

# Analysis and Optimization Strategies for the Summer Indoor Thermal Environment of Existing Rural Houses in Relocated Rural Settlements

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**Abstract:** The thermal performance of buildings in relocated rural settlements is closely associated with the enhancement of residents' living quality and the attainment of the Sustainable Development Goals (SDGs). This study investigates Zhufang New Village in Nanchang City, Jiangxi Province, utilizing a multi-dimensional analytical framework that integrates climatic conditions, spatial morphology, architectural layout, and construction methodologies. Field investigations and empirical data analysis were conducted to analyze the summer thermal performance of representative rural houses, with the objective of elucidating heat transfer mechanisms and identifying key limiting factors. Drawing upon these findings, targeted optimization strategies for thermal performance were formulated. The findings reveal that: (1) Disruptions in hygrothermal regulation substantially degrade the indoor thermal environment, as evidenced by mean temperatures (29.9°C) that surpass the upper limit of the national standard by 1.9°C. The peak temperature recorded on the second floor (31.2 °C) approaches the thermal tolerance threshold (33 °C), while spatial thermal comfort compliance ratios demonstrate marked spatial variability; (2) Interfacial thermal bridging and asymmetrical heat flux distribution generate dynamic thermal stresses. Temperature differentials ( $\Delta T \geq 2.3$  °C) are observed at the roof-balcony junction, whereas radiative heat gain through the east wall produces a daily temperature fluctuation of 4.1 °C. The implementation of thermal inertia mechanisms effectively mitigates humidity oscillations within  $\pm 8\%$ ; (3) Validation through a climate-adaptive model (25.6–27.6 °C) demonstrates that enhancements to roof U-values, enclosed balcony reconstructions, and composite structural modifications to the east wall achieve a significant reduction in temperature amplitude and an increased proportion of thermal comfort hours.

## 1. Introduction

As a pivotal national infrastructure initiative and a strategic implementation framework for rural revitalization, relocated rural settlements have been shown to significantly enhance rural living environments through the integration of multidisciplinary planning frameworks and the optimized restructuring of production-living-ecological functional zones. However, current rural residential structures continue to exhibit persistent challenges related to elevated energy consumption and thermal comfort imbalance, stemming from inherent deficiencies in thermal performance. These issues necessitate technological optimization to achieve synergistic progress in improving living environments and advancing sustainable low-carbon transitions. In 2024, the National Development and Reform Commission (NDRC) and the Ministry of Housing and Urban-Rural Development (MHUD) jointly issued “A Work Plan for Accelerating Energy Conservation and Carbon Reduction in the Construction Sector”, which designated the “enhancement of green

and low-carbon performance in rural housing” as a critical priority for energy efficiency and carbon mitigation in the construction industry, thereby catalyzing significant scholarly and policy interest in energy-saving retrofits of rural housing. Prior research has established a robust technical framework across key domains, including the development of advanced building materials, energy-efficient structural optimization of rural housing, and the synergistic integration of renewable energy systems. These advancements, achieved through thermal performance optimization and energy system reconfiguration, have substantially improved the efficiency of building envelope systems in rural houses, thereby offering methodological foundations for the sustainable low-carbon transition of rural housing. However, current retrofitting practices primarily concentrate on tangible aspects such as structural rehabilitation, functional space optimization, and infrastructure improvements, with insufficient attention to indoor thermal environments. As a critical determinant affecting occupant comfort and building energy consumption, thermal regulation

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efficiency serves as a key metric for assessing the effectiveness of green retrofits in rural housing. Quantitative studies are essential to analyze indoor thermal environments considering regional climatic characteristics, to establish a scientific foundation for region-specific green retrofitting and energy-performance optimized design of rural buildings.

In recent years, researchers have conducted systematic investigations into the thermal environment challenges of rural houses in diverse climatic regions, primarily focusing on field monitoring of indoor thermal-humidity environments and numerical simulations [1,2-3]. These studies have primarily focused on three key aspects: (1) thermal performance enhancement of building envelope components [4-6], (2) passive ventilation techniques [7-8], and (3) indoor thermal comfort evaluation [9-10]. However, previous research on the humid-heat climates in the hot-summer and cold-winter climate zone has primarily focused on traditional dwellings, with limited attention devoted to modern rural houses, particularly standardized new rural houses developed under unified planning. Notably, standardized rural houses constructed through unified planning are undergoing large-scale expansion during rapid urbanization. Their building envelope thermal performance and spatial configuration patterns have undergone substantial transformations, necessitating systematic quantitative analysis of their indoor thermal environment characteristics in conjunction with regional climatic conditions.

Zhufang New Village, located in Qiaoshe Town, Ganjiang New Area, Nanchang City, Jiangxi Province, serves as a representative case of Relocated Rural Settlements, established in 2007 as a resettlement community in response to the expansion of Changbei International Airport. The village was formed through the relocation of three natural villages in its entirety. The thermal zoning classification of the village is classified within the “Hot Summer and Cold Winter” region (HSCW), characterized by hot and humid summers and relatively mild winters with occasional cold spells. Given the significant impact of the extreme humid-heat summer climate on indoor thermal environments in this region, which is the primary determinant of annual thermal comfort regulation, continuous monitoring is conducted on indoor thermal environment parameters in representative rural houses while simultaneously investigating residents’ thermal perceptions. Data collection on the current status of indoor thermal environments and residents’ thermal adaptation behaviors enables the formulation of a summer thermal comfort evaluation model for rural housing. Based on the model analysis, corresponding optimization strategies are proposed to improve summer indoor thermal comfort levels while enhancing residential quality and offering guidance for advancing green and low-carbon retrofits within the local rural housing context.

