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Heat transfer characteristics and energy performance of lightweight building envelopes in hot summer and warm winter regions

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Abstract: This study investigates the application of an EPS light-gauge steel composite envelope system in rural buildings located in the hot-summer and warm-winter region of Hainan. An experimental building was constructed in Shitang Village, Ding'an County, Hainan Province, using traditional brick structures as a control for comparison. Energy consumption simulations, environmental simulations, and practical experiments were conducted between the experimental building and traditional rural buildings. The results indicated that the relative humidity of the EPS light steel structure building ranged from 55% to 75%, while that of the traditional rural building ranged from 65% to 85%. On sunny days with open windows, the indoor temperature of the EPS light steel structure building was consistently lower than that of the traditional rural building during the day (8:00 AM to 6:00 PM), with a maximum difference of 1.3 °C; the temperature variation was less influenced by outdoor temperatures. Additionally, the average indoor temperature at night in winter was 0.7°C higher in the EPS light steel structure building compared to the traditional rural building, indicating superior insulation performance in winter. By utilizing the low energy consumption approach of passive houses, buildings with EPS wall structures can provide a comfortable living environment, which holds practical significance for energy-saving development in rural buildings in Hainan Province.

Keywords: hot summer and warm winter regions; building wall insulation structure; heat transfer; building energy consumption

1. Introduction

The economic development level of a country and the quality of life of its citizens are often determined by its energy reserves. The three oil crises of the 20th century significantly impacted the global energy structure, making energy conservation a consensus in the energy development strategies of countries worldwide. The three primary areas of energy consumption are buildings, transportation, and industry [1], with building energy consumption characterized by high usage, significant proportions, and a clear growth trend [2]. Data indicates that over 70% of total heat consumption in buildings in China is attributed to heat transfer and consumption through the building envelope, distributed across walls, roofs, doors, and windows, with walls accounting for 60% to 70%, roofs for 20% to 30%, and windows for about 10% [3]. This highlights the critical role of the building envelope in energy conservation [4]. Energy conservation

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for building envelopes involves employing relevant technologies to enhance thermal performance [5]. In summer, the insulation effect of the envelope prevents outdoor heat from entering indoors; in winter, it prevents indoor heat from escaping outdoors, thereby minimizing the impact of outdoor climate factors on the indoor environment and achieving a comfortable temperature for occupants. This, in turn, reduces the workload of indoor equipment such as heating and air conditioning systems, facilitating energy-saving goals [6]. Given that the wall envelope structure constitutes a significant portion of the total heat consumption in buildings, research on wall envelope structures is essential.

The key to building energy conservation lies in improving the thermal insulation performance of buildings. It is widely recognized that enhancing insulation performance is the most crucial measure for building energy conservation [7]. This typically involves using insulation materials (thermal conductivity ≤ 0.12) as the outer barrier of buildings, which can yield substantial energy-saving effects. Consequently, countries are placing great attention to the production and development of insulation materials. In 2004, Cabeza and Castell [8] studied the insulation performance of extruded materials such as expanded polystyrene (EPS) boards, mineral wool, and foam polyurethane. Gieseler [9] asserted that insulation measures for building exterior walls could achieve energy savings exceeding 28%. Kossecka [10]and colleagues calculated the annual heating and cooling loads of buildings across six typical climate zones in the United States, concluding that the annual energy consumption of internally insulated buildings is higher than that of externally insulated buildings. In 2010, Daouas [11]and other scholars utilized Fourier transform analysis to investigate the thickness and thermal performance of insulation layers in building walls in Tunisia under steady-state and periodic conditions. Their simulations of various materials concluded that stone and brick walls are the most economical structural types in Tunisian buildings, with EPS as the insulation material. In 2018, Diao [12]and other scholars analyzed the thermal performance of wall materials in rural buildings in hot summer and cold winter regions. Through theoretical calculations and experimental tests, they identified rectangular porous block walls, composite ceramic block walls, and steam-pressed aerated block walls as superior wall types in terms of thermal performance.

In China, extensive research has been conducted on energy conservation theories for buildings in cold and severe cold regions, yielding significant results. For instance, Zhang [13] examined the quantitative relationship between design parameters of residential buildings in cold regions and energy conservation, employing statistical methods for regression analysis on simulation conclusions and variance analysis on corresponding variables. This research provided insights into energy consumption trends in relation to design variable changes and the influence of each variable on energy consumption. Guo tested and analyzed indoor temperatures of rooms in cold regions, designing energy-saving schemes for envelope structures using orthogonal experimental methods, achieving a heat transfer coefficient for the best energy-saving renovation scheme with an energy-saving rate of 53% [14]. Yan and others researched energy-saving technologies for prefabricated building envelope structures in cold regions, developing a new technical approach by selecting efficient insulation materials, designing integrated envelope structures, and optimizing composite roofs, external windows, and floors [15]. Mu proposed an energy-saving optimization model for external wall insulation layers of high-rise residential buildings in cold coastal areas based on vertical zoning, determining the optimal thickness of external wall insulation layers and calculating the energy-saving rate of the optimized scheme [16]. Research on energy-saving technologies for passive houses in hot summer and warm winter regions has also produced

notable results. For example, Fu [17]and Ji [18] conducted a comprehensive analysis of energy-saving technologies for buildings in these regions from the perspective of building envelope structures, concluding that building design should prioritize ventilation and shading. Yang [19]and others studied energy-saving control indicators for building insulation in South China, exploring energy-saving measures from various angles, including orientation, doors and windows, walls, and roofs, while identifying key envelope technologies for building energy conservation in this region.

According to domestic and international standards for the thermal conductivity of envelope structures, the thermal performance of building envelope structures in China significantly lags behind that of developed countries, even when considering current building energy-saving standards [20]. This discrepancy results in higher energy consumption for heating and air conditioning. Although China has established a foundation in both the theoretical and practical aspects of passive house design for residential buildings, most applications are concentrated in severe cold and cold regions. There is relatively little research on passive residential building technology in hot summer and warm winter regions, primarily due to the differing climatic conditions across these areas. Therefore, this paper builds on the conclusions of previous scholars, integrating the regional characteristics of hot summer and warm winter areas with passive house energy-saving technologies to achieve an optimized method and technology for passive building design.

