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Passive Cooling Mechanisms of Natural Ventilation in Traditional Huizhou Dwellings: Insights from Thermodynamic Simulation

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ABSTRACT

In the context of global energy crises and climate change, uncovering the passive design wisdom embedded in traditional architecture holds significant relevance for the advancement of modern green building practices. Traditional Huizhou dwellings, characterized by distinctive features such as skywells and hollow walls, create pleasantly cool indoor environments during summer, primarily through passive cooling driven by natural ventilation. However, the scientific mechanisms underlying this effect remain insufficiently quantified and systematically understood. Existing studies often rely on field measurements or steady-state simulation methods—the former struggles to disentangle and quantify individual heat flux components, while the latter fails to capture dynamic, non-steady-state processes. To address this gap, this study focuses on the passive cooling mechanisms of natural ventilation in Huizhou dwellings and develops a threefold approach. First, a dynamic thermodynamic model of Huizhou dwellings was established based on the first law of thermodynamics, with carefully defined simplifications and assumptions. Second, a refined heat balance analysis was conducted under typical summer conditions, systematically quantifying seven heat gain and loss processes, including solar radiation, heat transfer through the envelope, and skywell ventilation. Finally, drawing upon this analysis, the study elucidates the working principles of natural ventilation as the dominant cooling mechanism, with particular emphasis on its spatiotemporal synergy with building thermal inertia. The main contributions of this research lie in three aspects: (1) Methodological innovation: the development of a non-steady-state thermodynamic simulation framework that integrates dynamic climate conditions with the complex thermal performance of buildings, overcoming the limitations of conventional steady-state approaches; (2) Analytical innovation: a fine-grained decomposition of seven heat balance components, enabling a quantitative evaluation of natural ventilation cooling efficiency, beyond prior qualitative or correlative descriptions; (3) Theoretical innovation: the first systematic articulation of the "ventilation-thermal mass" synergy in Huizhou dwellings from the perspective of coupled energy flows and temporal dynamics, offering new insights for the advancement of passive design theory.

1. INTRODUCTION

Under the dual challenges of the global energy crisis [1-3] and climate change [4, 5], energy saving and carbon reduction in the building sector have become a key link to achieving sustainable development [6-8]. Shifting to passive design and drawing inspiration from traditional architectural wisdom is an important direction of current building energy-saving research. Chinese traditional dwellings, especially traditional Huizhou dwellings [9, 10], are outstanding examples of regional passive design strategies. With their unique spatial layout [11], material selection [12], and structural methods [13], they create relatively comfortable and cool indoor environments during the long summer, and the realization of this performance mainly relies on natural ventilation systems without mechanical power. Revealing the scientific principles contained in this system in depth is not only an inheritance of traditional architectural culture, but also provides valuable theoretical and practical support for modern green building design and innovation.

Conducting in-depth research on the passive cooling mechanism of natural ventilation in traditional Huizhou dwellings has important theoretical and practical significance. At the theoretical level, this study aims to go beyond the qualitative description of building forms, starting from the basic principles of the first law of thermodynamics [14] and fluid mechanics [15], to quantitatively analyze the energy flow paths and dynamic balance processes of natural ventilation as the dominant cooling means, thereby upgrading the traditional "empirical wisdom" into quantifiable "scientific mechanisms". At the practical level, clarifying this mechanism helps to extract universal passive cooling design strategies

[16-18], such as how to optimize opening design to strengthen stack ventilation, and how to select envelope materials to achieve synergy between heat storage and ventilation. These strategies can be directly applied to contemporary low-energy buildings, historical building conservation and renovation, as well as the planning and design of ecological villages, and have far-reaching impacts on promoting the green transformation of the building industry.

Although many scholars have paid attention to the thermal environment and ventilation of Huizhou dwellings, the existing research methods still have certain limitations. For example, the study in reference [19] mainly relies on on-site environmental parameter testing, which provides valuable measured data, but it is difficult to fully separate and quantify heat flow components such as ventilation heat exchange and envelope heat transfer, and its conclusions mostly remain at the level of correlation analysis. The study in reference [12] adopts steady-state simulation methods to analyze the thermal insulation performance of dwellings. This method cannot capture the dynamic non-steady-state processes under the interaction between periodic solar radiation and building thermal inertia in summer, and thus it is difficult to truly reflect the timeliness of the ventilation cooling mechanism during the alternation of day and night. The shortcomings of these studies, in summary, lie in the lack of a thermodynamic model that can integrate building structure, thermal performance of materials, and dynamic climate conditions, and that can systematically and quantitatively analyze the cooling performance of natural ventilation.

This paper aims to fill the above research gap, with the core content including three parts. The first part is to construct a high-precision thermodynamic model of traditional Huizhou dwellings and clarify its reasonable assumptions, laying the foundation for quantitative simulation. The second part, based on this model, conducts an in-depth heat balance analysis of the dwellings under typical summer conditions, systematically deconstructing their heat gain and loss mechanisms from seven aspects: building heat flow, solar radiation, internal heat sources, ground heat transfer, door infiltration, skywell ventilation, and envelope heat transfer. The third part, on the basis of the first two parts, comprehensively deduces and expounds the passive cooling mechanism of natural ventilation, with emphasis on revealing the spatiotemporal synergy between ventilation airflow and building thermal performance. The value of this study lies in that, through thermodynamic simulation as an advanced tool, it realizes the leap from "phenomenon description" to "mechanism explanation" of the passive cooling performance of traditional dwellings. The proposed analytical framework and conclusions not only deepen the understanding of the scientific value of Huizhou dwellings, but also provide a reliable theoretical basis and optimization direction for future passive building design.