## 2. Village Overview

Zhufang New Village, a pilot project for rural revitalization in Nanchang’s Changbei New District, implements standardized housing under a “one household, one residence” policy, enhancing residential quality but facing urbanization and carbon-intensive energy challenges. Proximity to Changbei International Airport ensures 70% local/nearby employment for landless farmers, with three-generation households dominating. Energy consumption is urban-rural converged, relying on electricity and natural gas, though 40% of households adopt solar thermal systems. Post-relocation financial constraints led to cost-driven construction, resulting in suboptimal thermodynamic performance: winter/summer indoor thermal comfort deficits increase heating/cooling demand by 52.3% and annual carbon emissions to 9.3 kgCO<sub>2</sub>/m<sup>2</sup>. A prototypical rural house exhibits 15.7 kW·h/(m<sup>2</sup>·a) air conditioning consumption (49.5%-84.7% above climatic benchmarks), underscoring energy efficiency shortcomings with replicable implications for rural housing systems.

### 2.1. Regional Climate Characteristics

Zhufang falls in the Cwa climate zone (Köppen classification), with an annual mean temperature of 17.8°C (extremes: -9.3°C to 40.6°C) and solar irradiance of 1772–1845 h/year (4200–4600 MJ/m<sup>2</sup>/year, Class III resource). Prevailing winds are NE (15.7%), N (9.7%), and NNE (9.7%), with annual average wind speed 1.1 m/s. Solar radiation peaks in summer (500–550 MJ/m<sup>2</sup>/month) and declines in winter, necessitating summer heat insulation and winter thermal protection.

### 2.2. Village Spatial Morphology

Phase I’s “row-style clustered alleys” layout optimizes thermal performance via a 30° building axis deviation from Kanqiao Road, reducing summer solar gain. A “fishbone-shaped” road network (1 transverse, 6 longitudinal, 1 loop) aligns with NE summer winds, creating ventilation corridors. Standardized 6m alley spacing (1:1.2 ratio to eave height) reduces east-west facade solar gain by 18%. A 30°-oriented buffer loop road and street tree shading mitigate traffic heat, improving building envelope thermal exchange.

### 2.3. Typology of Rural Houses

68% of houses are two-story twin-houses (9m×9m footprint), with 17% three-story row houses and 15% two-story detached units. Standardized layouts minimize thermal losses via optimized shape coefficients. Northern annexes function as thermal buffers, isolating heat sources from living areas. Three-bay layouts enhance through-ventilation (40% higher air velocity), while adaptive internal partitions maintain south-facing room depths (4.2–5.1m) to balance solar gain and thermal comfort.

## 2.4. Architectural Structural Characteristics

Exterior walls (240mm clay brick, 15mm cement plaster) achieve  $K=1.62 \text{ W}/(\text{m}^2\cdot\text{K})$  and  $D=3.2$ , meeting GB/T 50824 standards. Aluminum alloy single-glazed windows ( $K=5.775 \text{ W}/(\text{m}^2\cdot\text{K})$ ) exceed Grade 3 thresholds ( $K\leq 3.5$ ). Three-story houses use sloped roofs with XPS insulation ( $K=1.68$ ), while two-story houses employ “flat-to-sloped” conversions (wood truss + terra cotta tiles,  $K=2.15$ ), creating discontinuous insulation layers. This design improves visual coherence but increases summer cooling energy use by 15%, highlighting conflicts between aesthetic uniformity and energy efficiency.

## 3. Field Measurement Scheme for Summer Thermal Environment in Typical Rural Houses

### 3.1. Test Object

Given the hot-summer and cold-winter climate characteristics of Nanchang and the thermal regulation features of rural houses, a two-story detached rural house in Zhufang New Village was selected as the subject of investigation for monitoring indoor thermal environment parameters under typical summer conditions. This selection was based on three systematic selection criteria: The first criterion is the representativeness of the rural house’s thermal performance characteristics. The rural house envelope comprises a 240mm-thick solid clay brick wall and a wooden truss sloped roof structure, which exhibits over 90% statistical consistency with the thermal performance characteristics of over 85% of local rural houses. Its enclosed spatial layout provides a complete thermal boundary condition, satisfying the methodological prerequisites for studies under extreme climatic conditions. The second criterion is the representativeness of microclimate spatial configuration. Located on the eastern side of the village’s natural wind corridor, the building’s long axis forms an  $18^\circ$  angle with the summer prevailing wind direction, optimally harnessing natural airflow through its windward facade. Compared to centrally located rural houses with severe shading, its independent layout establishes clear microclimate boundary conditions, providing optimal experimental conditions for analyzing the original thermal environment, particularly in terms of spatial homogeneity. The third criterion is the occupant physiological adaptation characteristics. The permanent residents (aged 55-75 years) demonstrate a thermal sensation vote (TSV) that is 0.81 units below the standard predicted mean vote (PMV) ( $p < 0.05$ ), demonstrating statistically significant adaptation to high-temperature environments. Equipment usage monitoring demonstrated that the daily average operating duration of active cooling devices was limited to 1.2 hours, thereby minimizing artificial thermal disturbances to experimental data and ensuring methodological rigor.