Although EPS insulation materials have been widely applied in building envelope systems, comprehensive evaluations of EPS light-gauge steel composite envelope systems for rural residential buildings in Hainan's hot-summer and warm-winter region, based on both numerical simulation and field measurements, remain limited. Moreover, their energy consumption, indoor thermal-humidity environment, and energy-saving performance under typical operating conditions have not been systematically investigated. Therefore, this study combines DesignBuilder-based numerical simulation with field measurements to evaluate the thermal performance and energy-saving potential of an EPS light-gauge steel composite envelope system in rural residential buildings, providing a reference for the design of rural building envelope systems in hot-summer and warm-winter regions.

2. Materials and methods

2.1. Selection of materials

The comprehensive performance evaluation of building insulation materials can be conducted from several aspects, including thermal conductivity, density, strength, durability, environmental performance, and cost. Currently, commonly used insulation materials for energy-saving buildings include EPS boards, extruded polystyrene boards (XPS), polystyrene particle insulation mortar, and foam concrete lightweight boards (see Table 1).

From Table 1, it is evident that EPS boards offer advantages such as low thermal conductivity and cost; however, they also have disadvantages, including low strength and inconsistent quality. Although XPS boards exhibit low thermal conductivity, good strength, and durability, their complex production process and high technical standards render them high-end products in the insulation market, making them expensive and not widely adopted. In considering their potential application in rural building projects, material selection favors those suitable for the environmental conditions of hot summer and warm winter regions, as well as tropical island environments, while also addressing economic and

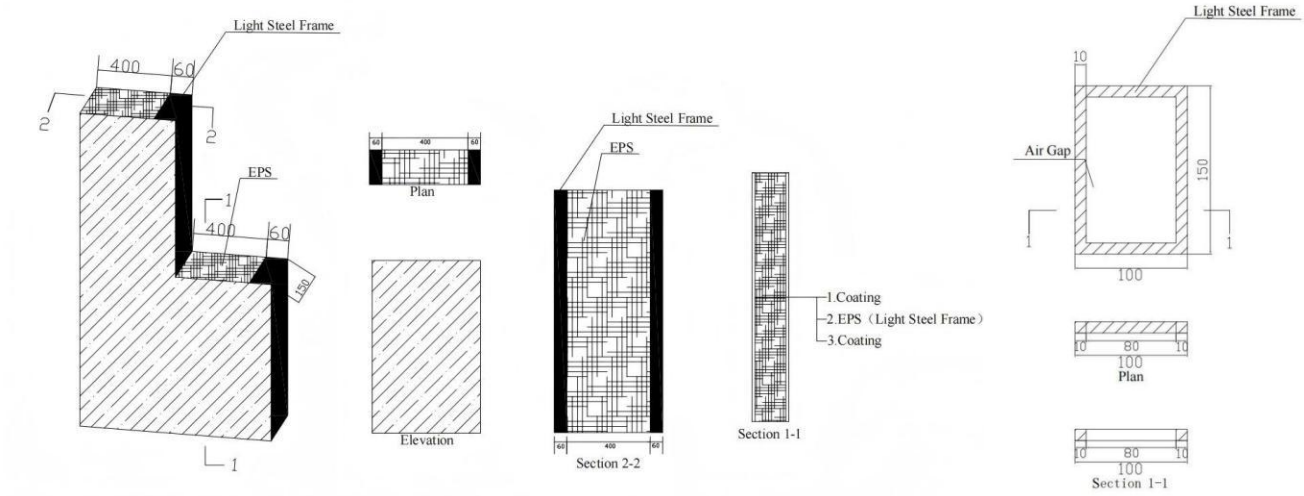
ecological factors. Consequently, the selected insulation material for the building wall is EPS, which will be combined with a light steel frame to enhance the building's load-bearing capacity due to its low strength.

Table 1. Comparison of performance of common wall insulation materials.

Material Performance	Thermal Conductivity (W/(m·K))	Density (kg/m³)	Strength	Durability	Environmental Performance	Cost
EPS Board	0.041	18–20	Poor	Average	Cannot be directly touched with adhesive during construction	Low
XPS Board	0.033	22–30	Some strength; can only bear load from the front	Good	Cannot be directly touched with adhesive during construction	High
Polystyrene Particle Insulation Mortar	0.069	250	Good; can withstand certain impacts	Good	Non-toxic	Somewhat low
Foam Concrete Lightweight Board	0.104	350	Good; can withstand certain impacts	Good	Non-toxic	Somewhat high

2.2. Physical model

The wall materials for the building have been selected, and considering the strength factors of the materials, the designed wall primarily consists of a combination of EPS and a light steel frame (see Figure 1). Detailed wall structure diagrams are provided. The wall envelope structure integrates EPS with a light steel frame, featuring a 15 cm thick light steel frame installed every 40 cm (see Figure 1), filled with EPS between the light steel frames, and finally coated with wall paint on both surfaces.



(a) (b)

Figure 1. Structural details of the EPS-light steel composite wall. **(a)** Detailed structure of EPS wall; **(b)** Detailed view of light steel material layer.

2.3. Calculation of the thermal conductivity coefficient of the wall envelope structure

The wall structure of a traditional brick house consists of solid bricks with a thickness of 20 cm, with 2 cm of mortar applied on both surfaces. The wall material combination of the traditional brick house is a multi-layer homogeneous material; thus, the calculation method for multi-layer homogeneous materials will be employed to calculate the thermal conductivity coefficient of the traditional brick house wall. The calculation formula is as follows:

$$K=1/(R_i+R_1+R_2+...+R_n+R_e) \quad (1)$$

In this formula, the thermal conductivity coefficient of the envelope structure wall is represented by K, the inner surface heat transfer resistance is represented by R_i, and the outer surface heat transfer resistance is represented by R_e. According to the "Standard for Thermal Design of Civil Buildings" [22] (GB 50176), R_i is taken as 0.11 m²·K/W, and Re is taken as 0.04 m²·K/W; the thermal resistance of each layer of the envelope structure is represented by $R_1+R_2+...+R_n$.

The thermal resistance R of a single material layer is calculated as follows:

$$R=d/\lambda \quad (2)$$

In this formula, λ represents the thermal conductivity of the material. According to the table, the thermal conductivity of solid bricks λ_1 is 0.65 W/(m·K), and the thermal conductivity of mortar λ= is 0.93 W/(m·K). The thickness of the solid brick is d1 = 0.2 m, and the thickness of the mortar is d_2 = 0.02 m. Substituting these values into formulas (1) and (2), the thermal conductivity coefficient of the traditional brick house is calculated as K_1 = 1.996 W/(m²·K).