2. CONSTRUCTION OF THE THERMODYNAMIC MODEL OF THE DWELLING AND HEAT BALANCE ANALYSIS

2.1 Building thermodynamic model and related assumptions

In order to deeply reveal the passive cooling mechanism of natural ventilation in traditional Huizhou dwellings, this paper carefully selected a representative dwelling as the research object. This dwelling is highly typical because it centrally reflects the core spatial structure and thermodynamic characteristics of Huizhou dwellings: with the skywells as the hub, it organizes the main living spaces such as the hall and wing rooms, and integrates typical constructions such as hollow brick walls, grey tile roofs, and elevated wooden floors. The thermodynamic model constructed in this study is based on this real physical space, aiming to quantitatively analyze the complex heat and moisture exchange processes between building envelopes and natural ventilation airflow under dominant cooling conditions in summer. The core of the model is to establish a dynamic heat balance system, regarding the building as a "thermal zone" surrounded by structures with different thermal properties, and to calculate its heat gain and heat loss to deduce the key mechanism that maintains the stability of the indoor thermal environment, especially the core cooling role undertaken by natural ventilation.

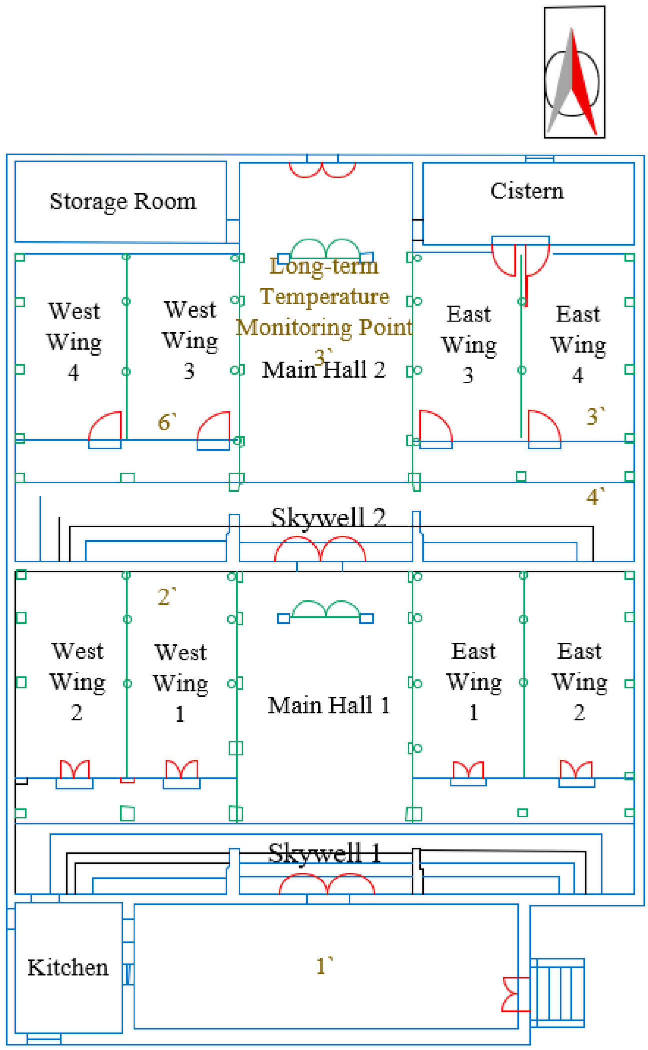


Figure 1. Building floor plan and arrangement of temperature measurement points

To ensure the computability of this complex system and the clarity of theoretical analysis, the model is established on a series of rigorously simplified assumptions. First, the model adopts a mixed calculation method to balance data availability and calculation accuracy: for external walls and ground with measured surface temperature data, an unsteady-state heat transfer indirect algorithm based on measured values is used, which can more accurately capture their heat storage and heat release dynamics; while for doors and roofs without surface temperature data, a steady-state calculation method is adopted, and its rationality lies in that the temperature fluctuations of these components are relatively small in summer. Second, the key simplifications of the model profoundly reflect the thermophysical characteristics of Huizhou dwellings: for example, the skywell is simplified into a vertical channel with an upper opening, with its core role focused on driving stack ventilation, while complex factors such as courtyard vegetation are ignored; the physical parameters of hollow brick walls and grey tile roofs are homogenized, highlighting their overall advantages of heat insulation and thermal inertia; in particular, it is assumed that the indoor air temperature is uniform, and this is taken as the basis for radiation calculation. Although this simplifies the internal radiation heat exchange, it strongly supports the core idea of regarding the space of the entire first courtyard as a "unit" for overall heat exchange under the action of ventilation. These assumptions all serve one goal: under the premise of ensuring the essential correctness of the physical process, to strip away secondary factors and focus on analyzing the passive cooling path of the collaboration between natural ventilation and building envelopes.

These model settings and assumptions closely revolve around the research target of the "passive cooling mechanism". By calculating the heat transfer of each envelope, the solar radiation heat gain, and the most critical ventilation heat exchange, the model can quantify how much heat is carried away by the ventilation airflow induced by the skywell stack effect and wind pressure effect under typical summer meteorological conditions, and can further analyze the contributions of different building components as "cold sources" or "heat sources" for ventilation airflow at different times of day and night. Finally, from the perspective of an integral energy balance, the model will reveal how Huizhou dwellings, through their unique material and spatial structure, transform natural wind, solar energy, and ground temperature into a cooling system that requires no mechanical power, is efficient, and self-regulating, thereby interpreting from the thermodynamic principle level the wisdom core of their sustainability. Figure 1 shows the building floor plan of the research object and the arrangement of temperature measurement points.

2.2 Summer heat balance analysis of the dwelling

The "passive cooling mechanism of natural ventilation" in traditional Huizhou dwellings is essentially a dynamic, multi-factor coupled process of energy flow and transformation. Studying ventilation in isolation cannot reveal its true effectiveness and working principle as a "cooling mechanism". The cooling effect of ventilation is reflected in its ability to continuously discharge excess indoor heat to the outside. Therefore, it is necessary to first clearly answer a core question: where exactly does the heat carried away by ventilation come from?

To solve this problem, this paper conducts a detailed heat balance analysis of the summer thermal environment of traditional Huizhou dwellings, in order to precisely quantify all the main sources and sinks of heat inside the building, and thereby place ventilation heat exchange at the core of the entire thermodynamic system for examination. By constructing a complete energy inventory that includes building heat flow, solar radiation, internal heat gain, ground heat transfer, door and window infiltration, and envelope heat transfer, we can trace the origin and destination of each part of heat, and finally convincingly demonstrate how, under the joint action of unique structures such as the highly insulating hollow brick walls, the heat-storing ground, and the shading and ventilating skywell, natural ventilation acts as the most critical "expenditure item" of heat, successfully offsetting various "income items" of heat, thereby achieving the dynamic balance of indoor thermal comfort.

