

Study on the influence of building envelope on indoor thermal comfort and heating energy demand

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ARTICLE INFO	ABSTRACT
<i>Article history:</i> Received March 26, 2026 Received in revised form May 14, 2026 Accepted July 10, 2026 Available online September 01, 2026 <i>Keywords:</i> Building envelope Cold climate Heating energy demand Indoor thermal comfort Simulation *Corresponding author: Mengmeng Hou School of Housing, Building and Planning, Universiti Sains Malaysia Email: hmm_houmengmeng@126.com	<i>Building envelope design is one of the effective parameters for reducing energy consumption and enhancing thermal comfort. This research explores the impact of building envelope performance on indoor thermal comfort and heating energy consumption in university classrooms located in cold regions of China. A numerical model was established using field measurement data and subsequently validated. Four building envelope optimization schemes were designed by altering wall thermal resistance, roof insulation thickness, and window solar transmittance. Results indicate that enhanced wall insulation yields the most significant benefits: winter indoor temperatures increase by up to 0.72 °C, summer temperatures decrease by 1.33 °C, and annual energy use intensity (EUI) drops by approximately 34 %. While roof insulation and reduced window solar transmittance provide weaker improvements in comfort and EUI reduction, they still contribute to enhanced indoor environments. The optimized building envelope effectively reduced winter cold discomfort and summer heat gain, stabilizing indoor conditions. However, even under optimal envelope conditions, complete thermal neutrality could not be achieved during extreme cold spells, indicating the need for supplemental heating strategies. These findings provide quantitative guidance for designing climate-adaptive building envelopes in educational facilities located in cold regions.</i>

Introduction

The building sector accounts for 30% – 40% of global energy consumption (Santamouris and Vasilakopoulou 2021). Building envelopes, serving as the interface between interior spaces and the external environment, play a critical role in controlling heat transfer, solar gain, and airflow, thereby significantly influencing occupant comfort and energy consumption (Barbhuiya et al. 2025). In cold climates, thermal losses through the building envelope may dominate heating demands (Hamdy et al. 2023; Gbran 2025). Studies indicate that heat transfer

through the envelope accounts for over 70% of a building's total lifecycle energy consumption (Fereidoni et al. 2023). Enhancing the thermal insulation of walls and roofs can substantially reduce energy use and improve comfort (Mutani and Todeschi 2020). However, better insulation also means reduced summer heat dissipation, potentially increasing cooling loads (Shahee et al. 2024). Similarly, reducing heat loss through high-performance windows in winter limits passive solar gain, potentially affecting summer comfort (Zahiri and Altan 2020).

Existing research confirms the impact of building envelope characteristics on indoor climate. Gha et al. Ghamari and Sundaram (2024)

demonstrated that adding thermal mass to well-insulated building envelopes can elevate average winter indoor temperatures and suppress temperature fluctuations, thereby significantly improving indoor environments. In tropical climates, combining high-performance envelope materials with advanced HVAC systems achieves substantial energy savings of 35 %-43 % while maintaining thermal comfort (Kajjoba et al. 2025). Teaching buildings typically exhibit high occupancy density during daytime hours, intermittent usage patterns, and limited nighttime heating setbacks, all of which interact with envelope thermal inertia (Jia et al. 2021). Large facade areas, extensive glazing, and aging construction assemblies further complicate heat transfer processes (X. Li and Wu 2025). Under such conditions, the envelope's thermal response determines not only the magnitude of heat loss but also the temporal alignment between heating supply and indoor thermal demand (Y. Li et al. 2019). As a consequence, energy consumption and comfort cannot be optimized independently; they are inherently linked through the transient heat-transfer behavior of the building envelope.

A growing body of literature has addressed envelope retrofitting strategies (Ghazwani, Beach, and Rezgui 2025), numerical simulation of building energy performance, and comfort assessment in cold climates (Kamel and Memari 2022). Studies employing steady-state indicators, such as U-values or heating degree day analysis, have provided valuable insights into heat-loss reduction potential (Harvey 2020). Meanwhile, transient simulation tools have enabled detailed prediction of indoor temperature evolution under varying envelope configurations (Wu et al. 2023). Despite these advances, most studies focus either on energy efficiency or on thermal comfort (Niza et al. 2022), without explicitly quantifying the coupling mechanisms that link envelope thermal response to comfort outcomes and energy consumption simultaneously (Nasrollahzadeh 2021). As a result, the causal pathways through which envelope properties influence comfort–energy trade-offs remain insufficiently clarified.

University buildings in cold regions face unique challenges: during the heating season (November 15 to March 15), low ambient temperatures and frequent cold-air incursions lead to high heat loss rates, while in summer, high temperatures and strong solar radiation cause

indoor overheating. The building envelope, as the interface between the indoor and outdoor environments, directly regulates heat transfer, solar radiation transmission, and moisture exchange, thereby determining indoor thermal conditions and energy demand (Guo et al. 2022). However, the coupled effects of different envelope components (walls, roofs, windows) on indoor thermal comfort and energy performance remain insufficiently understood, particularly in the context of Yuncheng's specific climatic conditions (Tang et al. 2023).

Existing studies have shown that optimizing envelope thermal performance can effectively reduce energy consumption while improving indoor comfort, but the effectiveness of different optimization strategies varies with climate, building type, and envelope component (Carlucci et al. 2018). This study focuses on university teaching buildings in Yuncheng, establishing a numerical simulation framework to evaluate the influence of wall, roof, and window configurations on indoor thermal comfort and heating energy demand. The research findings provide a theoretical basis and practical guidance for climate-adaptive envelope design and retrofit in cold-region university buildings.

Methods

Based on experimentally measured thermophysical properties and field monitoring data, this study establishes a dynamic building energy consumption simulation framework to investigate the interrelationships among thermal performance of building envelopes, indoor thermal environment, and energy demand in university teaching buildings.

Meteorological parameters

The study area is located in Yuncheng City, Shanxi Province, China, within the northern cold temperate climate zone of the country, at coordinates 35° 01' 36" N, 111° 00' 25" E, at an elevation of approximately 300 meters above sea level. According to the Building Climate Zoning Standard (GB 50178-93), Yuncheng is a typical cold climate zone city, as shown in figure 1 Yuncheng's climate has four distinct seasons, with longer winters and summers and shorter springs and autumns.