In the EPS light steel wall envelope structure, the light steel material does not constitute a homogeneous material combination. Therefore, the thermal conductivity coefficient of the light steel material should be calculated using the method for composite material layers. In contrast, the EPS material is homogeneous, allowing its thermal conductivity coefficient to be calculated using the single material layer method.

The average thermal resistance calculation formula for composite material layers is as follows:

$$\overline{R}=\left[F_0/(F_1/R_{0,1}+F_2/R_{0,2}+...+F_n/R_{0,n})-(R_i+R_e)\right]\varphi \quad (3)$$

In this formula, R represents the average thermal resistance; F_0 denotes the total heat transfer area perpendicular to the heat flow direction; F_1, F_2, …, Fn represent the various heat transfer areas divided parallel to the heat flow direction; $R_{0,1}$, $R_{0,2}$, …, R_0, n represent the total heat transfer resistances of each heat transfer part; and φ is the correction factor. The thickness of the stainless steel on both sides, $d_{0,1}$ and $d_{0,3}$ is taken as 0.01 m, while the thickness of the air layer in the middle $d_{0,2}$ is taken as 0.08 m. A calculation unit body is considered for the light steel material, divided into three layers in the horizontal heat flow direction, with the left and right layers being light steel sheet material layers. The respective heat transfer areas F_1, F_2, and F_3 are taken as 1, 8, and 1. The thermal conductivity of stainless steel isλ_1=45 W/(m·K). According to Formula (2), the thermal resistance of the light steel part is $R_{0,1}$ = $R_{0,3}$ = 0.0002 m²·K/W. According to the "Standard for Thermal Design of Civil Buildings" (GB 50176), the thermal resistance of the air layer is $R_{0,2}$ = R_{ag} = 0.17 m²·K/W. The correction factor φ is taken as 0.96, as per the "Standard for Thermal Design of Civil Buildings" (GB 50176).

Substituting F_1, F_2, F_3, $R_{0,1}$, $R_{0,2}$, and $R_{0,3}$ into Formula (3) and simplifying yields:

$$\overline{R}=[0.001-(R_i+R_e)]*0.96$$

EPS material is homogeneous, and its thermal conductivity coefficient will be calculated using the single material layer method. The thickness of the EPS is d0 = 0.15 m, and the thermal conductivity λ0 is 0.041 W/(m·K). Substituting this into formula (2) gives the thermal resistance R0 value of 3.659 m2·K/W.

The comprehensive thermal conductivity calculation formula for the EPS light steel wall is as follows:

$$K_o=1/(R_i+\overline{R}+R_o+R_e) \quad (4)$$

In this formula, R_i represents the inner surface heat transfer resistance ($m^2 \cdot K/W$), taken as 0.11 $m^2 \cdot K/W$; R_o represents the homogeneous material layer coefficient ($m^2 \cdot K/W$); and Re represents the outer surface heat transfer resistance ($m^2 \cdot K/W$), taken as 0.04 $m^2 \cdot K/W$.

Substituting the relevant data of the EPS light steel wall into Formula (4) yields the final thermal conductivity coefficient as K_o = 0.262 $W/(m^2 \cdot K)$.

The wall thermal resistance was calculated in accordance with the method specified in the Design Standard for Energy Efficiency of Civil Buildings (GB 50176), and the resulting overall heat transfer coefficient was used as an input parameter for the Design Builder model. Since this study focuses on evaluating the overall indoor thermal environment and energy performance of buildings, dedicated hot-box experiments were not conducted to validate the thermal transmittance of the wall assembly. Future work will incorporate heat flux measurements to further verify the calculated results.

3. Model establishment and simulation result analysis

3.1. Mathematical model

DesignBuilder is a comprehensive graphical user interface simulation software for building energy consumption dynamics using EnergyPlus. With DesignBuilder, models can be quickly established and visually displayed in 3D, allowing for the division of different functions within the building. The simulation results can be evaluated for heat transfer, energy consumption, and visual effects of the model ’s envelope structure, as well as the airflow organization, pressure, and temperature distribution within the building. Using the EnergyPlus simulation engine, annual energy consumption simulations can be performed year after year, month by month, day by day, and hour by hour. [23]

According to the relevant provisions of the “Energy-saving Design Standard for Public Buildings,” [24] a building model that meets energy-saving design standards was established, and a mathematical geometric model was created using DesignBuilder (see Figure 2). The shape is a regular rectangle, measuring 9.6 meters in length, 8.4 meters in width, with two floors and a height of 3 meters, covering an area of 80.64 m^2, designated for residential use. The building is located in Hainan, which is in the hot summer and warm winter climate zone of China, characterized by a tropical monsoon climate, with essentially no winter and a summer-like condition year-round.

3.2. Selection of model parameters

The experimental group house in this simulation is constructed with EPS light steel walls as the building envelope structure, while the control group house uses traditional brick materials for the building envelope. The envelope structure limit parameters were selected according to the energy-saving design standards for public buildings, as shown in Table 2:

To ensure a reliable comparison of the thermal performance between the two envelope systems, all building operation parameters were kept identical during the simulation, except for the envelope configuration and its thermophysical properties. Both building models were configured with the same building dimensions, floor height, orientation, window-to-wall ratio, and occupancy type. Each building was simplified as a single thermal zone without internal space subdivision. The outdoor air ventilation rate was set to 30 m^3/h, and the air infiltration rate was specified as 0.75 h^{-1}. The indoor cooling set-point temperature was maintained at 25 ℃, with a relative humidity of 60%. Cooling loads were calculated using the Ideal Loads Air System implemented in EnergyPlus, which automatically determines the hourly cooling demand based on the indoor temperature set-point. No cooling load was generated when the indoor temperature remained below the set-point. The occupancy, lighting, and equipment schedules adopted the default residential settings provided by DesignBuilder and were applied consistently to both building models. Consequently, any differences in the simulation results can be attributed solely to the thermal performance of the envelope systems. This simulation primarily studies whether the building can maintain a stable indoor temperature during the summer; thus, winter heating is not considered, and only the simulation of summer cooling load calculations is referenced. The COP curve for summer cooling machines is set to a typical COP = 2.5 performance curve determined by ASHRAE. Other parameters within the building are set according to the characteristics of Hainan residential houses. Specific parameter settings are shown in Table 3:

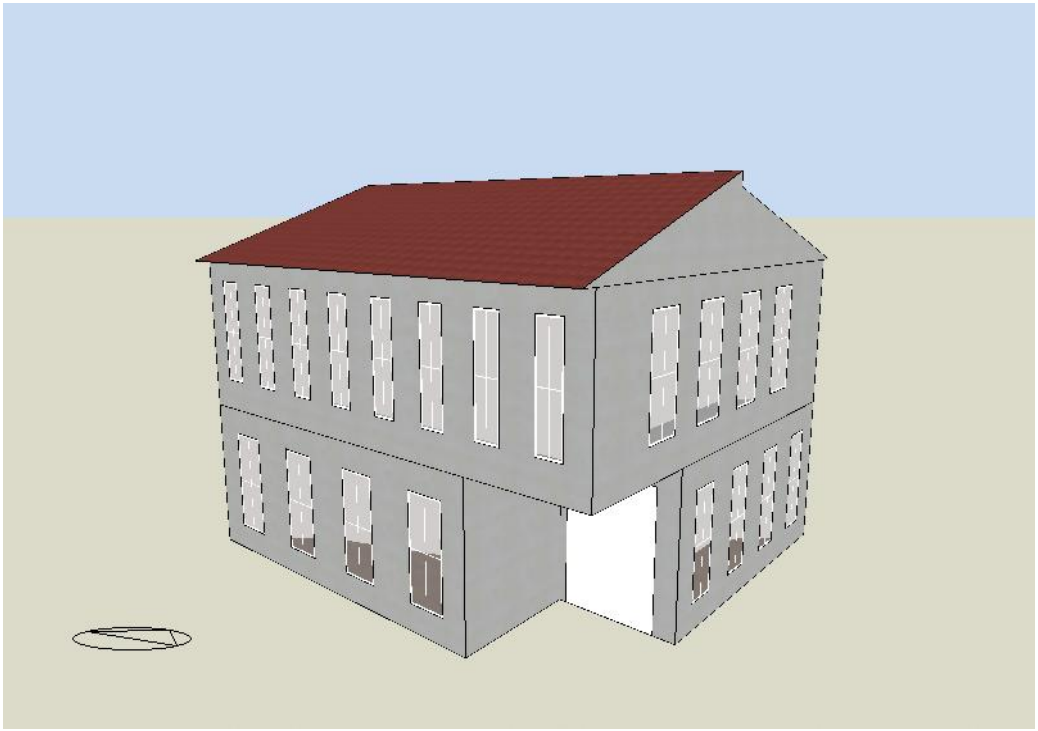


Figure 2. Building model established using DesignBuilder software.

Table 2. Basic parameters of building model envelope structure.

Model Type	Part	Structure	Comprehensive Thermal Conductivity Coefficient W/(m²·K)
Experimental Group	Exterior Wall	150mm EPS + Light Steel Frame + Double-sided Coating	0.262
	Ground	Compacted Clay 250mm + Cement Mortar Plastering 25mm	0.149
	Roof	100mm Foam Board + Steel Wire Mesh + Double-sided Sandwich Board	0.42
	Exterior Window	Insulated Aluminum Alloy Window Frame with Double-layer Radiation Rate ≤ 0.25 Low-E Hollow Glass	2.682
		Window-to-Wall Ratio	30%
Control Group	Exterior Wall	200mm Brick + Double-sided Cement Mortar Plastering 20mm	1.996
	Ground	100mm Concrete + 70mm Cement Mortar Plastering 70mm + 30mm Wood Flooring	1.463
	Roof	13mm Gypsum Board + 100mm Concrete + 19mm Asphalt	2.505
	Exterior Window	Ordinary Glass	3.633
		Window-to-Wall Ratio	30%

Table 3. Baseline building simulation design parameters.

Parameter Name	Value
Summer Indoor Set Temperature (°C)	24–26
Summer Indoor Relative Humidity (%)	60
Fresh Air Volume (m^3/h)	30
Infiltration Air Volume (times/h)	0.75
Occupancy Density (people/m^2)	0.03
Average Clothing Thermal Resistance (clo)	0.9

To compare the energy consumption between the EPS building and the traditional brick building, the external environment for this simulation study is based on the temperature data from Ding'an County in May 2021, as shown in Table 4. The simulation duration is set for one month (30 days). By analyzing the energy consumed by both buildings to maintain an indoor temperature of 25℃, the simulation results will be evaluated.

Table 4. Basic temperature data for Ding'an in May and November 2021[25,26].

Month	Average Maximum Temperature (°C)	Average Minimum Temperature (°C)	Average Humidity (%)
May 2021	35	25	75
November 2021	26	18	79

3.2. Analysis of model calculation results

Through the establishment of the DesignBuilder model, relevant parameters were applied as boundary conditions, defining the wall envelope structure and the external environment, executing control settings, and ultimately simulating the building's internal cooling load energy consumption, external surface temperature, and indoor humidity changes.

3.3.1 Building internal cooling load energy consumption

The simulation results indicate that the EPS light steel building (hereinafter referred to as the experimental group) exhibits lower overall cooling load energy consumption compared to the traditional brick building (hereinafter referred to as the control group).

Under the temperature conditions in May, the average overall cooling load energy consumption of the experimental group was 28.25 kWh, while that of the control group was 42.31 kWh. In the simulation, the area of the experimental group was 197.9 m^2, while the area of the control group was 196.2 m^2, and the cooling load calculation simulation time was 30 days. The final result showed that the annual active air conditioning energy consumption of the experimental group was 4.28 kWh/($m^2 \cdot$a), while that of the control group was 6.47 kWh/($m^2 \cdot$a), indicating that the experimental group saved approximately 33.9% of the active air conditioning energy consumption compared to the control group. Under the temperature conditions in November, the average overall cooling load energy consumption of the experimental group was 17.66 kWh, while that of the control group was 26.86 kWh. The annual active air conditioning energy consumption of the experimental group was calculated to be 2.68 kWh/($m^2 \cdot$a), while that of the control group was 4.11 kWh/($m^2 \cdot$a), indicating that the experimental group saved about 34.8% of the active air conditioning energy consumption compared to the control group.