Huizhou dwellings are not a highly sealed shell, but a complex system that actively exchanges energy with the natural environment. The hollow brick walls provide good thermal insulation performance but also have certain thermal inertia, the grey tile roof heats up sharply under solar radiation, the ground space under the elevated wooden floor provides a relatively cool contact surface, and the core skywell simultaneously plays multiple roles such as solar radiation heat gain, long-wave radiation heat dissipation, and driving ventilation. In summer, strong solar radiation becomes the main heat gain item through multiple paths such as direct solar penetration in the skywell and conduction through the roof; and the thermal inertia of the building makes the envelope continuously release heat to the indoor at night. Against this background, heat balance analysis enables us to quantify the "benefits" and "costs" of skywell ventilation: that is, while ventilation introduces outdoor air that may be slightly higher in temperature to promote air exchange, its true cooling effectiveness lies in its ability to efficiently "carry away" and discharge the accumulated radiant heat on roofs, walls, and indoor surfaces as well as the heat generated by indoor activities.

Next, this paper conducts quantitative comparison from seven aspects of heat gain and heat loss, to precisely evaluate how large a cooling share natural ventilation undertakes in the entire building thermal load, thereby empirically proving from the perspective of energy flow its core position and efficiency as a passive cooling mechanism.

(1) Heat Flow Analysis

The basic principle of building heat flow analysis in this paper is rooted in the first law of thermodynamics. In studying the summer thermal environment of traditional Huizhou dwellings, we regard the entire building space as a dynamic open thermodynamic system that exchanges energy and mass with the outside. The core feature of this system is: in the absence of active heating and cooling equipment, the formation of the indoor thermal environment is the result of the dynamic balance between various internal heat gain items and heat loss items. The passive cooling mechanism of natural ventilation is essentially the most critical and active heat loss item in this system. Therefore, the basic principle of heat flow analysis is to quantify the size and direction of each energy flow by establishing and solving the energy balance equation of this system, and thereby fundamentally reveal how natural ventilation, as a dominant regulation means, offsets the thermal load brought by other heat sources, and finally achieves indoor cooling. Specifically, this principle requires us to precisely identify and calculate all heat flow paths through the building boundaries and interior, which includes attributing system heat gain to solar radiation heat gain through skywell and envelope, internal heat release of people and equipment, and ground heat transfer, while attributing system heat loss mainly to envelope conduction, air infiltration, and the dominant heat loss item driven by the skywell—ventilation heat exchange. Finally, the system internal energy change characterized by indoor air temperature fluctuation is the expression of the algebraic sum of these heats.

In summer, strong solar radiation becomes the most important heat gain item, especially the direct and scattered radiation through the large skywell opening, as well as the heat transmitted indoors after being absorbed by the grey tile roof and hollow brick walls. At the same time, the envelope with large thermal inertia absorbs and stores heat during the day, and releases it indoors at night, which makes heat flow analysis have to consider time delay effects, rather than simple steady-state processes. And the large skywell opening directly connected to the outside, which is a disadvantage in winter, turns into a core advantage in summer. In the heat balance equation, the magnitude of the "ventilation heat exchange" term is directly determined by the skywell opening area, indoor-outdoor air density difference, and wind pressure. The basic principle of heat flow analysis is to unify all the above complex and interrelated physical processes into the framework of "heat gain" and "heat loss" for quantitative comparison. Specifically, assuming solar radiation heat gain as W_{SUN}, internal heat release as W_{INT}, ground heat transfer as $W_{h,z}$, infiltration/ventilation heat gain as W_{INF}, skywell ventilation heat gain as W_{VEN}, and envelope heat transfer heat gain as W_{CON}, then the heat flow equation is:

$$W_{SUN} + W_{INT} + W_{h,z} + W_{INF} + W_{VEN} + W_{CON} = \Delta W_{SYS} \quad (1)$$

The system increment $\triangle W_{SYS}$ on the right side of the equation can be characterized by indoor air temperature change, with "+" representing heat gain and "-" representing heat loss. Through calculation, it can be clearly demonstrated that in Huizhou dwellings, the powerful natural ventilation flow actively created by the skywell structure serves as an efficient "heat transporter", continuously discharging the solar radiation heat accumulated on roofs, walls, and indoor surfaces as well as the heat generated by internal heat sources to the outside, thereby overwhelming other heat gain items and realizing the core mechanism of passive cooling.

(2) Solar Radiation Gain

The basic principle of solar radiation gain analysis is the law of conservation of energy and the law of photothermal conversion: that is, when electromagnetic waves reach the surface of a non-transparent object, their energy will be absorbed or reflected according to the optical properties of the material. The absorbed part will be converted into the internal energy of the object, leading to a temperature rise, and then transferred to the lower temperature indoor environment through conduction, convection, and radiation. For the in-depth analysis of Huizhou traditional dwellings, it is necessary to go beyond the simplified model that regards them as homogeneous bodies, but instead refine it to different components: the grey-tile roof, due to its dark color, slope, and direct exposure to the sky, absorbs the highest intensity of solar radiation and becomes the main heat gain source, whose heat is transferred into the interior through the boarding or the air layer between purlins in a complex convection and radiation coupling way; the white lime-plastered walls of the skywell, on the other hand, have high reflectivity, reflecting most of the solar radiation and reducing their own heat gain; while the direct solar radiation penetrating the skywell opening, although less in summer due to the high solar altitude angle, still has key contributions through its scattered radiation and nighttime longwave radiation heat dissipation process. Specifically, assuming that the surface area of the transparent envelope structure is represented by X, and the solar radiation perpendicular to the transparent envelope structure is represented by U_s, the solar radiation entering the skywell can be calculated by the following formula:

$$W_{SUN} = X \cdot U_s \quad (2)$$

This analysis aims to precisely describe how the solar radiation energy received by the building exterior surface is converted into indoor heat load through different "gateways" and paths, thus laying the foundation for quantifying the core cooling load that natural ventilation needs to overcome.