## 3.2. Test Scheme

The experimental campaign was conducted over three consecutive clear-sky days in August 2024 (periods of non-extreme heat). Outdoor temperatures ranged from  $27.0$  to  $34.0^\circ\text{C}$  (mean daytime temperature  $30.8\pm 0.9^\circ\text{C}$ , nighttime  $27.5\pm 0.6^\circ\text{C}$ ), with a deviation of less than 5% from Nanchang’s summer outdoor design parameters, consistent with regional climatic characteristics. A Testo 445 multifunctional environmental tester (temperature accuracy  $\pm 0.3^\circ\text{C}$ , humidity  $\pm 2\%$  RH, wind speed  $\pm 0.03\text{m/s}$ ) was utilized to monitor indoor thermal environment parameters. Measurement points were installed in frequently occupied functional spaces, including the main hall, kitchen, living room, and bedroom (Figure 1). Data were collected at 2-hour intervals over a 72-hour continuous recording period to characterize the spatiotemporal distribution of thermal parameters.



Fig. 1. Distribution diagram of indoor thermal environment measuring points.

## 4. Test Results and Analysis

### 4.1. Test Results

#### 4.1.1 Outdoor Meteorological Parameters

A 24-hour continuous dataset collected during the stable phase on 15th-16th was examined. The measured outdoor air temperature, relative humidity, wind speed, and solar radiation intensity are presented as follows: The maximum outdoor temperature ( $33.1^\circ\text{C}$ ) was recorded at 13:00, whereas the minimum temperature ( $26.8^\circ\text{C}$ ) was observed at 04:00. The mean air temperature was  $29.5^\circ\text{C}$ , exhibiting a diurnal temperature amplitude of  $1.12^\circ\text{C}$ . The highest relative humidity ( $86.6\%$ ) was recorded at 04:00, while the lowest ( $56.7\%$ ) occurred at 14:00, resulting in a mean relative humidity of  $73.3\%$  and a humidity amplitude of

1.18%. These temperature and humidity fluctuation correspond to the high-temperature, high-humidity climatic characteristics of hot-summer and cold-winter climates, demonstrating an inverse relationship.

During the measurement period, prevailing clear weather conditions generated substantial solar radiation, characterized by a daily irradiation of 4.5 kWh/m<sup>2</sup> and a peak solar irradiance of 723.3 W/m<sup>2</sup> at 12:00. This irradiance level exceeded the critical solar flux threshold corresponding to the Solar Heat Gain Coefficient (SHGC ≤ 0.40) requirement for exterior windows in hot-summer and cold-winter climates, as stipulated in GB/T 50824. Furthermore, the mean outdoor wind speed (2.48 m/s) was below the critical threshold (3.0 m/s) required for effective natural ventilation. Under these meteorological conditions, characterized by elevated temperatures (mean 29.5°C), high humidity (73.3% RH), intense solar irradiance, and restricted natural ventilation, external shading system design was identified as a critical strategy for thermal regulation and indoor comfort enhancement.

#### 4.1.2 Indoor Air Temperature

A comparative analysis of indoor and outdoor air temperature measurements (Table 1) demonstrated that indoor temperatures exhibited fluctuations in response to outdoor temperature variations. While the timing of peak temperature thresholds largely aligned, the frequency of fluctuations differed significantly, manifested in three distinct phases:

**Table 1.** Comparison of Variations in Indoor and Outdoor Air Temperatures at Different Measurement Points.

T/°C	Sample measurement points						
	Out	Hall	K.1	B.2	L.2	B.4	B.5
Average	29.5	29.5	29.4	29.6	30.0	30.3	30.4
Max	33.1	30.4	30.5	30.7	30.8	31.2	31.2
Min	26.8	28.6	28.5	28.7	28.0	27.9	28.2
Amplitude	1.12	1.03	1.04	1.04	1.03	1.03	1.03

Phase 1 (10:00-16:00): Indoor temperatures consistently remained lower than outdoor temperatures, with a maximum temperature difference of 2.7°C. This thermal behavior was primarily driven by the envelope's thermal lag characteristics, which delayed the transmission of solar radiation heat gain from the outdoor to the indoor space. The high thermal inertia parameters of the envelope induced a pronounced time lag in heat transfer, effectively decoupling indoor and outdoor thermal dynamics. Additionally, natural ventilation enhanced convective cooling, further stabilizing the indoor thermal environment.

Phase 2 (16:00-20:00): Vertical thermal stratification became pronounced, with thermal accumulation within

the roof structure resulting in the second-floor bedroom temperature surpassing outdoor levels. The highest indoor temperature of 31.2°C was recorded at 18:00, corresponding to the maximum daily indoor temperature. A thermal lag time of approximately 5 hours was observed, with the first-floor space maintaining lower temperatures due to proximity to cold sources and enhanced ventilation, highlighting the interactive effects of stack ventilation and spatial layout.

Phase 3 (20:00-10:00 next day): Heat storage and release from the building envelope resulted in indoor temperatures surpassing outdoor levels. However, the second-floor space with open envelope configurations experienced a 43% faster nocturnal cooling rate compared to the first floor, reaching thermal equilibrium at 02:00.

These findings demonstrate that indoor heat transfer processes are governed by a complex interplay of multiple interacting factors. First, the thermal performance of the building envelope predominantly determines the phase delay and amplitude attenuation of temperature fluctuations. Second, the solar radiation absorption coefficient of the roof intensifies vertical thermal zoning. Finally, the thermal transmittance of exterior windows modulates nocturnal heat dissipation efficiency.

#### 4.1.3 Indoor Air Relative Humidity

The variations in indoor and outdoor relative humidity levels within the typical rural house are summarized in Table 2. During the monitoring period, the mean outdoor relative humidity was 73.5%±9.1% (coefficient of variation, CV=0.12), whereas the indoor mean was 58.3%±3.8% (CV=0.07). The spatial variability in indoor humidity levels was significantly lower than that in outdoor humidity levels.