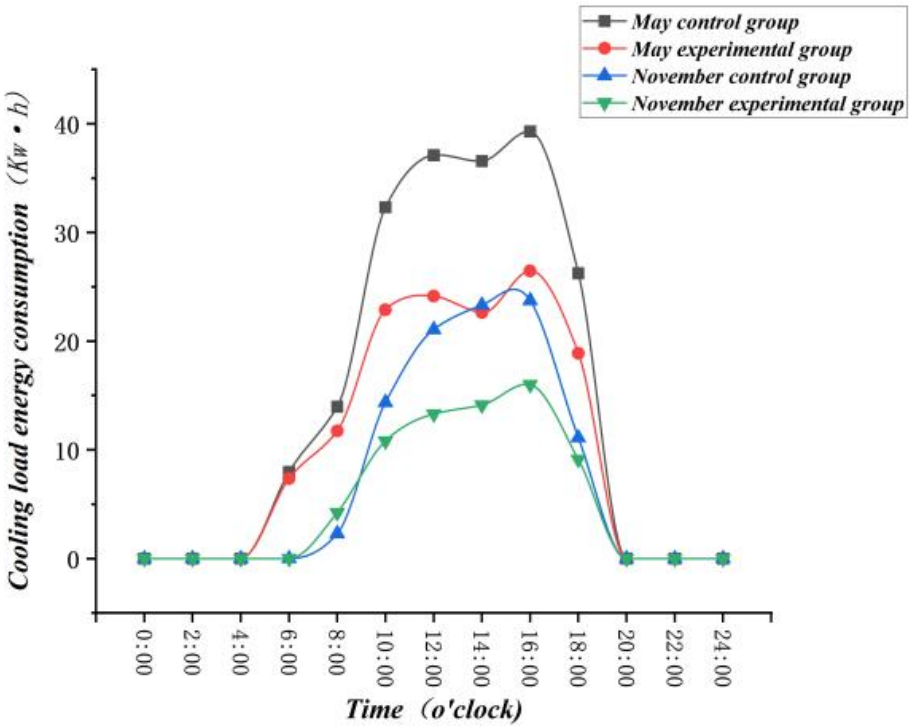


Figure 3. Comparison of internal cooling load energy consumption of simulated buildings in May and November.

3.3.2 Building external surface temperature

The building temperature simulation results reveal that under the simulation in May, with the same outdoor temperature conditions, the average external surface temperature of the experimental group was 25.78℃, while that of the control group was 27.16℃, resulting in a temperature difference of 1.38℃. Based on the standard comfortable temperature range for human living conditions in summer (22–26℃), the experimental group is more suitable for indoor living conditions than the control group. In the November simulation, the average external surface temperature of the experimental group was 24.93℃ , while that of the control group was 25.05 ℃ , with a temperature difference of 0.12 ℃ ; however, compared to the indoor temperature changes, the experimental group exhibited greater stability.

3.3.3 Building indoor humidity

The indoor humidity simulation results indicate that in the May simulation, the indoor humidity of the experimental group and the control group did not differ significantly. However, in the November simulation, the humidity range of the experimental group was 55.86% to 75.28%, while that of the control group was 55.6% to 82.97%. Compared to the comfortable humidity range for human living conditions in summer (30%–60%), the experimental group is more conducive to meeting the residential comfort needs of individuals.

To evaluate the reliability of the DesignBuilder model, the simulated indoor temperature and relative humidity were compared with the corresponding field measurements obtained in November. The results show good agreement in the overall variation trends, with both the simulation and measurements indicating that the EPS light-gauge steel envelope system provides a more stable indoor thermal-humidity

environment and smaller indoor temperature fluctuations. These results demonstrate that the established model can reasonably capture the thermal behavior of the building and is therefore suitable for subsequent energy performance analysis.

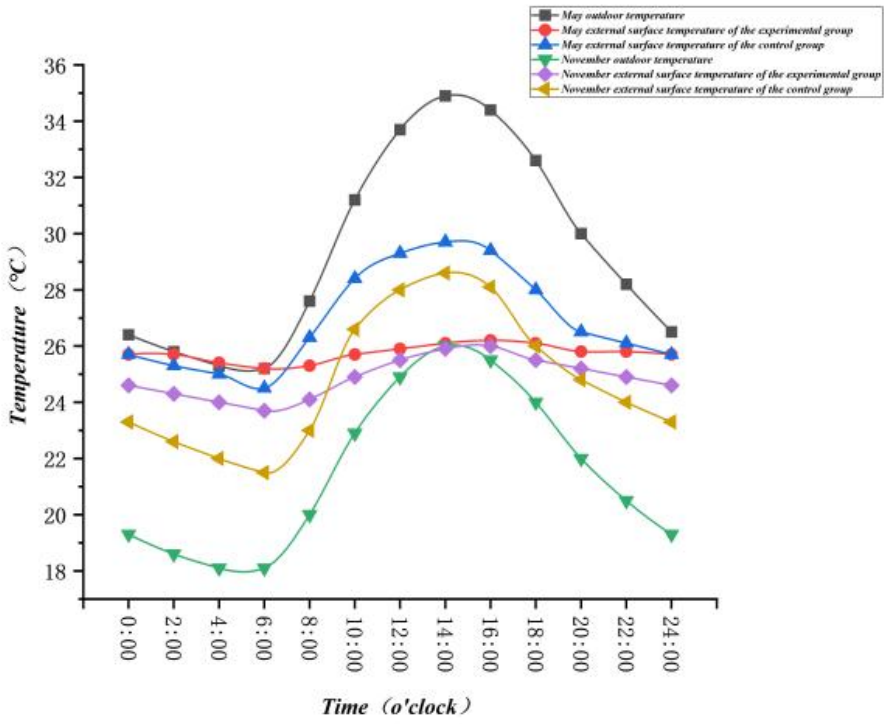


Figure 4. Comparison of external surface temperatures of simulated buildings in May and November.