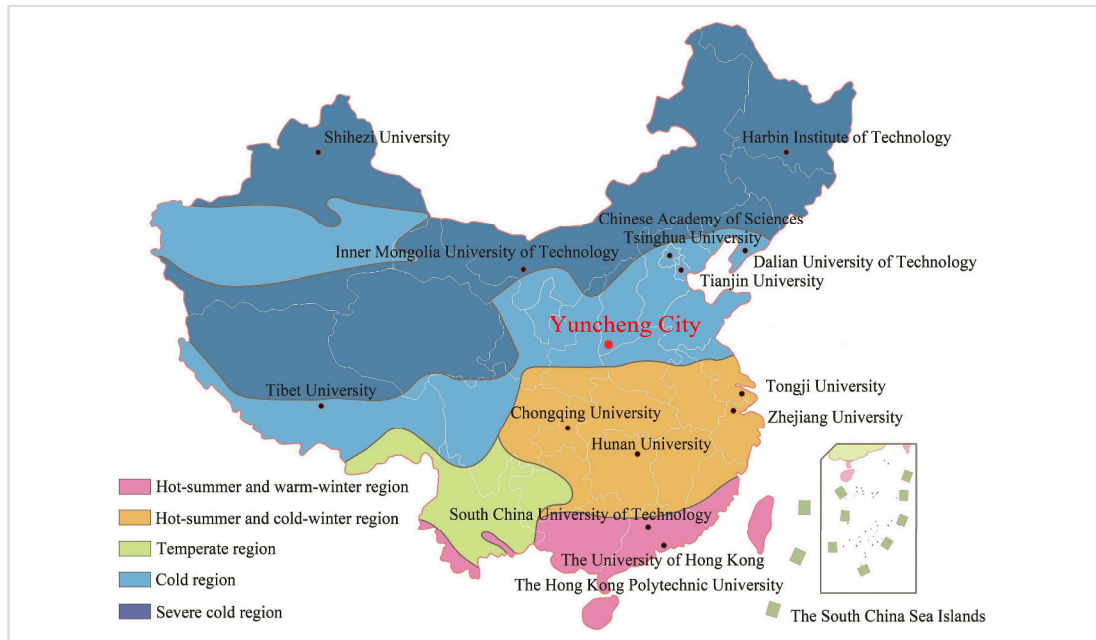


Figure 1. Cold area Yuncheng location map

Yuncheng is characterized by a typical continental monsoon climate, featuring cold and dry winters, hot summers, and distinct transitional seasons. According to long-term meteorological statistics, the annual mean air temperature in Yuncheng is approximately 13–14°C, while the average temperature during the coldest month (January) generally ranges from −2°C to −4°C,

with extreme minimum temperatures occasionally dropping below −10°C (see figure 2). The heating season typically lasts from mid-November to mid-March, during which low ambient temperatures and frequent cold-air incursions significantly increase building heat-loss rates.

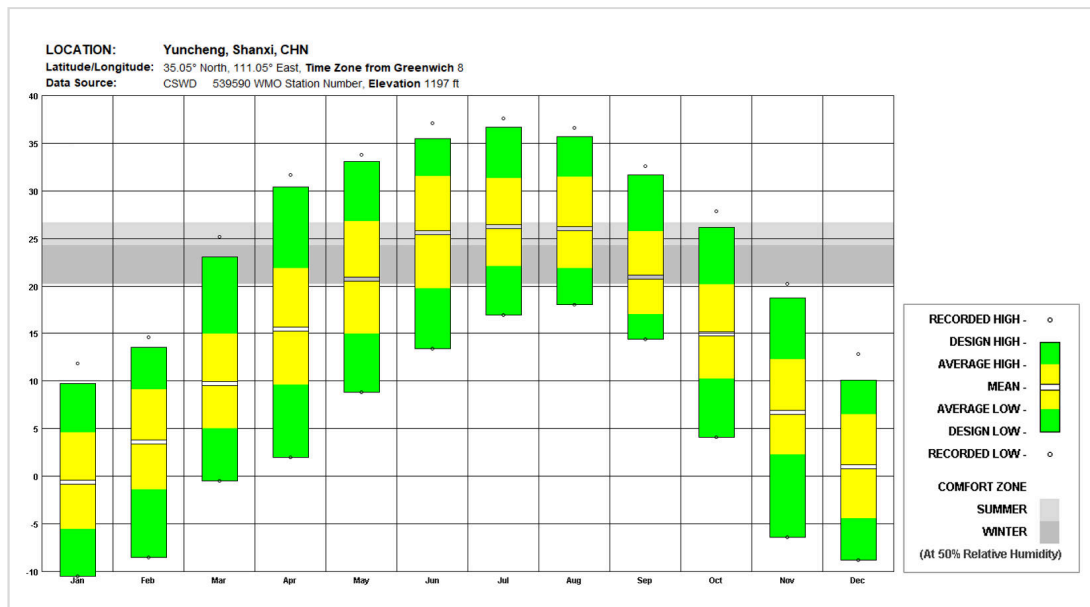


Figure 2. Variation of annual temperature range in Yuncheng

Summer conditions in Yuncheng are characterized by high temperatures and strong solar radiation. The average temperature in July, the hottest month, commonly exceeds 26 – 28°C, with daytime maximum temperatures often reaching above 35°C during heatwave periods. Although this study focuses primarily on heating-season performance, the large annual temperature amplitude often exceeding 30°C between winter and summer extremes imposes substantial thermal stress on building envelopes.

Solar radiation in Yuncheng exhibits a clear seasonal pattern. The region receives relatively abundant solar resources, with annual total solar radiation typically in the range of 5,000–5,500 MJ/m². During winter months, however, solar radiation intensity is significantly reduced due to lower solar altitude, shorter daylight duration, and increased atmospheric attenuation. Typical daily global solar radiation in winter is markedly lower than in summer, which limits passive solar heat

gains through facades and increases reliance on heating systems.

In addition to temperature and solar radiation, other meteorological parameters including relative humidity and wind conditions also influence the thermal environment. Yuncheng generally experiences low winter humidity, often below 50%, which enhances sensible heat loss and intensifies perceived thermal discomfort indoors. Average wind speeds are typically moderate, commonly ranging from 1.5 to 3.0 m/s, but winter northerly winds can increase convective heat loss at building surfaces and exacerbate outdoor thermal stress.

Field measurement

The environmental parameters measured in this research include air temperature (T_a), black sphere temperature (T_g), relative humidity (RH), and air velocity (V). The instruments used for each environmental parameter are shown in [table 1](#).

Table 1. Basic information of the test instrument

Test Equipments	Measured Parameters	Unit	Range	Accuracy
TR-72wb	T_a /RH	°C/%	0 - 55 10 - 95	±0.5/ ±5
AZ87786	T_g	°C	-40 - 120	±0.1
ISA-68	V	m/s	0.05 - 30	0.05

The instruments can automatically record data every five minutes. The testing range and testing accuracy of each instrument meet the requirements of ISO7726 standard. The measurement point was chosen at a height of 1.1 m from the ground around the subject, corresponding to the height of the human face in the seated position. Four TR-72wb temperature

and humidity collectors were set up at the diagonal and four three-equidistant points on the diagonal of an ordinary classroom in accordance with the Standard for Methods of Testing the Thermal Environment of Buildings. Set up the wind speed instrument and black globe temperature collector in the center of the classroom. See [figure 3](#) for details.