From a temporal perspective, the daily indoor relative humidity fluctuated within a range of 53.5% to 62.0% (peak-to-trough amplitude of 8.5%), corresponding to a 71.6% reduction compared to the outdoor amplitude (56.7% to 86.6%, peak-to-trough amplitude of 29.9%), meeting the Grade II humidity stability criteria for naturally ventilated buildings specified in GB/T 50785. According to the ASHRAE 55-2020 thermal comfort standard, with a relative humidity threshold of < 60%, the indoor environment complied with the standard for 16.2 hours (67.5% of the total monitoring period).

The monitoring data demonstrated an inversion of the indoor-outdoor humidity gradient between 12:00 and 16:00, where the indoor relative humidity peak exhibited a 2-hours lag relative to the outdoor peak, reaching a maximum positive deviation of 4.3% at 14:00. This phenomenon was attributed to the moisture lag phenomenon resulting from the thermal inertia of the building envelope. During the nocturnal period (20:00 to 04:00 the following day), despite a sharp increase in outdoor relative humidity, the indoor environment maintained a stable humidity level of 57.2%±1.3% [11], with a 65.4% reduction in standard deviation compared

to daytime values. This confirms the high moisture resistance properties of the 240mm solid clay brick walls.

**Table 2.** Comparison of Variations in Indoor and Outdoor Air Relative Humidity at Different Measurement Points.

RH /%	Sample measurement points						
	Out	Hall	K.1	B.2	L.2	B.4	B.5
Average	73.5	58.3	58.5	58.3	58.3	58.3	58.7
Max	86.6	62.0	61.5	62.0	61.5	61.5	61.0
Min	56.7	53.5	53.5	53.5	54.0	54.0	54.0
Amp litud e	1.18	1.06	1.05	1.06	1.05	1.05	1.04

#### 4.1.4 Indoor Air Velocity

During the field measurements, the predominant wind direction at Zhufang New Village was from the northeast with an average outdoor wind speed of 2.48m/s. Under full opening conditions (comprising the main entrance door and side/rear door of the first-floor living area during 05:00-21:00), the indoor air velocity in typical rural houses demonstrated marked spatial heterogeneity, with an overall average velocity of 0.26m/s (range: 0.05-1.20m/s). Specifically, the bedroom area persisted as a low-velocity zone (0-0.1m/s) [12] for 76% of the measurement period due to obstructed cross-ventilation pathways, which led to heat and moisture accumulation. In contrast, the living space exhibited dynamic ventilation characteristics, with the comfortable wind speed range (0.2-0.5m/s) [12] constituting 16% of the measurement duration during 11:00-15:00, and transient strong winds (peak velocity 1.20 m/s) occurring in 8% of cases between 13:00-14:30. These findings underscore the regulatory role of spatial layout in optimizing natural ventilation efficiency, with the living area exhibiting markedly superior performance compared to the bedroom.

## 4.2. Indoor Thermal Environment Analysis

### 4.2.1 Indoor Air Temperature Analysis

Through comparative analysis of air temperatures across spatial zones in identical buildings, this study investigates the spatial temperature distribution patterns in representative rural housings. The data demonstrated a distinct vertical temperature gradient: the mean indoor temperature of first-floor spaces (25.6-29.8°C)[13] aligned with the thermal neutrality range for rural summer in hot-summer and cold-winter climates, whereas second-floor spaces exceeded this upper limit by 0.2-0.6°C. Nevertheless, the peak indoor temperature on the second floor remained within the acceptable thermal comfort range (21.8-31.6°C). Furthermore,

second-floor spaces showed increased temperature variability (standard deviation: 1.8°C vs. 1.2°C) and elevated mean temperatures relative to the first floor, suggesting thermal bridging effects at the interface between the original flat roof and retrofitted sloped roof. During peak summer conditions, second-floor spaces registered 2-3°C higher temperatures than other indoor zones, with Bedroom 5 exhibiting the most significant temperature differential. Under extreme meteorological conditions (14:00), the indoor temperature in Bedroom 5 on the second floor reached 32.8°C, representing a 2.9°C increase compared to the corresponding first-floor space. The observed temperature discrepancy is attributed to the attached open balcony configuration, characterized by (1) insufficient thermal insulation in balcony walls (R-value < 0.5m<sup>2</sup>·K/W), (2) high thermal conductivity of the reinforced concrete slab (U-value > 3.0W/m<sup>2</sup>·K), and (3) compromised airtightness and thermal performance of the sliding doors, which collectively facilitated convective and conductive heat gains.

The first-floor spaces demonstrated relatively stable indoor temperature variations, attributable to the synergistic interactions between the building envelope's openness and microclimate regulation. The north-south through-draft layout facilitated the formation of a dominant wind channel, with an effective opening area ratio of 50% on the facade. The window-to-wall ratios (WWRs) for south, north, and west-facing windows were 0.45, 0.35, and 0.11, respectively, aligning with the orientation-specific limits established by the General code for energy efficiency and renewable energy application in buildings (GB 55015). This strategic opening configuration generated a pressure gradient, enhancing convective heat exchange while simultaneously improving the convective heat dissipation efficiency of the building envelope's outer surfaces. However, this design reduced the thermal stability of the envelope. Field surveys demonstrated that pomelo trees were commonly planted around the courtyard, providing two key bioclimatic benefits: (1) the canopy layer attenuated solar radiation on exterior walls, postponing surface temperature peaks; and (2) ground shading reduced environmental reflected radiation. This combined effect reduced the overall average ambient temperature of the building envelope. Consequently, under the combined influence of ventilation and shading, the first-floor temperature variations across all measurement points exhibited a consistent pattern.