(3) Internal Heat Source

The basic principle of internal heat source analysis is to regard the building interior as a thermodynamic system containing distributed heat sources, and according to the law of energy generation and conversion, all sensible heat and latent heat released by life activities and energy consumption activities indoors will be directly and immediately added to the indoor air and the surrounding surfaces. In Huizhou traditional dwellings in summer, although the internal heat source intensity was relatively low in historical periods, its action pattern has spatiotemporal distribution characteristics: during the day, human activities may be concentrated in the hall, producing local heat loads; at night, human body heat dissipation in the side rooms becomes one of the main factors for maintaining indoor temperature. Specifically in quantification, the internal heat source needs to be set as a function varying with time, with part of its heat directly heating the air through convection, and another part being absorbed by the indoor envelope structure surfaces through radiation and then slowly released. The significance of this analysis lies in clarifying the "internal disturbance" that the natural ventilation system needs to handle, that is, the ventilation airflow must be able to effectively discharge this continuously generated heat in time to prevent its accumulation indoors from causing overheating.

(4) Ground Heat Transfer

The basic principle of ground heat transfer analysis is that the earth, as a huge constant-temperature body, exchanges heat with the building ground through an unsteady-state conduction process. The soil temperature at a certain depth remains stable throughout the year, close to the local annual average temperature. In summer, this temperature is usually lower than the average outdoor daytime temperature and indoor temperature. Therefore, the sand-stone concrete floor of the hall directly in contact with the soil actually plays the role of a "natural cold source", where heat will be transferred from the higher-temperature indoor environment to the lower-temperature deep soil through the ground. Its heat transfer process follows Fourier's law of heat conduction, and due to the great thermal inertia of soil, the heat transfer has significant delay and attenuation. For the wooden floor with a raised structure in the side rooms, the principle is transformed into a complex air interlayer natural convection and radiation coupling heat exchange problem, where the 400 mm high under-floor space forms a buffer layer, and its ventilation condition determines the air temperature of this space, which in turn affects the amount of heat transfer. Specifically, assuming that the heat transfer area of the sand-stone concrete floor in the hall is represented by X, the convective heat transfer coefficient is represented by g, the ground temperature is represented by s_h, and the air temperature is represented by

s_{AIR}, then the quantitative formula for ground heat transfer is:

$$W_{h,z} = Xg\left(s_h - s_{AIR}\right) \quad (3)$$

This analysis reveals how Huizhou traditional dwellings cleverly utilize the thermal stability of the earth to provide a continuous and stable cooling contribution from the bottom of the building, forming a vertical coordination with the ventilation cooling of the skywell at the top.

(5) Heat Gain from Door Infiltration

The basic principle of heat gain from door infiltration is the theory of gap flow in fluid mechanics, driven by wind pressure and thermal pressure. The heavy wooden double doors of Huizhou dwellings cannot achieve perfect sealing and have inherent gaps. In summer, the dominant driving force is usually thermal pressure: indoor air decreases in density as it heats up and rises, forming positive pressure at the top area of the door, driving hot air to leak outward; simultaneously, negative pressure forms at the bottom area of the door, drawing in relatively cooler, denser outdoor air. This process constitutes a continuous air circulation through door gaps. In analysis, the door gaps need to be simplified and modeled, and the infiltration air volume is related to the equivalent gap area, the indoor-outdoor air density difference, and wind speed. Assuming the air specific heat at constant pressure is represented by Z_o, outdoor air density by ϑ_{qv}, infiltrated air quantity by M, outdoor temperature and indoor temperature by s_{qv} and s_v, the heat gain from door infiltration can be quantified as:

$$W_{INF} = 0.28 Z_o \vartheta_{qv} M\left(s_{qv} - s_v\right) \quad (4)$$

Assuming the length of the external door gap is m_1, the comprehensive correction coefficient l under the combined effect of wind pressure and thermal pressure, considering building shape, internal partitions, and air circulation for doors and windows of different orientations and heights, the gap airflow index of doors and windows is y, and the air infiltration per 1 meter door gap under purely wind pressure without considering orientation correction and internal partitions is M_0, then the door gap infiltration volume M can be calculated by:

$$M = M_0 m_1 l^y \quad (5)$$

Assuming the external door and window gap infiltration coefficient is x_1, the average outdoor wind speed in summer is n_0, then M_0 can be calculated by:

$$M_0 = x_1\left(\frac{\vartheta_{qv}}{2} n_0^2\right)^y \quad (6)$$

Assuming the thermal pressure coefficient is Z_e, the wind pressure difference coefficient is ΔZ_d, the orientation correction coefficient for wind-driven infiltration of cold air is v, the ratio of effective thermal pressure to effective wind pressure on doors is Z, and the height correction coefficient is Z_g, then l is calculated as:

$$l = Z_e \cdot \Delta Z_d \cdot \left(v^{1/y} + Z\right) \cdot Z_g \quad (7)$$

Assuming the centerline elevation of the external door is g, the neutral plane elevation under thermal pressure is g_c, and the temperature of the vertical shaft generating thermal pressure indoors is s'_v, then Z is calculated as:

$$Z = 70 \cdot \frac{\left(g_c - g\right)}{\Delta Z_d n_0^2 g^{0.4}} \cdot \frac{s_v^{'} - s_{qv}}{273 + s_v^{'}} \quad (8)$$

This analysis aims to quantify the heat and moisture exchange brought by this unorganized, uncontrolled infiltration ventilation. Although its ventilation volume is much smaller than the organized skywell ventilation, it serves as a “background” link in the overall building airtightness and ventilation system, and its precise consideration is crucial for constructing a complete and accurate thermal balance model.