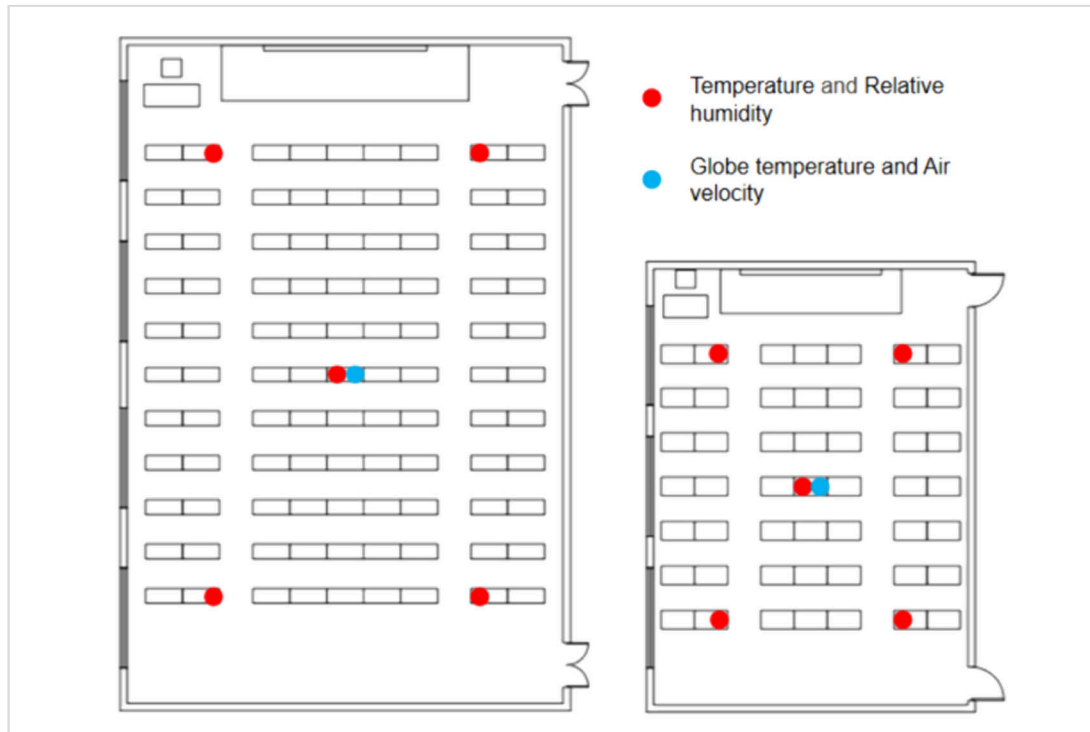


Figure 3. Location of measurement points

In addition, the data processing of the test results should comply with the following provisions:

- The air temperature and relative humidity of each classroom is the average value of the air temperature and relative humidity of each measurement point in the classroom.
- In the process of processing the data provided by the two instruments, the obvious bad values should be appropriately excluded to avoid the impact on the actual results.

Numerical model establishment and validation

The numerical simulation was conducted using EnergyPlus software, a widely used building energy simulation tool that can accurately calculate indoor thermal environments and energy consumption under various climatic and operational conditions. As shown in figure 4, the simulated building was a typical university teaching building in Yuncheng, with a rectangular plan (length $\times$ width $\times$ height = 36 m $\times$ 12 m $\times$ 4.5 m) and a total floor area of 432 m². The building envelope components included external walls, roofs, and windows, with specific baseline configurations.

External walls were composed of a 240 mm thick clay brick layer, a 20 mm thick cement

mortar layer, and a 5 mm thick exterior finish, with a thermal conductivity of 0.81 W/(m·K) and a thermal resistance of 0.35 m²·K/W. The roof consisted of a 100 mm thick reinforced concrete slab, a 20 mm thick cement mortar layer, and a 5 mm thick waterproof layer, with a thermal conductivity of 1.74 W/(m·K) and a thermal resistance of 0.08 m²·K/W. Windows were single-layer ordinary glass with a thickness of 5 mm, a thermal conductivity of 0.81 W/(m·K), and a solar transmittance of 0.84.

The indoor heat gains included internal heat gains from occupants, lighting, and equipment. The number of occupants was set to 40 (1 person per 10.8 m²), with a sensible heat gain of 108 W/person and a latent heat gain of 46 W/person. Lighting power density was 15 W/m², and equipment power density was 20 W/m². The heating system operated from 8:00 to 22:00 daily during the heating season, with a setpoint temperature of 18 °C. The cooling system was not activated during the simulation period, as the study focused primarily on heating-season performance, while summer conditions were analyzed to understand the seasonal influence of envelope performance.

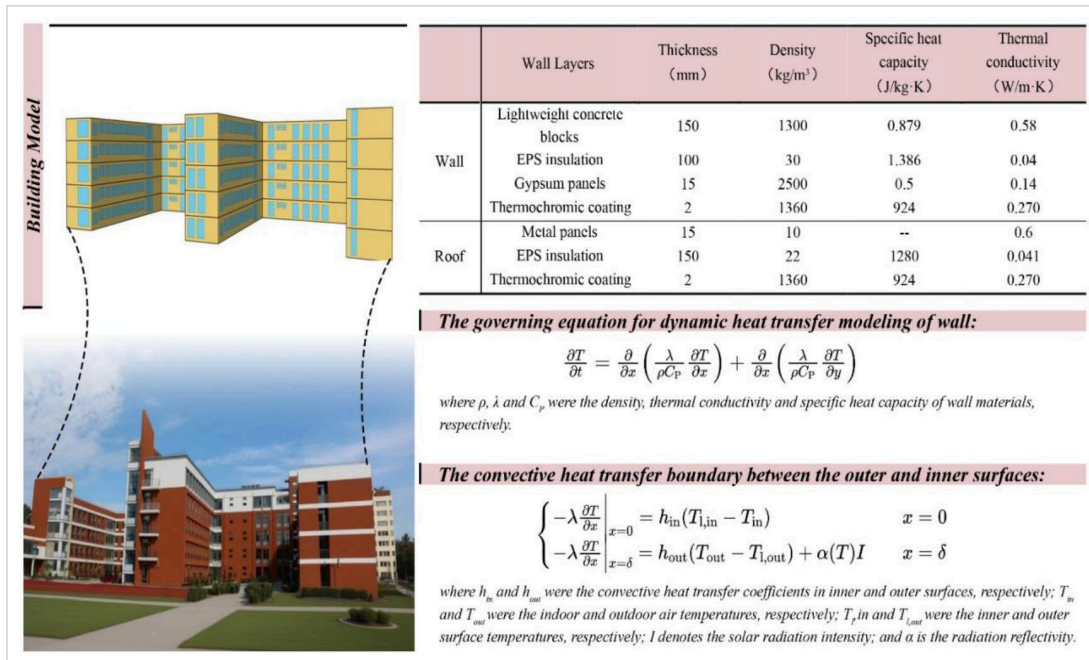


Figure 4. Building model configuration and governing equations for dynamic heat transfer analysis