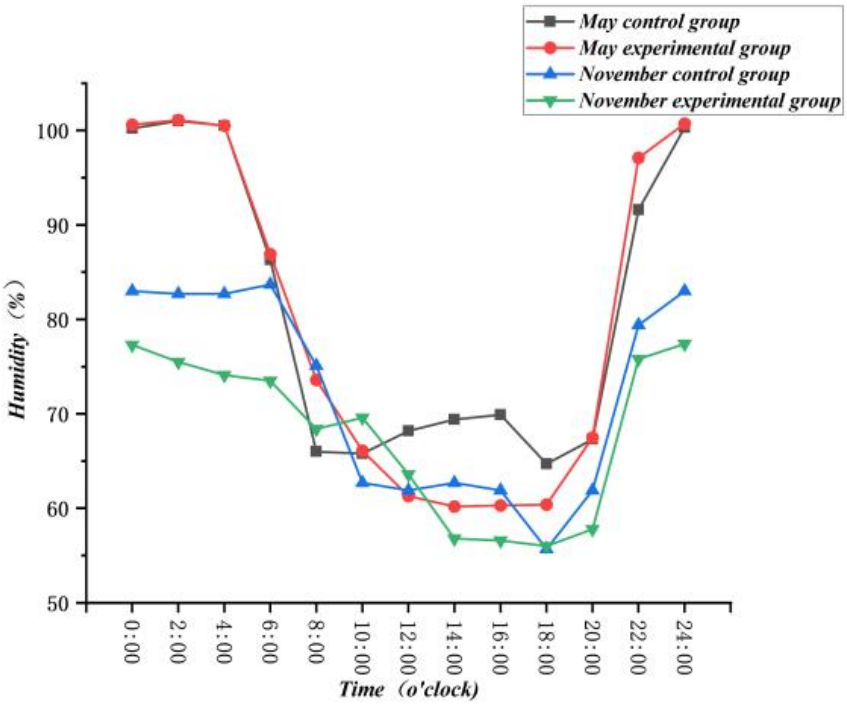


Figure 5. Comparison of indoor humidity of simulated buildings in May and November.

4. Experimental research on passive buildings

To explore the impact of EPS wall structures compared to traditional brick wall structures on indoor temperature and humidity, this study established a comparative testing platform for EPS buildings and traditional brick buildings in Shitang Village, Longhe Town, Ding'an County, Hainan Province. The EPS building consists of walls made of EPS and light steel frames, in contrast to adjacent residential buildings, which are traditional brick structures, to conduct experimental research (Figure 6). Indoor air temperature and relative humidity were continuously monitored using UAHANWEI temperature and humidity data loggers, with measurement accuracies of ±0.1℃for temperature and ±1.5% RH for relative humidity. To ensure a reliable comparison, the EPS light-gauge steel building was compared with a neighboring traditional brick-concrete residential building. The two buildings were located within 5 m of each other and shared the same microclimatic conditions. In addition, both buildings had the same orientation, minimizing the influence of environmental factors such as solar radiation and wind speed associated with differences in geographical location.



(**a**) (**b**)

Figure 6. Actual views of the EPS building. **(a)** Actual photo of EPS building; **(b)** Indoor view of EPS building

4.1. Experimental content

This experiment employed the method of building environmental temperature and humidity detection, primarily to measure the temperature and humidity environment of the building and compare it with the adjacent residential building (i.e., the traditional brick building). By controlling factors such as window opening and weather, the heat dissipation effects of the building were analyzed. The experiment recorded the temperature and humidity of the building throughout the day, taking hourly measurements, totaling 24 sets of data, and analyzed the differences in indoor temperature and humidity between the experimental group and the control group. The experiment was conducted in November 2021, with specific times shown in Table 5.

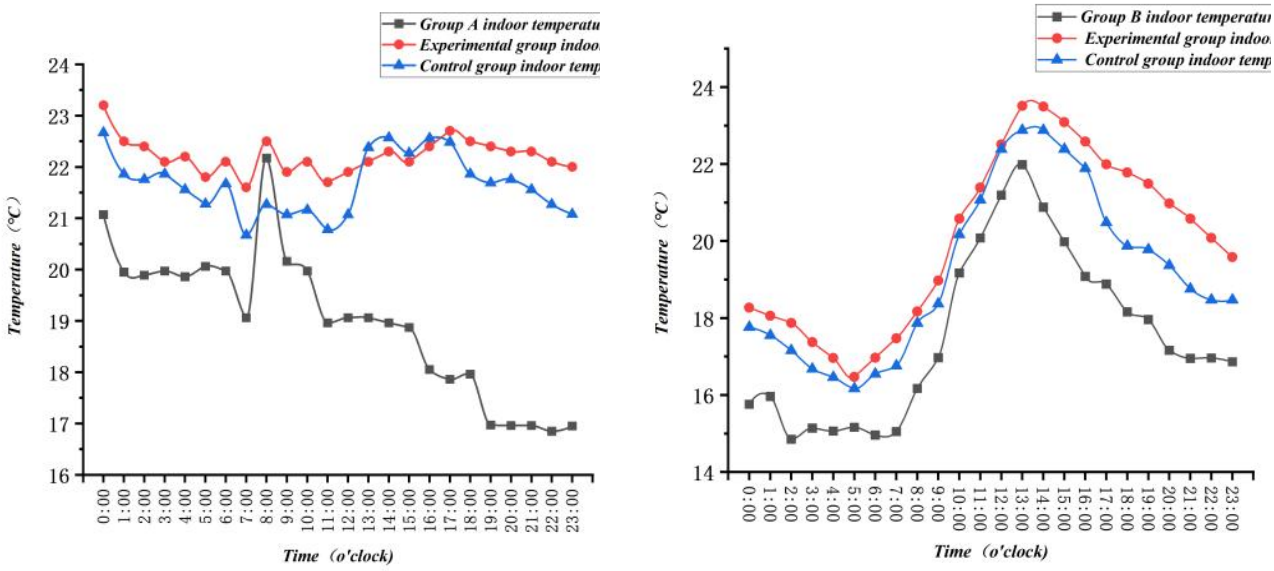
Table 5 Experimental timing of buildings.

Experimental Time	Experimental Group	Weather Conditions
November 8, 2021	Cloudy Open Window Group (Group A)	Cloudy, Northeast Wind, Wind Force 1–2, Wind Speed:4km/h, All-day Temperature: 15°C–22°C, Relative Humidity: 76%
November 9, 2021	Cloudy Closed Window Group (Group B)	Cloudy, Northeast Wind, Wind Force 1–2, Wind Speed:8km/h, All-day Temperature: 17°C–21°C, Relative Humidity: 74%
November 19, 2021	Sunny Closed Window Group (Group C)	Cloudy, North Wind, Wind Force 1–2, Wind Speed:3km/h, All-day Temperature: 19°C–27°C, Relative Humidity: 79%
November 20, 2021	Sunny Open Window Group (Group D)	Cloudy, North Wind, Wind Force 1–2, Wind Speed:3km/h, All-day Temperature: 20°C–29°C, Relative Humidity: 85%

4.2. Analysis of experimental results

Through the data obtained under the two different influencing factors of weather and window opening, the changes in indoor temperature and humidity of the experimental group and control group rooms were derived.