(6) Heat Gain from Skywell Ventilation

The basic principle of skywell ventilation heat gain analysis is the macroscopic fluid mechanics law of the combined effect of thermal pressure and wind pressure. The skywell, as a large vertical channel, heats the air inside through solar radiation, reducing its density and generating upward buoyancy. This upward airflow exits at the top, while cooler air is drawn in from the rooms and openings at the bottom, forming a stable thermally driven airflow. The ventilation rate is determined by the well-known “chimney effect” formula, with core parameters being the height difference between inlet and outlet, the inlet and outlet areas, and the indoor-outdoor air density difference. Assuming the skywell volumetric airflow is M_{VEN}, air density is ϑ, air specific heat is z, outdoor temperature is s_p, and indoor temperature is s_u, then the ventilation heat transfer at the energy level is calculated by the following mass-energy balance formula:

$$W_{VEN} = M_{VEN} \vartheta z\left(s_o - s_u\right) \quad (9)$$

In typical summer conditions, the indoor-outdoor temperature difference is negative, indicating that ventilation acts as a strong heat loss term, i.e., a cooling effect. This analysis is the core of the study, directly and quantitatively revealing the equivalent power of this passive strategy as an active cooling device, which is the ultimate indicator for evaluating its mechanism efficiency.

(7) Heat Gain from Envelope Conduction

The basic principle of envelope conduction heat gain analysis is the periodic heat transfer theory under unsteady-state conduction control. Intense summer solar radiation causes the exterior surface temperature of the roof and walls to fluctuate violently with a 24-hour period, and the heat transfer into the interior is not instantaneous but is significantly influenced by the thermal inertia of the materials, manifesting as attenuated amplitude and delayed peak of temperature. For the hollow brick walls of Huizhou dwellings, the air layer in the middle provides additional thermal resistance, effectively attenuating heat flow; the heavy grey-tile roof has a large thermal capacity, capable of absorbing and storing a large amount of heat during the day, delaying its transfer to the interior, and at night, when outdoor temperature drops, dissipates heat both indoors and outdoors. Analyzing this periodic heat transfer usually requires solving a one-dimensional unsteady-state heat conduction differential equation. Specifically, assuming the heat transfer of exterior walls, roof, and doors is represented by w_{WA}, w_{RO}, and w_{DO}, then the total envelope heat transfer of the dwelling can be quantified as:

$$W_{CON} = \sum \left(w_{WA} + w_{RO} + w_{DO} \right) \tag{10}$$

Among them, a portion of the exterior wall heat transfer is exchanged with indoor air by convection w_{zp}, and another portion by radiation w_{ep} with the indoor environment. The roof and door heat transfer are both obtained using steady-state calculation:

$$w = XJ\left(s_p - s_u\right) \tag{11}$$

Here, X is the area of the roof or door, and J is the heat transfer coefficient of the roof and door. The significance of this analysis lies in revealing the strategic coordination of the envelope's thermal performance with the natural ventilation mechanism in the time dimension: thermal inertia delays part of the daytime heat load to the nighttime, when ventilation efficiency is highest, thereby greatly optimizing the overall passive cooling effect, embodying the essence of traditional architectural wisdom.

3. PASSIVE COOLING MECHANISM OF NATURAL VENTILATION IN DWELLINGS

Based on the aforementioned seven aspects of thermal balance analysis, this study further derives several core conclusions regarding the passive cooling mechanism of natural ventilation in traditional Huizhou dwellings.

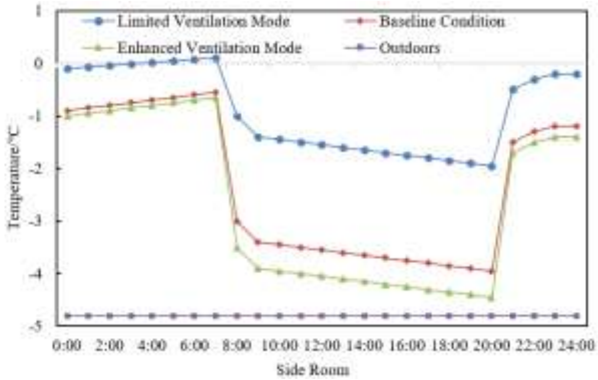
First, the passive cooling mechanism of natural ventilation does not exist in isolation, but functions as a "dominant regulatory variable" within a complex thermal system composed of heat gains and heat losses. Through quantitative analysis, we can infer that the core of this mechanism lies in "driving heat with wind". Specifically, in summer, strong solar radiation heat gain and internal heat sources are the main pressures driving indoor temperature rise. Thermal balance analysis will clearly show that the magnitude of "skywell ventilation heat gain" during most periods, especially during daytime high-temperature periods, is far greater than the sum of other heat loss terms and may even exceed the sum of all heat gain terms. This directly demonstrates that the continuous ventilation airflow generated by the skywell has sufficient capacity to timely and efficiently "flush" and expel the majority of solar radiation heat and internally generated heat entering the interior, thus maintaining indoor thermal balance and keeping the temperature significantly lower than outdoors. Furthermore, by comparing ventilation volume and thermal load at different times, we can infer the effectiveness of the ventilation mechanism: at night and in the early morning, when the outdoor environment is cooler, the ventilation air exchange volume may be slightly lower due to reduced temperature difference, but the heat carried per unit of air is highly efficient, quickly cooling the building's main structures and resetting its thermal capacity.

Second, the analysis reveals a subtle "spatiotemporal synergy" between natural ventilation and the thermal performance of building envelope structures. This is a deeper-level inference regarding dynamic regulation. The hollow brick walls and grey-tile roofs of Huizhou dwellings are not perfect insulators and have significant thermal inertia. Thermal balance analysis will show that during the day, solar radiation heat is not transmitted entirely into the interior instantly but is mostly absorbed and stored by the envelope structures, causing their temperature to rise and delaying and attenuating the heat transferred indoors. This is the essence of its wisdom: the ventilation mechanism and thermal inertia achieve temporal staggered coordination. During the day, ventilation mainly addresses instantaneous solar radiation and internal heat gains; at night, when outdoor temperature drops and ventilation efficiency increases, it not only expels indoor air heat but also accelerates the dissipation of heat accumulated in the envelope structures during the day. Meanwhile, ground heat transfer analysis may show that the floor in contact with soil acts as a stable "cold source" in summer, providing baseline cooling. Therefore, the complete cooling mechanism inference is: the building bottom provides stable cooling through ground heat transfer, the top dynamically discharges heat through skywell ventilation, and the thermal inertia of the intermediate envelope structures acts as a "peak-shaving and valley-filling" filter to smooth temperature fluctuations. These three elements form a complete passive cooling system.