Two key error indicators were used to validate the model: Root Mean Square Error (RMSE) and Coefficient of Variation (CV). RMSE quantifies the average magnitude of prediction errors, reflecting the dispersion between simulated and measured values, while the CV provides a normalized measure of error variability relative to the mean of the measured data. The validation results show that the prediction accuracy of exterior wall surface temperatures varies with orientation. The RMSE for the east-facing exterior wall surface was 2.62°C, representing the largest deviation between simulated and measured values, whereas the north-facing exterior wall exhibited the lowest RMSE of 0.99 °C. This suggests that solar radiation exposure and directional climatic effects introduce varying levels of complexity in thermal prediction, with east-facing surfaces being more sensitive to transient solar gains.

Similarly, the coefficient of variation for the east-facing exterior surface reached 8.22%, while the north-facing surface exhibited the smallest coefficient of variation at 3.22%. Despite these directional variations, all error metrics remained within the acceptable ranges reported in previous studies, indicating satisfactory model performance.

Working conditions

Four representative cases (CASE 1 to CASE 4) were designed by varying key envelope parameters, including wall thermal resistance, roof insulation thickness, and window solar transmittance. These working conditions were constructed to isolate the influence of individual envelope components while maintaining consistent building geometry, internal loads, operational schedules, and climatic boundary conditions, see [table 2](#).

Table 2. Working condition parameters for different optimization strategies

Strategy parameters	CASE 1	CASE 2	CASE 3	CASE 4
Wall: Adding air layer				
Thickness (cm)	5	10	15	20
Roof: Adding EPS insulation				
Thickness (cm)	10	15	20	25
Window: Changing the solar transmittance				
Solar Transmittance	0.84	0.23	0.33	0.38

For wall optimization, an additional air layer was introduced into the wall assembly to enhance thermal resistance and modify the transient heat-transfer behavior of the envelope. The thickness of the air layer was progressively increased from 5 cm to 20 cm across the four cases. This parametric variation allows evaluation of how incremental increases in wall thermal resistance influence heat-loss reduction, thermal lag, and indoor temperature stability.

Roof thermal performance was improved by adding an EPS insulation layer, with thicknesses ranging from 10 cm to 25 cm in the four cases. The roof was selected as a key optimization target due to its direct exposure to outdoor climatic forcing and its significant contribution to heat loss during the heating season. The selected thickness range reflects practical retrofit scenarios commonly considered for existing educational buildings.

Window performance was adjusted by varying solar transmittance. The solar transmittance values were set to 0.84, 0.23, 0.33, and 0.38 for CASE 1 through CASE 4, respectively. These variations capture a wide spectrum of window behaviors, from high solar-

gain glazing to more solar-restrictive configurations.

Results and discussion

Indoor Thermal Environmental Data Analysis

The winter field experiment was conducted from December 4 to December 16, 2023. As shown in [table 3](#), the average indoor temperature in university classrooms was 18.98 °C, with a fluctuation range of 16.5°C to 21.3°C. This was significantly higher than the outdoor temperature, primarily due to centralized heating systems implemented in university classrooms across cold regions during winter. The average operating temperature was 19.05 °C, this indicates that indoor temperatures remained close to the human thermal comfort range for most of the time. Relative humidity ranged from 27.7% to 39%, with an average of 32.06%. The low RH suggests that the indoor environment was relatively dry during winter.

Table 3. Summary of indoor environmental parameters in winter

Parameter	Ta (°C)	Top (°C)	RH (%)	V (m/s)
Mean	18.98	19.05	32.06	0.16
Standard Deviation	1.38	1.39	2.65	0.06
Minimum	16.5	16.6	27.7	0.1
Maximum	21.3	21.33	41.7	0.41

The summer field experiment was conducted from June 9 to June 22, 2024. As shown in [table 4](#), the average indoor temperature in university classrooms was 30.69 °C, with an average operating temperature of 30.73 °C. The average wind speed was 0.55 m/s, and relative humidity fluctuated between 27.1 % and 53.4 % ,

representing a deviation of 7.36 % . The high deviation value resulted from frequent changes in classroom occupancy. During class sessions, students congregated together, causing RH to rise. After class, RH decreased as the number of occupants in the classroom diminished.

Table 4. Summary of indoor environmental parameters in summer

Parameter	Ta (°C)	Top (°C)	RH (%)	V (m/s)
Mean	32.46	32.41	44.03	0.55
Standard Deviation	1.29	1.34	7.36	0.26
Minimum	27.9	27.62	31.7	0.17
Maximum	34.3	33.49	53.4	1.29

Influence of envelope components on indoor environmental conditions Influence of wall thermal performance