From the indoor temperature comparison (Figure 7), it can be concluded that the indoor temperature of the experimental group room is relatively stable when windows are open, with less fluctuation compared to the traditional building. Particularly in Group D (sunny day with windows open), as shown in d, utilizing the building's natural ventilation system, the average indoor temperature during the day (6:00 AM to 6:00 PM) is lower than that of the control group, with a maximum temperature difference of 1.3℃. Additionally, the indoor temperature of the experimental group remains between 22℃ and 24℃ throughout the day, demonstrating less influence from outdoor temperature changes compared to the control group. In terms of insulation performance, during the night (6:00 PM to 6:00 AM), the average indoor temperature of the experimental group is approximately 0.7℃ higher than that of the control group.



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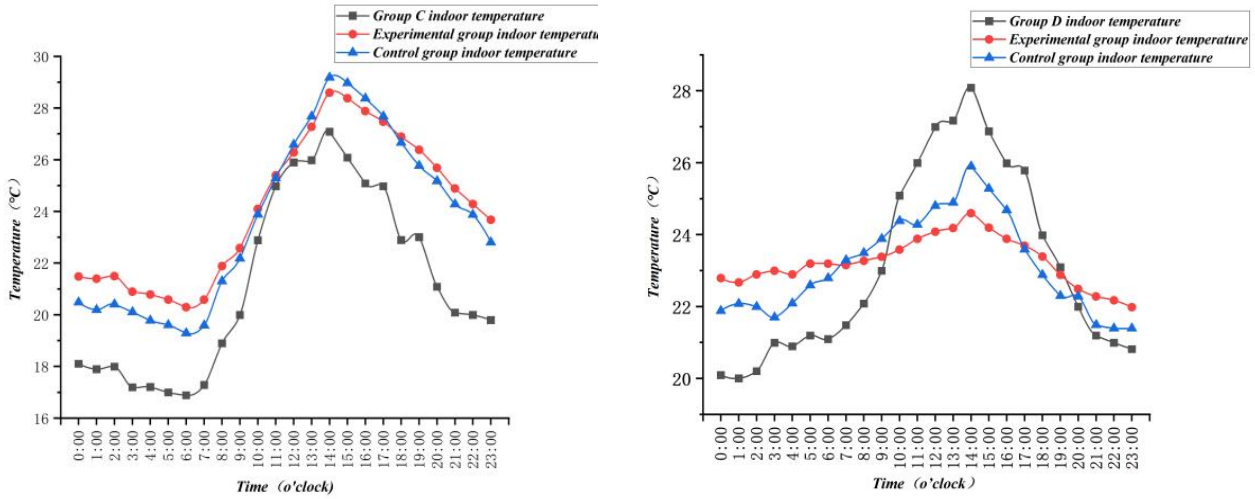
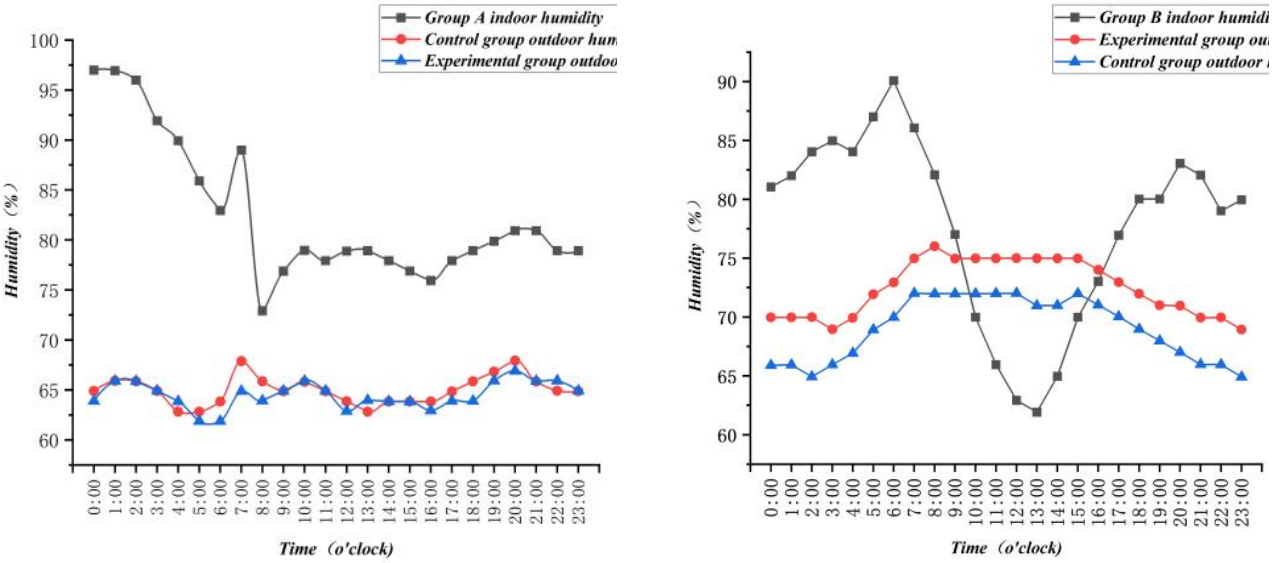


(c) (d)

Figure 7. Comparison of indoor temperatures among different experimental groups. **(a)** Indoor temperature comparison for group A; **(b)** Indoor temperature comparison for group B; **(c)** Indoor temperature comparison for group C; **(d)** Indoor temperature comparison for group D.

From the indoor humidity comparison (Figure 8), it is evident that the average indoor humidity of the experimental group ranges from 55% to 75%, while that of the control group ranges from 65% to 85%. According to ASHRAE Standard 55 and previous studies on indoor thermal environments in China, an indoor relative humidity range of 40% to 70% is generally considered beneficial for thermal comfort. For residential buildings in Hainan, a relative humidity range of 55% to 75% is considered to provide an acceptable indoor comfort environment under the local climatic conditions. comparison of the average indoor humidity between the two groups indicates that the experimental group is more likely to meet the comfort needs of residents.