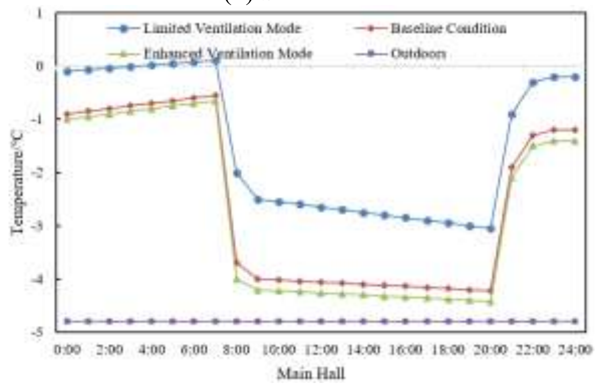
Finally, based on thermal balance analysis, the cooling mechanism of Huizhou dwellings can be summarized as a "thermodynamics-based adaptive passive climate control system". The working principle of this system is: using the skywell as the "engine", utilizing thermal pressure generated by solar radiation heating the air in the skywell as the core driving force; using building openings and gaps as "wind channels" to guide airflow along predetermined paths through main living spaces; using envelope structures with high thermal inertia as "heat storage-release buffers"; and using the cool ground as an "auxiliary cold source". The operation of the entire system is fully driven by external climatic conditions and intelligently responds through the building's own physical characteristics. The quantified data of each term in the thermal balance analysis serves to verify the energy flow status and efficiency limits of this system under different conditions, thereby scientifically explaining how this traditional architectural wisdom achieves high thermal comfort and environmental sustainability without consuming fossil energy.

4. EXPERIMENTAL RESULTS AND ANALYSIS

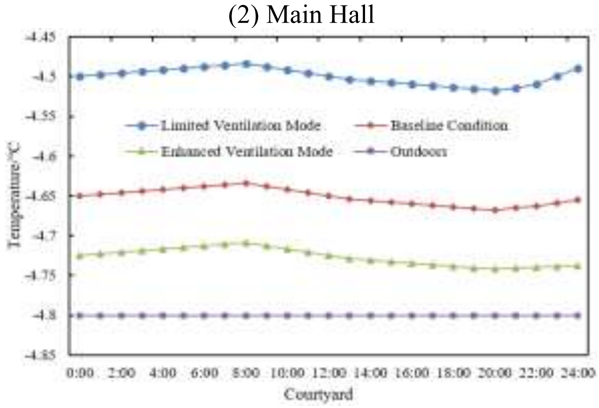
Figure 2 clearly shows the dynamic temperature responses of side rooms, the main hall, and courtyard in traditional Huizhou dwellings under different ventilation strategies on a typical day in the transitional season. Experimental results indicate that under the three conditions, there are significant differences between indoor temperature curves and outdoor temperature curves, revealing the core regulatory role of natural ventilation. Specifically, under Condition Three (restricted ventilation), the daily maximum temperatures of the side rooms and main hall reach approximately 26.5℃ and 27.8℃, respectively, about 2-3℃ higher than the concurrent outdoor temperature, and the daily temperature curves are the flattest. This indicates that with insufficient ventilation, the interior experiences significant "overheating" due to solar radiation and internal heat gains, and the building's thermal inertia becomes a disadvantage in this context. In contrast, under Condition Two (enhanced ventilation), the indoor temperature curves almost overlap with outdoor temperature curves, showing large fluctuations; the daily maximum temperatures match the outdoor peaks, but nighttime temperatures quickly drop below those of side rooms and main hall under Condition One. Condition One (baseline intermittent ventilation) presents the most ideal thermal environment: the daily maximum temperatures are effectively controlled at 25.5°C for the main hall and 24.8°C for the side rooms, lower than Condition Three, while the minimum nighttime temperatures maintain approximately 16.5°C (main hall) and 17°C (side rooms), significantly higher than Condition Two, forming the flattest and most comfortable "flat and gentle" temperature curves throughout the day.



(1) Side Room



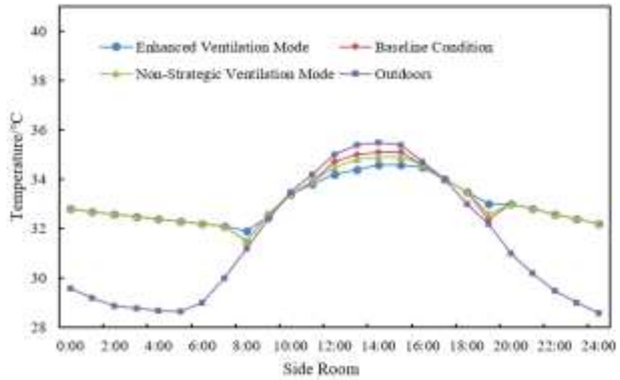
(2) Main Hall



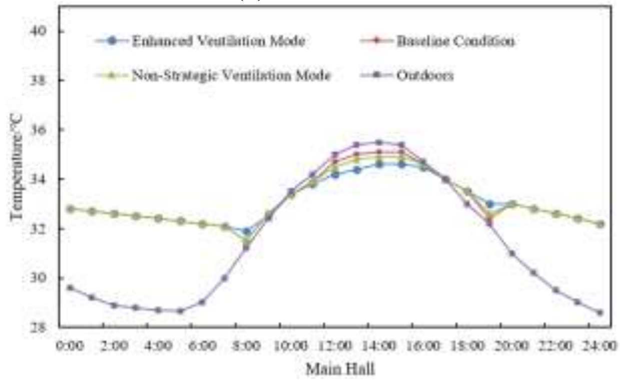
(3) Courtyard

Figure 2. Temperature comparison under different conditions on a typical day in the transitional season