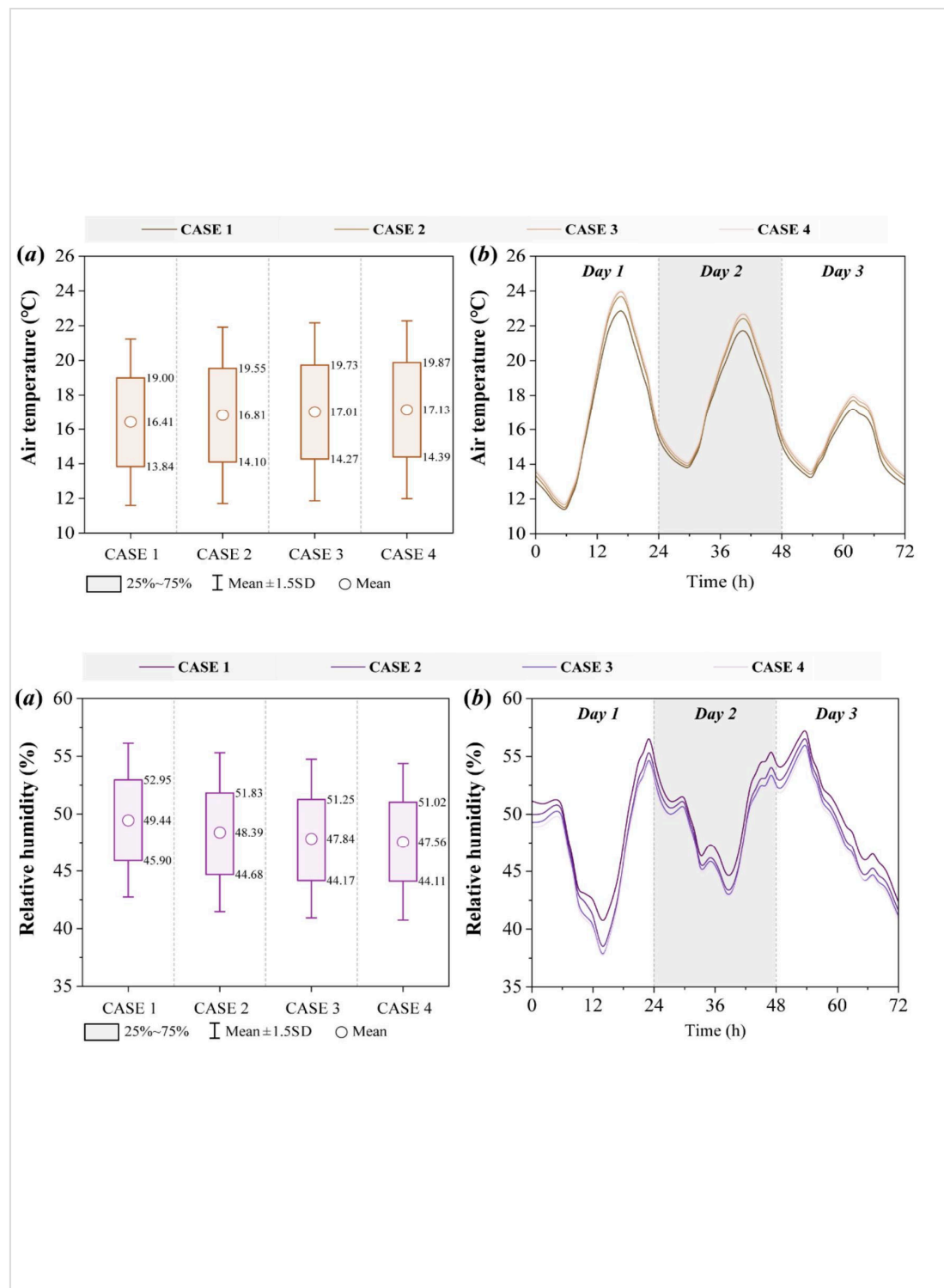


Figure 5. Statistical distribution and temporal variation of indoor air temperature and relative humidity in winter

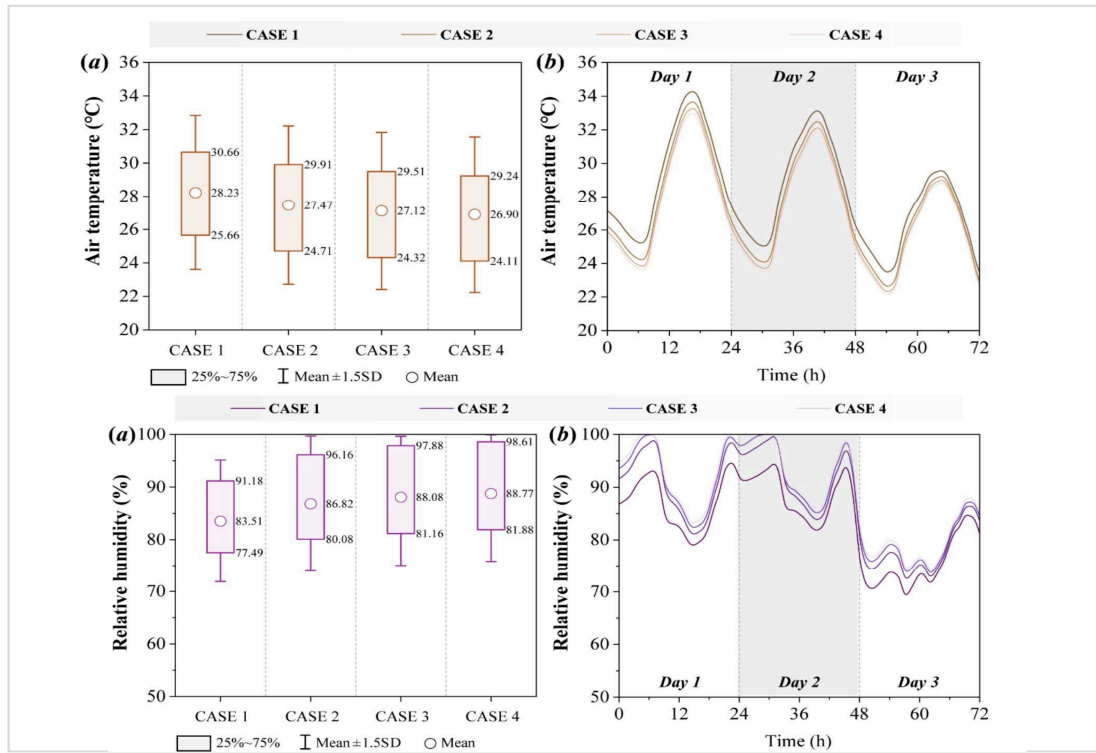


Figure 6. Statistical distribution and temporal variation of indoor air temperature and relative humidity in summer

To investigate the impact of wall thermal performance on indoor environmental conditions by altering the thermal resistance of walls. As shown in figure 5, simulation results show that increasing wall thermal resistance has a dual regulatory effect on the indoor environment during winter: it elevates indoor air temperature while simultaneously reducing relative humidity. The mean indoor air temperature rises from 16.41 °C in CASE 1 to 17.13 °C in CASE 4, indicating that the enhancement of wall thermal performance effectively improves the overall indoor thermal level during the heating period. At the same time, the interquartile range (25 % - 75 %) becomes slightly narrower from CASE 1 to CASE 4, suggesting that improved wall insulation contributes to stabilizing indoor thermal conditions and reducing temperature dispersion.

During summer, enhanced wall thermal performance exerts a dual effect: it reduces indoor air temperature and suppresses peak overheating, but simultaneously leads to higher indoor relative humidity. The average indoor air temperature decreases from 28.23 °C in CASE 1 to 26.96 °C in CASE 4, while the mean indoor relative humidity increases gradually from 83.51 % in CASE 1 to 88.18 % in CASE 4. This trend is attributed to the

reduction in indoor air temperature, which lowers the saturation vapor pressure of indoor air when absolute moisture content remains relatively constant.