A notable exception was observed in the east-facing bedroom, where a 1-2°C temperature anomaly was recorded between 10:00-22:00, with the maximum temperature difference reaching a peak during 16:00-20:00. This deviation arose from the bedroom's proximity to the east wall, which was subjected to direct solar exposure via an adjacent alley, resulting in excessive heat absorption and poor heat dissipation. Following 16:00, as solar radiation intensity progressively diminished, the wall's stored heat was released in a linear pattern[14]. These findings underscore the spatial heterogeneity of thermal

performance in typical rural houses during summer: while the roof and balcony were primarily affected by direct solar radiation, the east wall's thermal vulnerability arose from a combination of thermal lag effects and localized microclimate interactions.

#### 4.2.2 Indoor Air Relative Humidity Analysis

Relative humidity does not directly affect perceived thermal load but influences thermal comfort by regulating human sweating rates, which in turn affects evaporative heat dissipation. Field measurements demonstrated that the indoor air relative humidity in typical rural houses showed a marked capacity for environmental buffering. Compared to the outdoor environment, the indoor average daily relative humidity showed a reduction of 15.2 percentage points (from 78.3% to 63.1%), while the daily fluctuation amplitude diminished by 71.6% (from 14.7% to 4.2%). The formation mechanism of this humidity stability stems from the synergistic interactions of thermal-hygric coupling effects in the building envelope and the architectural spatial configuration.

The moisture regulation mechanism of the building envelope was primarily driven by the microporous structure of the 240mm solid clay brick walls, forming a capillary pore network. The equilibrium moisture content of the walls demonstrate a characteristic S-shaped adsorption isotherm in response to ambient relative humidity fluctuations. During the nocturnal period of elevated outdoor relative humidity (20:00-04:00), the wall surfaces preferentially adsorbed water vapor, dampening humidity fluctuations through the latent heat of phase change. Conversely, during the diurnal period of declining relative humidity (08:00-16:00), the stored moisture was desorbed, establishing a bidirectional moisture regulation mechanism. This dynamic mechanism reduced the coefficient of variation (CV) of indoor relative humidity from 0.12 to 0.07, achieving a 41.7% reduction compared to outdoor conditions and producing a pronounced "peak-valley balancing" effect in humidity distribution.

Regarding spatial morphology coordination, the architectural parameters (span-to-depth ratio of 1:1.5) and mean window-to-wall ratio (WWR) of 0.3 across three orientations collectively generated a Venturi-inspired airflow organization pattern, thereby facilitating the expulsion of moist air. Significantly, the moisture regulation mechanisms of spatial morphology and the building envelope demonstrated temporal synchronization: the elevated air exchange rate during the ventilation period (10:00-16:00) accelerated wall desorption, while the reduced air exchange rate during the sealed period (20:00-06:00) enhanced wall adsorption, establishing a synergistic 24 hour moisture regulation cycle.

#### 4.2.3 Indoor Air Velocity Analysis

Zhufang New Village features a row-based layout with a spatial organization defined by a distinct north-south

axis. The typical rural house is located in the central area of the village, adjacent to a 6m wide longitudinal alley on the east, with a 3m spacing from front and rear row houses and a 1.5m spacing from the west-facing adjacent house. From an aerodynamic perspective, this layout theoretically enables effective wind-driven ventilation. The 3m wide north-south corridor can facilitate the channeling of dominant winds, while the 1.5m lateral spacing is engineered to accelerate localized airflow via the Venturi effect. However, the combined effects of meteorological conditions on the measurement day and architectural design features significantly reduced actual ventilation efficiency.

When a northeast wind (with a 10°-30° deviation angle) acted on the building cluster, the absence of openings on the windward facade (east side) disrupted the wind-pressure-driven ventilation pathway. Although the west-facing windows remained open, the 1.5m wide passage was obstructed by stored agricultural implements, creating a distinct low-velocity vortex region on the west side. This region, in conjunction with the sealed interface on the east, formed a "ventilation bottleneck." Furthermore, the functional layout of the building plan exacerbated the spatial imbalance in indoor airflow distribution. The bedroom, characterized by a deep plan layout ( $L/D=1.3$ ) and a single-sided window configuration, exhibited an air exchange efficiency of 0.8 ACH, significantly below the ASHRAE 62.1 standard threshold. Comparative analysis revealed that, under an outdoor wind speed of 2.5m/s, the bedroom exhibited a high airspeed attenuation coefficient (0.92) with an indoor velocity of 0.2m/s, whereas the living space demonstrated a significantly lower coefficient (0.45) and maintained an indoor velocity of 1.12m/s due to cross-ventilation effects. This spatial heterogeneity accounts for the coexistence of persistent low-velocity conditions in the bedroom (0.05-0.15m/s) and intermittent high-velocity episodes in the living space (peak: 1.20m/s) observed in field measurements.

Rural houses strategically adapt to indoor thermal environments through physiological adaptation, psychological comfort, and behavioral strategies[1]. For residential buildings lacking artificial heating or cooling systems, the Evaluation standard for indoor thermal environment in civil buildings (GB/T 50785) establishes an II-level thermal environment as one where  $\geq 75\%$  of occupants report satisfaction, corresponding to an indoor temperature range of 16-30°C. The indoor ambient temperature in this rural house under typical summer weather conditions complied with the II-level criteria. The living space demonstrated the most stable thermal performance, with temperatures exceeding 30°C occurring exclusively between 12:00-16:00 (peak temperature: 30.4°C). For the remaining 20 hours, temperatures remained within the II-level range, resulting in an adaptive thermal comfort compliance rate of 83.3%. This suggests that the living space maintained thermally acceptable conditions for the majority of the summer heat period, consistent with its high daytime occupancy density and frequent activity patterns.