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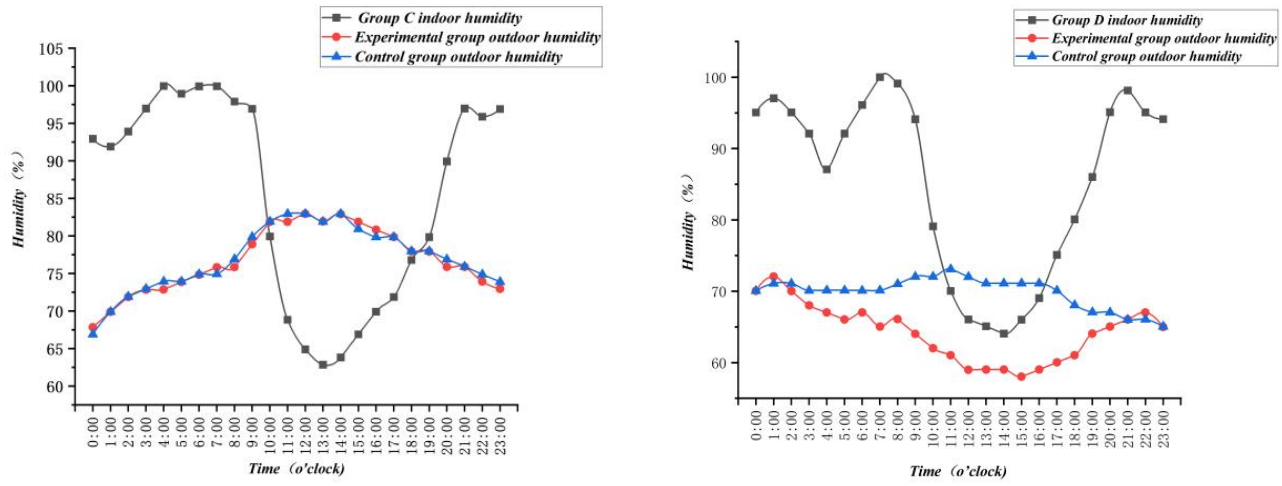

(c) (d)

Figure 8. Comparison of indoor relative humidity among different experimental groups. **(a)** Indoor humidity comparison for group A; **(b)** Indoor humidity comparison for group B; **(c)** Indoor humidity comparison for group C; **(d)** Indoor humidity comparison for group D.

5. Discussion

The building thermal model was developed using DesignBuilder based on the EnergyPlus simulation engine, and its reliability was evaluated through comparisons with field measurements. The results indicate good agreement between the simulated and measured indoor temperature and relative humidity in terms of the overall variation trends, demonstrating that the model can reasonably capture the thermal behavior of the building under changing outdoor climatic conditions. Although minor deviations were observed in the peak values, the overall consistency suggests that the model is suitable for comparative evaluations of different envelope systems rather than precise prediction of absolute building energy consumption.

The simulation results indicate that the EPS light-gauge steel composite envelope system exhibits lower cooling loads and a more stable indoor thermal environment than the conventional brick-concrete envelope. This improvement is mainly attributed to the low thermal conductivity of the EPS insulation layer, which increases the overall thermal resistance of the envelope and reduces heat transfer from the outdoor environment to the indoor space. Consequently, indoor temperature fluctuations are alleviated, leading to reduced cooling demand. These results demonstrate the potential of the EPS light-gauge steel envelope system for improving the thermal performance and energy efficiency of rural residential buildings in hot-summer and warm-winter regions.

It should be noted that the high thermal conductivity of light-gauge steel members may introduce localized thermal bridge effects, which can influence the actual heat transfer performance of the envelope. In this study, the envelope was simplified as an equivalent homogeneous structure, and the local two-or three-dimensional thermal bridge effects were not explicitly considered. Therefore, further studies incorporating detailed thermal bridge modeling or experimental measurements are recommended to provide a more comprehensive evaluation of the thermal performance of EPS light-gauge steel envelope systems.

6. Conclusions

This study employed EPS and light steel frames as the building wall envelope structure, constructed experimental houses utilizing natural ventilation technology, established building models using DesignBuilder simulation software, and conducted simulations of building energy consumption, temperature, and humidity. Additionally, comparative experiments were performed between the EPS building and traditional brick building regarding indoor temperature and humidity environments. The following conclusions were drawn from the research:

According to the DesignBuilder simulation software, under May weather conditions, the active air conditioning energy consumption of the EPS light steel wall building is 4.28 kWh/(m²·a), while that of the traditional brick building is 6.47 kWh/(m²·a), indicating a reduction of approximately 33.9% in active air conditioning energy consumption. Under November weather conditions, the active air conditioning energy consumption of the EPS light steel wall building is 2.68 kWh/(m²·a), compared to 4.11 kWh/(m²·a) for the traditional brick building, reflecting a reduction of about 34.8% in active air conditioning energy consumption.

The DesignBuilder simulation software indicates that under the same outdoor temperature conditions, the average external surface temperature of the EPS light steel wall building in May is 25.78℃, while that of the traditional brick building is 27.16℃, demonstrating a reduction of 1.38℃ for the EPS light steel building compared to the traditional brick building. In November, the average external surface temperature of the EPS light steel wall building is 24.93℃, while that of the traditional brick building is 25.05℃, indicating a reduction of 0.12℃ for the EPS light steel building compared to the traditional brick building, with indoor temperature changes being relatively more stable. Therefore, the EPS light steel building is more suitable for human habitation.

The experimental research indicates that the indoor temperature fluctuations of the EPS light steel wall building are less influenced by outdoor temperatures, particularly on sunny days with windows open, where the average indoor temperature of the EPS light steel wall building is lower than that of the traditional brick building, with a maximum temperature difference of 1.3℃. The average indoor humidity of the EPS light steel wall building ranges from 55% to 75%, while that of the traditional brick building ranges from 65% to 85%, making the EPS light steel wall building more conducive to meeting the comfort needs of residents.

Compared with the conventional brick-concrete building, the EPS light-gauge steel envelope system exhibited a lower overall heat transfer coefficient, a more stable indoor thermal-humidity environment, and lower cooling energy demand under the same building dimensions and operating conditions. These results indicate that the proposed envelope system is better suited for energy-efficient rural residential buildings in Hainan’s hot-summer and warm-winter region.

Declaration of generative AI and AI-assisted technologies

During the preparation of this manuscript, the authors used generative AI tools only to improve language and readability. The authors take full responsibility for the content of the manuscript.

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Authors' contribution

Conceptualization, Li Li and Jiacheng Jiao; methodology, Li Li, Dawei Mu and Jiacheng Jiao; software, Li Li; validation, Li Li and Dawei Mu; formal analysis, Li Li and Dawei Mu; investigation, Li Li and Dawei Mu; data curation, Li Li; visualization, Li Li; writing—original draft preparation, Li Li; writing—review and editing, Dawei Mu and Jiacheng Jiao; supervision, Jiacheng Jiao; project administration, Jiacheng Jiao; funding acquisition, Dawei Mu. All authors have read and agreed to the published version of the manuscript.

Conflicts of interests

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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