Influence of roof thermal performance

As shown in figure 7, simulation results show that increasing roof insulation thickness contributes to improving indoor thermal conditions during the heating season, with the mean indoor air temperature increasing from 16.41 °C in CASE 1 to 16.69 °C in CASE 4. Although the magnitude of temperature increase is moderate, the upper quartile and maximum temperature values show a clear upward trend, suggesting enhanced heat retention within the indoor space.

The temporal profiles of indoor air temperature show that higher insulation cases (CASE 3 and CASE 4) maintain higher nighttime temperatures and slightly reduced temperature decay during off-peak hours, indicating that improved roof thermal performance enhances thermal inertia and reduces heat loss through the roof, particularly during nighttime periods when outdoor temperatures are lowest.

During summer, improving roof thermal performance has a moderate cooling effect on indoor air temperature, primarily through attenuation of solar heat gains, while simultaneously inducing a slight increase in indoor relative humidity. As shown in figure 8,

the average indoor air temperature decreases from 28.23°C in CASE 1 to approximately 28.05°C in CASE 4, and the mean indoor relative humidity increases gradually from 83.51% in CASE 1 to 84.21% in CASE 4.

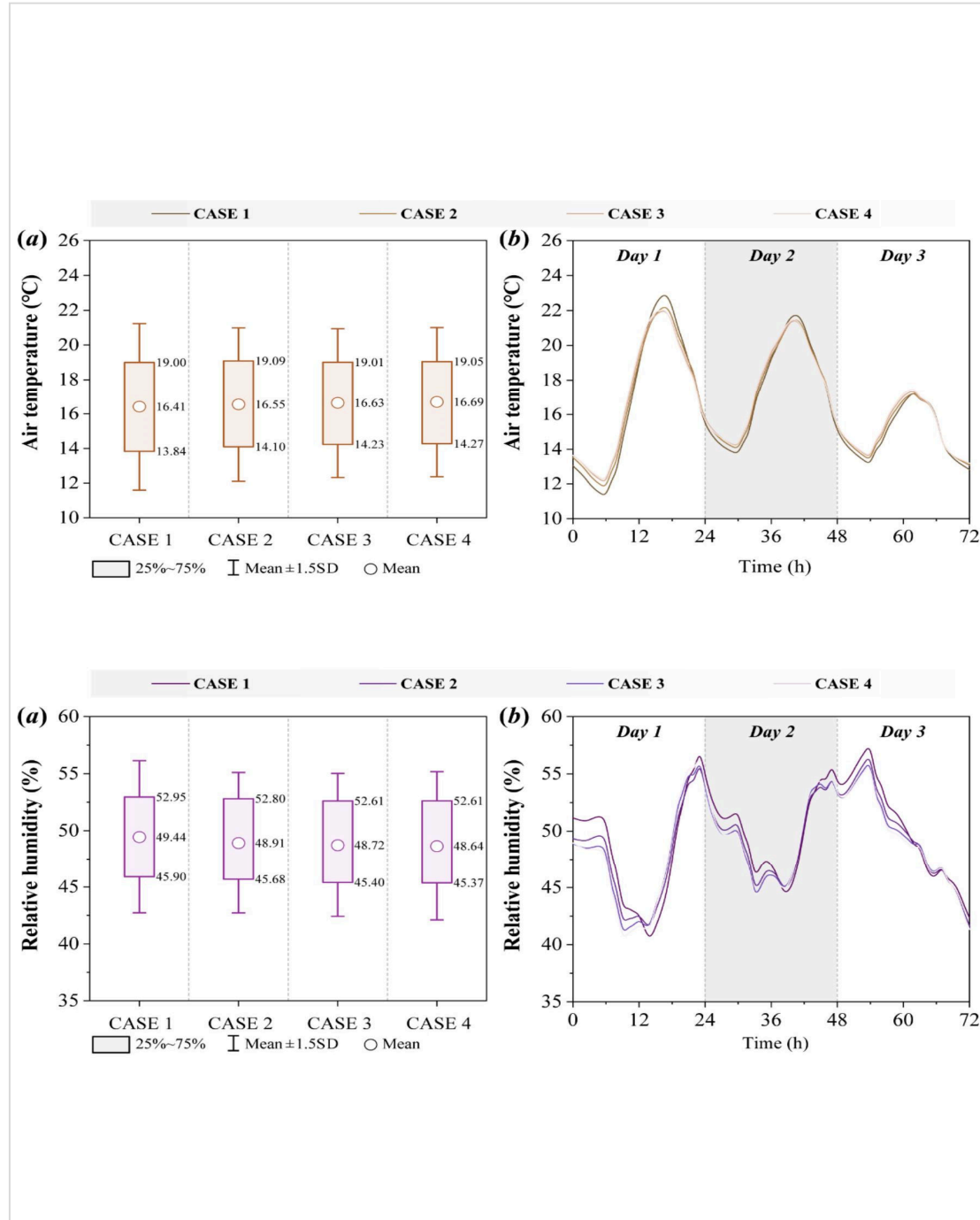


Figure 7. Statistical distribution and temporal variation of indoor air temperature and relative humidity in winter

