure stability and consistency in the thermal regulation of highly glazed facades. This work develops a novel EAHE-VDSF coupled system as a promising energy-efficient pathway to utilize shallow geothermal energy, enhance thermal performance, and reduce environmental impacts on buildings. Future research should prioritize comprehensive life-cycle cost analysis, full-scale or pilot-scale validation, and comprehensive performance investigations across diverse climates.

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Abbreviations

The following abbreviations are used in this manuscript:

Nomenclature

EAHE	earth-to-air heat exchanger
VDSF	ventilated double-skin facades
T	temperature, K
C	specific heat, J/(kgK)
D	thickness, m
m	mass flow rate, kg/h
R	thermal resistance, m·K/W
r	radius, m
L	layer
Nu	Nusselt number
Q _{cool}	cooling load, W/m ²
Q _{heat}	heating load, W/m ²
W	width, m
H	height, m
l	length, m
V	volume flow rate, m ³ /h
A	amplitude
ε	emissivity
α	absorptance
z	soil depth, m
h	heat transfer coefficient, W/(m ² K)

I	normal incident solar radiation, W/m ²
σ	Stefan–Boltzmann constant
ρ	density, kg/m ³
Subscripts	
a	air
amb	ambient air
s	soil
out	outlet
In	indoor
j	section j
r	radiative heat transfer
c	convective heat transfer
sol	solar
g	glass
1	outer glazing
2	sealed air cavity
3	middle glazing
4	ventilated cavity
5	inner glazing

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