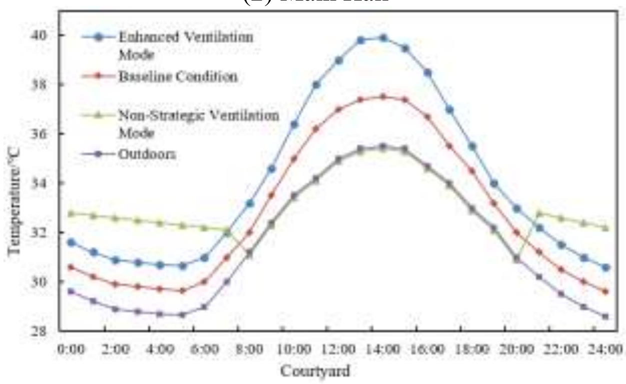
Analysis of the above experimental results indicates that the passive cooling mechanism of Huizhou traditional dwellings is essentially a precise temporal coordination between natural ventilation and building thermal inertia effects. During the day, as shown in Condition One, timely ventilation efficiently expels solar radiation heat absorbed by roofs and walls as well as heat generated by indoor activities, effectively suppressing indoor temperature spikes and avoiding overheating as seen in Condition Three. At night, when outdoor temperature decreases, moderately reduced ventilation allows heat stored in the envelope during the day to be slowly released indoors, compensating for heat loss caused by low nighttime temperatures and preventing overly rapid cooling as seen in Condition Two. This dynamic strategy of "ventilation-dominated heat discharge during the day and thermal inertia-dominated heat retention at night" embodies the essence of climate adaptability. The main hall, being directly adjacent to the skywell, exhibits more sensitive ventilation effects and greater temperature fluctuations than the relatively enclosed side rooms, further confirming the skywell's core role as the "engine" of thermally driven ventilation.



(1) Side Room



(2) Main Hall



(3) Courtyard

Figure 3. Temperature comparison under different conditions on a typical day in summer

Figure 3 provides temperature data on a typical summer day, clearly demonstrating the decisive impact of different ventilation strategies on the indoor thermal environment of traditional Huizhou dwellings. Experimental results indicate that under extreme summer heat, outdoor temperature peaks approach 38°C. The "non-strategic ventilation mode", i.e., daytime ventilation and nighttime closure, leads to the most adverse indoor conditions, with the daily maximum temperatures of side rooms and main hall approaching or even reaching 38°C, almost synchronous with outdoor high temperatures, and nighttime temperatures remain high, resulting in elevated daily temperature curves. In contrast, the "enhanced ventilation mode", i.e., optimized maximum nighttime ventilation, exhibits excellent cooling performance, successfully reducing daily maximum temperatures of side rooms and main hall to 30-32℃, 6-8℃ lower than outdoor peaks, with the flattest daily temperature curves. The "baseline condition", representing traditional wisdom, i.e., nighttime ventilation and daytime closure, shows an intermediate state, with daily maximum temperatures around 34-36℃, better than non-strategic ventilation but less effective than enhanced ventilation, indicating that traditional ventilation habits have room for optimization.

Table 1. Comparison of air temperature in different spaces under different ventilation speeds in the transitional season (Unit: ℃)

Space Location	Ventilation Speed 0.5 *m/s*	Ventilation Speed 1.0 *m/s*	Temperature Change (Δ*T*)
West Side Room	24.42	24.53	+0.11
East Side Room	24.48	24.75	+0.27
Main Hall	25.66	25.89	+0.23
Courtyard (Outdoor)	24.47	24.80	+0.33

Table 2. Comparison of air temperature in different spaces under different ventilation speeds in summer (Unit: ℃)

Space Location	Ventilation Speed 0.5 *m/s*	Ventilation Speed 1.0 *m/s*	Temperature Change (Δ*T*)
West Side Room	30.25	28.77	-1.48
East Side Room	29.76	29.36	-0.40
Main Hall	33.32	30.60	-2.72
Courtyard (Outdoor)	29.85	27.62	-2.23

Table 3. Comparison of west-facing wall and floor temperature under different ventilation speeds in summer (Unit: ℃)

Location	Ventilation Speed 0.5 *m/s*	Ventilation Speed 1.0 *m/s*
West Side Room - West Wall	33.97	30.73
Main Hall Floor	34.30	30.33

In-depth analysis of the data differences indicates that the passive cooling mechanism of Huizhou dwellings is essentially a dynamic process of precise temporal coordination between "nighttime ventilation-driven cooling" and "building thermal inertia heat retention". The success of the "enhanced ventilation mode" lies in its maximal utilization of this synergy: sufficient nighttime ventilation acts as a thorough "cold recharge" for the building, efficiently expelling heat accumulated in walls, floors, and other envelope structures during the day, lowering their temperatures to a minimum; when doors and windows are closed during the day, these pre-cooled, high thermal capacity components act as a "natural cold source", continuously absorbing heat from indoor air and effectively blocking the intrusion of outdoor high temperatures, maintaining indoor coolness. Conversely, the "non-strategic ventilation mode" completely disrupts this synergy: daytime ventilation continuously "injects" hot air indoors, while nighttime closure blocks the only heat dissipation path, causing heat to accumulate inside and within the building structure, ultimately resulting in system failure. The main hall, being directly connected to the courtyard, responds more sensitively to ventilation strategies and exhibits greater fluctuations than relatively enclosed side rooms, further confirming the courtyard's critical role as the core driving component of thermally driven ventilation.

The data in Tables 1-3 clearly reveal the core principles of the passive cooling mechanism of natural ventilation. Under high summer temperatures, increasing ventilation speed has a significant positive impact on the indoor thermal environment. The most critical finding is that the highest temperature locations experience the most pronounced cooling effect. The air temperature in the main hall decreased by 2.72℃, while the west-facing wall of the west side room, which suffers the most solar exposure, experienced a substantial surface temperature reduction of 3.24℃. This phenomenon strongly confirms that the cooling efficiency of natural ventilation is proportional to the thermal driving force, i.e., the temperature difference between indoor and outdoor air or between surfaces and air. The greater the temperature difference, the stronger the ability of ventilation to carry away heat. The main hall, due to solar radiation in the skywell acting as an air "heat source", and the west wall, due to solar radiation acting as a surface "heat source", therefore experience the most effective cooling from ventilation.