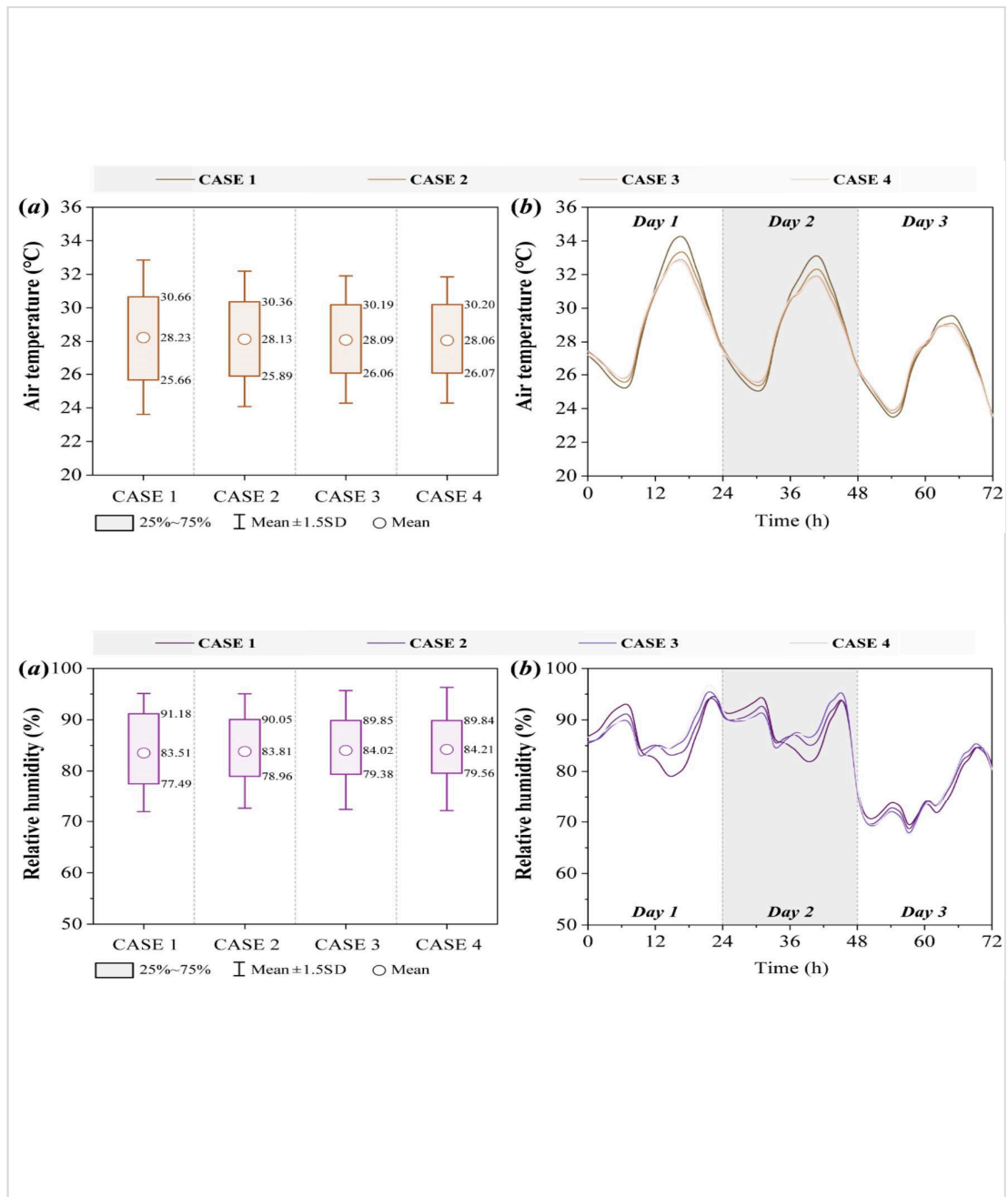


Figure 8. Statistical distribution and temporal variation of indoor air temperature and relative humidity in summer

Influence of window thermal and solar properties

As shown in figure 9, During winter, variations in window properties lead to noticeable differences in indoor thermal conditions, with the mean indoor air temperature decreasing from 16.53°C in CASE 1 to 15.74°C in CASE 2, and then increasing slightly in CASE 3 and CASE 4. This non-monotonic trend reflects the combined

influence of window thermal transmittance and solar transmittance on indoor heat balance. CASE 1, characterized by higher solar transmittance, exhibits higher daytime peak temperatures, indicating stronger passive solar heat gains through the window. In contrast, CASE 2 shows lower daytime temperature peaks and reduced solar contribution, leading to a lower overall indoor temperature level.

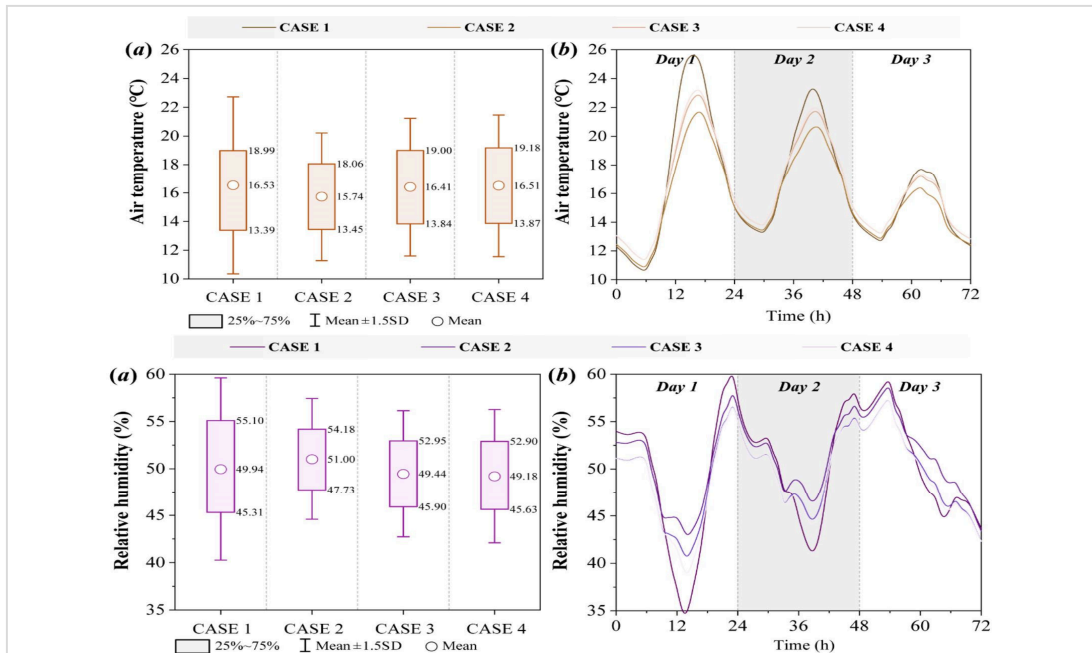


Figure 9. Statistical distribution and temporal variation of indoor air temperature and relative humidity in winter

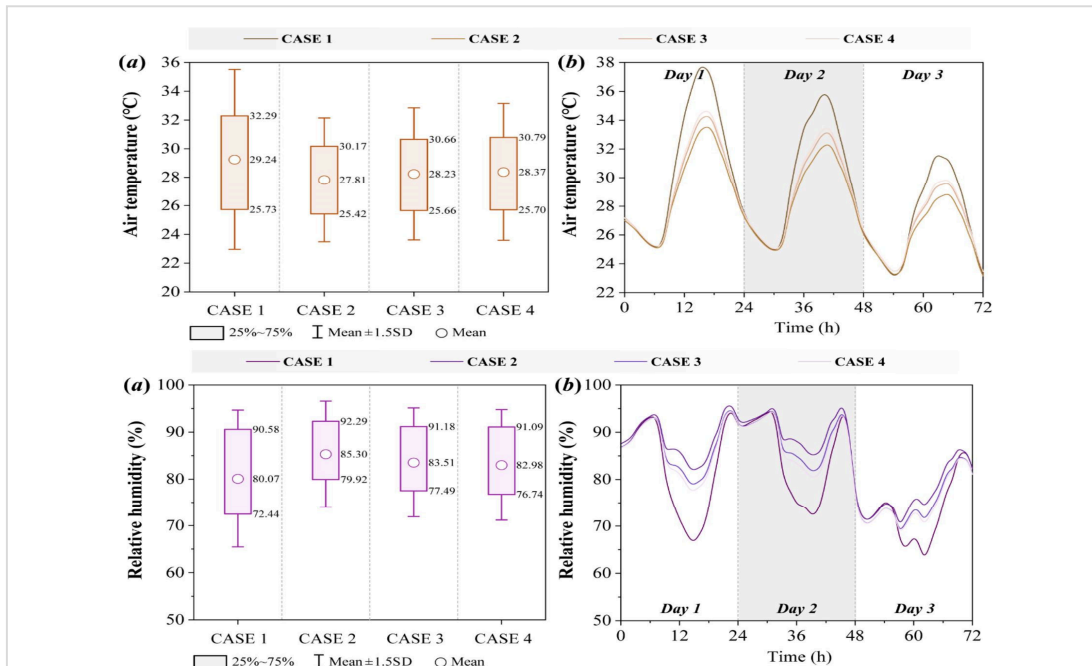


Figure 10. Statistical distribution and temporal variation of indoor air temperature and relative humidity in summer