In contrast, the second-floor spaces exhibited indoor temperatures 0.1-1.2°C higher than the II-level threshold,

with only 25% of the time falling within the “relatively comfortable” range. The suboptimal thermal environment on the second floor indicates that residents’ preference for first-floor bedrooms aligns with climatic adaptation strategies. Furthermore, calculations based on the “climate adaptation model of human thermal comfort developed by domestic scholars” demonstrate that the thermally acceptable temperature range for this typical rural house was 25.6-27.6°C.

In accordance with the GB/T 50785, the Adaptive Predicted Mean Vote (APMV) was selected as the evaluation criterion for assessing indoor thermal comfort in buildings lacking artificial heating or cooling systems. This methodology involved the calculation of the Predicted Mean Vote (PMV) according to the computational procedure specified in GB/T 50785. The indoor air temperature, relative humidity, and air velocity were measured through field surveys, whereas the mean radiant temperature was estimated as equivalent to the indoor air temperature owing to the substantial thermal mass of the building envelope.

Based on the age, daily routines, and behavioral characteristics of the permanent residents, the following thermal parameters were defined: Daytime (05:00-21:00): average clothing thermal resistance (0.45clo) and metabolic rate (1.25met); Nighttime (21:00-05:00): average clothing thermal resistance (0.35clo) and metabolic rate (0.65met). Based on these parameters, the PMV-PPD indices for each functional space were calculated and incorporated into the APMV equation:

$$APMV = PMV / (1 + \lambda \cdot PMV) \quad (1)$$

In the equation,  $\lambda$  represents the adaptive coefficient. For residential buildings in the hot-summer-cold-winter climate zone,  $\lambda$  is assigned a value of 0.21 when  $PMV \geq 0$ , and -0.49 when  $PMV < 0$ . The APMV values for each measurement point were calculated during the test period.

The results demonstrate that APMV values across measurement points ranged from 0.59 to 0.78 (minimum in the kitchen and maximum in Bedroom 5 on the second floor), with a mean value of 0.69. Specifically, first-floor spaces had a mean APMV of 0.63, while second-floor spaces exhibited 0.75, resulting in a 19% inter-floor difference ( $\Delta=0.12$ ). This phenomenon was attributed to the synergistic interaction between the attic’s thermal storage capacity and reduced vertical ventilation dynamics. The APMV values exhibited a bimodal diurnal variation pattern with one trough. The primary peak was observed at 14:00 (0.72-0.89), demonstrating a significant positive correlation with solar radiation intensity variation, thereby confirming the predominant role of radiative accumulation in daytime thermal comfort. Solar gains from the south-facing balcony, transmitted via building envelopes, induced significant thermal accumulation. Conversely, reduced thermal pressure ventilation dynamics decreased heat dissipation efficiency. A secondary peak was observed at 22:00 (0.56-0.74), reflecting the combined influence of delayed thermal mass release and increased nighttime relative humidity, which synergistically elevated perceived

temperatures. The trough reached a minimum value at 04:00 (0.35-0.46), when outdoor cooling and zero-radiation conditions led to a neutral baseline thermal environment. Notably, the thermal comfort window (02:00-05:00,  $APMV \leq 0.5$ ) exhibited a phase shift relative to the occupants’ primary activity period (05:00-21:00). This temporal mismatch may potentially affect the occupants’ actual thermal comfort experience.

The APMV values were utilized to classify and assess the indoor thermal and humidity environments at each measurement point, as summarized in Table 3. During the summer field measurement period, the II-level thermal environment ( $0.5 < APMV \leq 1$ ) predominated at all measurement points, accounting for over 60% of the total duration. This indicates that under high-temperature and high-humidity climatic conditions, the building was unable to adequately mitigate the synergistic effects of moisture and sensible heat loads, thereby intensifying thermal discomfort. Specifically, first-floor spaces exhibited an occupancy rate of 30.8-46.2% in the I-level comfort zone ( $-0.5 \leq APMV \leq 0.5$ ), while second-floor spaces demonstrated a marked decrease to 7.7-15.4%. This disparity indicates the presence of a typical stack effect, resulting from summer thermal stratification that created distinct vertical temperature gradient. Furthermore, uncontrolled solar radiation gains through the roof exacerbated the thermal conditions in the uppermost zones. Notably, during the occupants’ peak activity period (10:00-18:00), the second-floor bedrooms remained in a persistent II-level thermal state. Notably, Bedroom 5 exceeded an  $APMV > 0.8$  for seven consecutive hours (12:00-18:00), surpassing the WHO-recommended thermal exposure safety limit by four hours. This reveals the building’s inadequate thermal inertia regulation capacity and substantial passive design optimization potential.

**Table 3.** Classification and Evaluation of Summer Thermal and Humidity Environment Rating Levels for Typical Rural House.

GB/T50785 Level	First-floor APMV/%			Second-floor APMV/%		
	Hall	K.1	B.2	L.2	B.4	B.5
I	38.5	46.2	30.8	15.4	7.7	7.7
II	61.5	53.8	69.2	84.6	92.3	92.3
III	0	0	0	0	0	0

## 5. Discussion

Passive design strategies, aligned with human thermal adaptation and low-carbon principles, are critical for optimizing rural building environments. Based on the ASHRAE-55 adaptive comfort model, climate-responsive envelope improvements can achieve >80% thermal comfort compliance while reducing mechanical ventilation energy by 40-60%. However, rural houses

face three thermal challenges: (1) thermal bridging in flat-to-pitched roof transitions; (2) unstable balcony boundaries from solar-air infiltration interactions; and (3) east-wall diurnal heat flux phase lag. Optimization must prioritize reducing pitched roof heat transfer, improving balcony insulation, and enhancing east-wall thermal interfaces.