Table 4. Simulation of ventilation performance under different skywell height-to-width ratios and opening ratios (Facing South)

Skywell Design Parameters (Height-to-Width Ratio / Opening Ratio)	Winter Average Air Change Rate (ACH)	Summer Average Air Change Rate (ACH)
3.3 / 100:30	1.12	3.45
3.3 / 100:20	1.01	3.31
3.3 / 90:30	1.08	3.34
3.3 / 90:20	1.01	3.27
3.0 / 100:30	1.09	3.53
3.0 / 100:20	1.03	3.50
2.8 / 100:30	1.09	3.65
2.8 / 100:20	1.03	3.61

Further analysis indicates that this cooling mechanism results from the dynamic synergy between the thermal performance of the building structure and the ventilation airflow. In summer, the building envelope, including the west wall, roof, and floor, absorbs a large amount of solar radiation, causing surface temperatures significantly higher than indoor air temperatures. Enhanced ventilation first efficiently removes the high-temperature indoor air, lowering the air temperature in the main hall from 33.32℃ to 30.60℃. Subsequently, the lower air temperature combined with faster airflow enhances convective heat transfer with the high-temperature surfaces, effectively acting as "forced convective cooling", accelerating the removal of heat stored in the wall surfaces and significantly reducing their temperatures. This process perfectly exemplifies the wisdom of Huizhou dwellings: structures such as courtyards drive ventilation, and the airflow not only removes heat from indoor air but also actively carries away heat stored in the envelope, resetting the thermal state of the building in preparation for the next day's heat load. This study quantifies the cooling magnitude under different ventilation speeds, providing solid scientific evidence for this traditional wisdom and confirming that optimizing ventilation is a key strategy to improve summer thermal comfort in traditional dwellings.

Table 5. Simulation of ventilation performance under different skywell height-to-width ratios and opening ratios (Facing North)

Skywell Design Parameters (Height-to-Width Ratio / Opening Ratio)	Winter Average Air Change Rate (ACH)	Summer Average Air Change Rate (ACH)
3.3 / 100:30	1.07	2.21
3.3 / 100:20	1.05	2.25
3.3 / 90:30	1.05	2.20
3.3 / 90:20	1.02	2.15
3.0 / 100:30	1.09	2.27
3.0 / 100:20	1.01	2.34
2.8 / 100:30	1.10	2.31
2.8 / 100:20	1.03	2.39

Finally, the complete data in Tables 4 and 5 further reinforce and refine the design logic of the passive cooling mechanism of Huizhou traditional dwellings' skywells. The most significant conclusion remains the decisive role of building orientation. The summer air change rates of south-facing skywells, ranging from 3.27 to 3.65 ACH, are generally about 50% higher than those of north-facing skywells, ranging from 2.15 to 2.39 ACH. This quantitatively confirms the great advantage of the "north-facing back, south-facing front" layout in utilizing solar energy to drive thermally induced ventilation. South-facing skywells receive more abundant and longer-duration solar radiation, which heats the internal air to generate stronger buoyancy, forming a more efficient "chimney effect", which is the fundamental thermodynamic principle behind their passive cooling performance exceeding that of north-facing skywells.

After clarifying the dominant role of orientation, detailed analysis of geometric parameters reveals deeper patterns. For south-facing skywells, the data show that appropriately lowering the height-to-width ratio combined with larger openings achieves the best summer ventilation performance, with the 2.8/100:30 combination reaching 3.65 ACH. This indicates that a relatively "short and wide" skywell is more conducive to absorbing and storing solar energy, thereby enhancing the driving force of thermally induced ventilation. However, this pattern changes significantly for north-facing skywells: variations in height-to-width ratio have very minor effects on ventilation rates, fluctuating around 2.2 ACH, with ventilation performance more dependent on local optimizations such as opening ratios. This contrast inversely confirms that solar radiation is the core driving force of thermal ventilation: in the absence of this primary driving source, the performance improvement achievable through geometric adjustments alone is very limited.

In summary, the conclusions of this simulation experiment strongly support the core argument of the paper: the passive cooling mechanism of natural ventilation in Huizhou traditional dwellings is a highly climate-adaptive intelligent design system. Its core lies in first maximizing the use of solar energy through building orientation and then optimizing ventilation performance through fine adjustments of skywell geometry and opening ratios. This "macro-orientation priority, micro-geometry optimization" design philosophy scientifically explains how traditional dwellings, under limited technological conditions, achieve a high level of harmony with the environment, providing clear and quantifiable theoretical support for passive design in modern green buildings.

5. CONCLUSION

This study constructs a transient thermodynamic model of Huizhou traditional dwellings and conducts a detailed summer thermal balance analysis, systematically revealing the essence of their natural ventilation passive cooling mechanism. The results show that the mechanism is not a single ventilation behavior but a dynamic system in which skywell thermally driven ventilation, building thermal inertia regulation, and reasonable ventilation strategies are precisely coordinated. Specifically, the skywell acts as a "thermal engine", using solar radiation to generate strong thermally induced ventilation to effectively remove indoor heat; the thermal inertia of envelope structures such as hollow brick walls and tile roofs serves as a "thermal energy buffer", delaying and attenuating external thermal disturbances and efficiently coordinating with nighttime ventilation to achieve building "cold charging". Ultimately, by optimizing ventilation timing, this system can be regulated to achieve optimal cooling performance, keeping indoor temperatures significantly lower than outdoor temperatures during hot summer conditions. The value of this study lies in translating the traditional perceptual experience of "warm in winter, cool in summer" into quantifiable thermodynamic principles from the perspective of energy flow and temporal coupling, confirming that Huizhou dwellings are highly climate-adaptive, efficient passive buildings. They provide modern green architecture not with mere formal imitation but with deep design philosophy and optimization strategies based on thermodynamic principles.

However, this study has certain limitations. First, although the thermodynamic model necessarily simplifies the complex reality, this may slightly affect simulation accuracy. Second, the study mainly focuses on a single case under typical meteorological conditions, and the generalizability of the conclusions under climate variations in different years, broader Huizhou dwelling variants, and dynamic occupant behaviors requires further verification. Based on this, future research directions may focus on the following: conducting comparative studies across multiple cases and climate zones to verify and refine more universal design rules; advancing coupled heat and moisture simulations to more realistically reflect human thermal comfort; introducing dynamic occupant behavior models to study the impact of human-building interactions on energy-saving potential; and exploring how the parametric design strategies embedded in traditional wisdom can be integrated with modern building information modeling and performance-based design tools to achieve creative transformation and application in contemporary architectural practice.

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