As shown in figure 10, during summer, reducing window solar transmittance effectively suppresses indoor overheating, with the mean indoor air temperature decreasing from 29.24°C in CASE 1 to 27.81°C in CASE 2. However, excessive solar reduction leads to increased

indoor humidity and diminishing marginal cooling benefits, with CASE 2 showing the highest humidity levels (mean 85.30 %) and CASE 3 and CASE 4 maintaining intermediate levels.

Comparative energy performance of envelope components

Energy performance, evaluated using energy use intensity (EUI), is a critical criterion for evaluating envelope optimization strategies. As shown in figure 11, simulation results show that increasing wall insulation thickness has the most

significant impact on energy efficiency, with the annual EUI decreasing from 114.90 kWh/m² to 88.51 kWh/m². Increasing roof insulation provides a moderate contribution to EUI reduction, while adjusting window solar transmittance shows a distinct comfort-energy coupling mechanism.

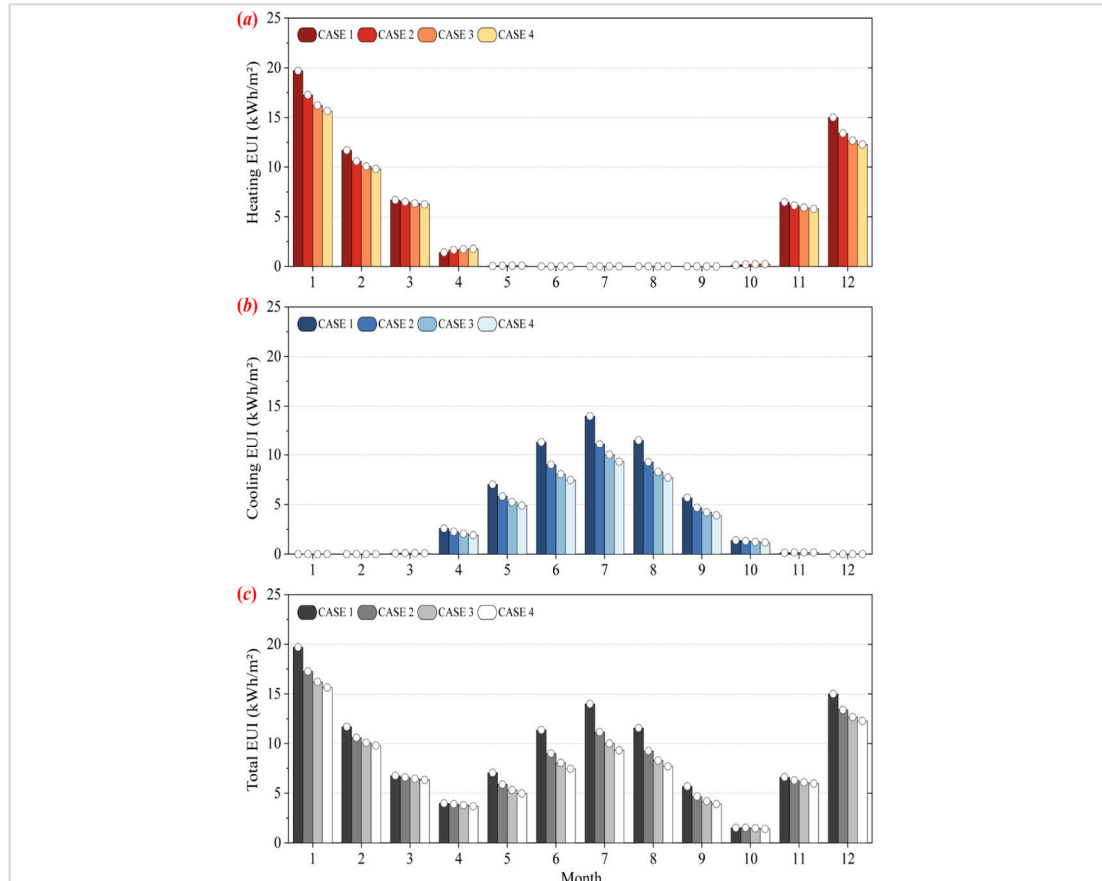


Figure 11. Wall-Induced energy use intensity response under different thermal resistance configurations

The comparative analysis reveals that walls are the most influential envelope component in reducing heating energy demand, followed by roofs and windows. This is attributed to the larger surface area of walls and their direct exposure to outdoor temperature variations. Windows, however, play a critical role in balancing passive solar gains and heat loss, with their optimization requiring careful consideration of seasonal trade-offs.

Conclusions

This study systematically investigates the influence of building envelope performance on indoor thermal comfort and heating energy demand in university buildings in Yuncheng, a cold-region city in China. Wall insulation has the greatest impact. In winter, it raised mean indoor temperature by up to 0.72°C, while in summer it lowered indoor temperature by up to 1.33°C. The corresponding annual energy use intensity fell by about 30% – 34% with the enhanced insulation scenario. Roof insulation provides stabilization. It slightly increased winter nighttime temperature

and reduced heat loss, resulting in a modest temperature rise (+0.27°C winter mean) and an 18 % drop in annual EUI. Lowering window solar transmittance markedly reduced summer overheating and cut cooling-related energy use. In this cold-region case, window shading proved effective at mitigating cooling loads.

Acknowledgments

The authors would like to express their sincere gratitude to Professor Muhamad Azhar Bin Ghazali from the Universiti Sains Malaysia (USM) for his invaluable guidance and patient supervision throughout the entire research process.

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Author(s) contribution

Mengmeng Hou contributed to the research concepts preparation, methodologies, investigations, data analysis, visualization, articles drafting and revisions.

Muhamad Azhar Bin Ghazali contribute to the research concepts preparation and literature reviews, data analysis, of article drafts preparation and validation.

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