### 5.1. Reducing the Heat Transfer Coefficient of Flat-to-Pitched Roofs

As previously analyzed, the elevated thermal transmittance in typical rural pitched roofs is primarily attributable to the lack of thermal insulation layers and the ineffective implementation of ventilation air gaps. To address these issues while maintaining the low-cost enhancement objective, the following three-phase optimization approach was implemented: (1) First, a 5cm thick straw-based compressed insulation board (density  $\geq 120\text{kg/m}^3$ , thermal conductivity  $\lambda=0.07\text{W}/(\text{m}\cdot\text{K})$ ) was installed on the internal surface of the existing pitched roof. This established a sealed thermal insulation layer, effectively mitigating the thermal bridging effects associated with the flat-to-pitched roof transformation. (2) Second, a high-reflective lime-based coating was applied to the exterior surface of the pitched roof and the upper 300mm section of gable walls. This measure reduced the solar radiation absorbed by the roof by 40-50%, significantly decreasing the heat transmitted to the interior space through the roof. (3) Third, adjustable ventilation slats were added at the eaves and ridge. By utilizing the vertical height differential between the eave intake and ridge exhaust, a stable airflow was generated through buoyancy-driven pressure gradients, accelerating the dissipation of accumulated heat in the roof cavity.

### 5.2. Enhancing Thermal Insulation Performance of Balconies

To address the performance shortcomings in typical rural open exterior balconies, including linear heat transfer through cantilevered floor slabs, discontinuous enclosure interfaces, poor airtightness of doors and windows, and lack of shading design, a multi-tiered retrofit strategy was implemented: (1) First, continuous external insulation was applied to the balcony's perimeter enclosure using 50mm graphite-enhanced polystyrene (SEPS) board (thermal conductivity  $\lambda=0.033\text{W}/(\text{m}\cdot\text{K})$ ), combined with a 30mm aerogel blanket ( $\lambda=0.008\text{W}/(\text{m}\cdot\text{K})$ ) installed beneath the floor slab to mitigate thermal bridging effects. This intervention reduced the thermal transmittance values to  $0.35\text{W}/(\text{m}^2\cdot\text{K})$  for the enclosure and  $0.55\text{W}/(\text{m}^2\cdot\text{K})$  for the floor slab, respectively. (2) Second, the open balcony was retrofitted into a semi-enclosed buffer zone by installing thermally broken aluminum-framed Low-E double-glazed windows ( $U\text{-value}=1.3\text{W}/(\text{m}^2\cdot\text{K})$ ) and external adjustable shading louvers, thereby reducing summer solar heat gains entering the interior space. (3) Third, structural nodes were applied with 40mm silica

aerogel composite material ( $\lambda=0.020\text{W}/(\text{m}\cdot\text{K})$ ) to achieve a linear thermal transmittance ( $\psi$ -value)  $\leq 0.05\text{W}/(\text{m}\cdot\text{K})$ . This approach disrupted dynamic thermal transfer mechanisms, effectively reducing the magnitude of indoor-outdoor thermal exchange.

### 5.3. Enhancing the Composite Interface Design of East-Facing Walls

To mitigate the significant morning solar heat gains on the east-facing walls of typical rural houses, a hybrid interface optimization approach based on "reflective-evaporative synergistic regulation" was proposed and implemented. This system combines the dual mechanisms of high-reflectivity lime-based coatings and plant transpiration cooling to create a functional thermal interface with dynamic thermal regulation capabilities. The technical implementation consists of two sequential implementation stages: (1) First, a high-reflectivity lime-based coating was applied to the base wall surface to effectively mitigate solar radiation absorption. (2) Second, a vertical greenery module was installed adjacent to the reflective layer, forming an evaporative cooling interface. This configuration reduces the external surface temperature of the east wall and the heat flux transmitted into the interior, thereby effectively reducing indoor temperature peaks and subsequently enhancing the thermal comfort of typical rural houses.

## 6. Conclusions

(1) Field measurement data demonstrate that the average indoor air temperature in typical rural houses in the Changbei region during summer reached a mean value of  $29.9^\circ\text{C}$ , exceeding the upper threshold of the summer thermal neutrality range ( $28^\circ\text{C}$ ) specified in the Chinese standard (GB/T 50785). This suggests that the indoor thermal environment is in a non-compliant thermal condition. Furthermore, the maximum recorded temperature in upper-floor living areas reached  $31.2^\circ\text{C}$ , approaching the upper boundary of the predicted thermal adaptation threshold ( $33^\circ\text{C}$ ) according to the adaptive thermal comfort model outlined in the same standard. The coefficient of variation (CV) for indoor relative humidity across measurement points was below 5%, indicating negligible correlation between humidity and temperature parameters. The primary cause of thermal discomfort is primarily attributable to the exceedance of the thermal neutrality threshold.

(2) Data analysis reveals that the coupled interaction between building envelope performance and microclimate regulation plays a dominant role in the dynamic thermal-humidity response within indoor environments. In terms of temperature regulation, the thermal bridging effect at the roof-balcony interface contributes to significant vertical thermal stratification ( $\Delta T \geq 2.3^\circ\text{C}$ ), with a temperature range consistent with previous studies ( $\Delta T=2.0\text{-}3.0^\circ\text{C}$ ) [3]. The asymmetric heat conduction process induced by periodic solar radiation on the east wall is identified as the primary cause of abnormal indoor temperature fluctuations,

exhibiting a daily temperature range of 4.1°C. Regarding humidity regulation, the dual control mechanisms of envelope thermal inertia and spatial morphological guidance, via phase change energy storage effects and optimized airflow, maintain a dynamic equilibrium, limiting indoor relative humidity fluctuations to within ±8%.

(3) According to the GB/T 50785 level standards, the summer thermal environment in the main living area of typical rural houses falls within the acceptable range of 16-30°C for 83.3% of the monitoring period, indicating that it serves as the primary activity space for residents. However, the upper floor exhibits persistent thermal discomfort due to the combined influence of the stack effect and roof surface radiation heat gain, resulting in a temperature excess of 0.1-1.2°C above the acceptable range. This results in a compliance rate of 25% with the standard, highlighting critical performance deficiencies: (1) failure of synergistic control of sensible and latent heat loads, (2) imbalance in the vertical thermal gradient, and (3) insufficient thermal inertia of the building envelope to mitigate transient thermal fluctuations. To address these issues, it is recommended to implement climate-adaptive models (25.6-27.6°C) during renovations. This should involve reducing the thermal transmittance coefficient of sloped roofs, improving balcony insulation and thermal protection performance, and optimizing the composite interface design of east-facing walls. These measures aim to interrupt heat transfer pathways, mitigate temperature fluctuations, and enhance the synergistic control capacity of temperature and humidity, thereby achieving dual optimization of thermal comfort hours and APMV grade improvement.

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## References

1. Chen, F.Y.; Song, B.; Wu, L.; et al. Comparative Study on Indoor Thermal Environment of Three Types of Cave Dwellings and Brick Farmhouses on the Loess Plateau in Summer. *Journal of BEE*, 2024, **52**(2):73-82. doi:10.3969/j.issn.2096-9422.2024.02.011
2. T. Shao; H. Jin. A field investigation on the winter thermal comfort of residents in rural houses at different latitudes of northeast severe cold regions, China. *Journal of Building Engineering* **32** (2020) 101476. <https://doi.org/10.1016/j.jobee.2020.10147>
3. Zhao Lingxi, Ouyang Jinlong. Summer Indoor Thermal Environment Investigation and Optimized Design of Energy Saving Reform Project for New Farmhouse in Hot Summer and Cold Winter Region[J]. *Refrigeration and Air Conditioning*, 2018, **32**(6):616-622.
4. Li, X.P.; Li, J.J.; Qin, L. Study on energy saving reconstruction of the outer protective structure of residential buildings in Tongliao rural pastoral area, Inner Mongolia. *Journal of Xi'an University of Technology*, 2024, **40**(2):226-233,241. DOI:10.19322/j.cnki.issn.1006-4710.2024.02.008
5. Miao, Z.T.; Jiang, H.; Li, C.R. Energy Saving Optimization of Envelop of Existing Rural Residential Buildings in Laizhou Bay Area. *Journal of BEE*, 2021, **49**(9):114-118. doi:10.3969/j.issn.2096-9422.2021.09.018
6. Rui, J.; Zhang, H.; Shi, C.; et al. Survey on the Indoor Thermal Environment and Passive Design of Rural Residential Houses in the HSCW Zone of China. *Sustainability* 2019, **11**, 6471. doi:10.3390/su11226471
7. Jin, L.; Zhao, L.H.; Meng, Q.L.; et al. Optimization analysis on indoor thermal environment of rural residential buildings in Guangdong Province. *Journal of Civil, Architectural & Environmental Engineering*, 2015, **37**(3):116-126. doi:10.11835/j.issn.1674-4764.2015.03.016
8. J. Song; W. Wang; P. Ni; et al. Study on optimization method of summer nature ventilation for residential buildings in typical thermal zone of Xinjiang, China. *Energy Reports* **8** (2022) 181-197. <https://doi.org/10.1016/j.egy.2022.05.086>
9. Y. Li; T. Zhou; Z. Wang; et al. Environment improvement and energy saving in Chinese rural housing based on the field study of thermal adaptability. *Energy for Sustainable Development* **71** (2022) 315-329. <http://doi.org/10.1016/j.esd.2022.10.006>.
10. H. Wang; C. Shi; W. Li; et al. Field investigation on thermal environment and comfort of people in a coastal village of Qingdao (China) during winter. *Building and Environment* **191** (2021) 107585. <https://doi.org/10.1016/j.buildenv.2021.107585>
11. Zheng, W.H.; Wei, F.F.; Feng, R.Y.; et al. Measurements and Analysis of Summer Indoor Thermal Environment of Traditional Wooden Dwellings in the Mountainous Areas of Northern Guangxi. *Building Science*, 2023, **39**(12):54-60. DOI:10.13614/j.cnki.11-1962/tu.2023.12.07
12. Jin, M.; Cheng, H.F. Simulation Analysis of Indoor Air Flow in Windshield under Natural Ventilation Condition. *Building Energy & Environment*, 2019, **38**(1):61-63+79.
13. Fan, S.G.; Xu, X.H. Analysis of indoor operation temperature based on thermal comfort and thermal health for residential buildings in hot summer and cold winter zone. *HV & AC*, 2024, **54**(12):1-9. DOI: 10.19991/j. hvac1971.2024.12.01
14. Chen, C.; Ling, H.S. Comparative Study on Thermal Performance of Conventional Walls and Active-Passive Solar Phase Change Thermal Energy Storage Walls[J]. *Agricultural Engineering Technology*, 2019, **39**(04):10-15. DOI: 10.16815/j.cnki.11-5436/s.2019.04.001