Journal of Research in Science and Engineering (JRSE)
ISSN: 1656-1996 Volume-7, Issue-5, May 2025
DOI: 10.53469/jrse.2025.07(05).03

Climate-adaptive Design and Performance Optimization of Double-layer Hollow Topology Interlocking Roof Tiles

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Abstract: ***Aiming at the problems of insufficient thermal insulation performance, poor structural stability and complex installation process of traditional roof structures, a new type of double-layer hollow topological interlocking roof tile system is proposed in this study. By introducing its structure, the composite thermal insulation principle driven by thermal pressure-wind pressure coupling is revealed. Focusing on the thermal insulation performance of the double-layer hollow topological interlocking roof tile, the technical route of combining computational fluid dynamics (CFD) simulation with dynamic thermal performance simulation verification is adopted. The parametric three-dimensional model is established by Rhino, and the architectural morphology is combined with computational fluid dynamics. The Phoenics software is used to simulate the fluid dynamics of the hollow layer height (0-140 mm), and the optimal hollow layer height is determined to be 80 mm. Further combined with Ladybug + Honeybee to carry out thermal performance simulation verification, under typical summer solstice conditions, the indoor air temperature of the roof system is 21 % lower than that of the ordinary roof, which verifies the hot pressing-wind pressure composite driving mechanism. The research results provide a quantitative design basis for high-performance roof systems.***

Keywords: Roof tile, Ventilation and heat insulation, Topological interlocking, Thermal performance, Structural optimization**.**

1. Introduction

Against the backdrop of rising global building energy consumption, optimizing the thermal performance of building envelopes has become a key technical path to achieving the goal of carbon neutrality. The thermal performance of the roof, as the most significant part of the external surface of a building that receives heat from solar radiation, directly affects the overall energy consumption level of the building. Studies have shown that in hot climates, heat gain through the roof can account for 50% to 60% of the total building cooling load [1]. Therefore, optimizing the thermal performance of the roof has become an important breakthrough for reducing building energy consumption and improving indoor thermal comfort [2].

Currently, ventilated roofs have received widespread attention due to their excellent thermal performance, and the double-layer ventilated structure can effectively enhance convection heat dissipation and reduce the internal surface temperature of the roof [3], Zhou Fanwen compared the thermal performance of different roof structures and thermal insulation materials, and Liu Sheng et al. further investigated the influence of structural parameters on the dynamic thermal characteristics of double-layer ventilated pitched roofs by numerical simulation [4]. It is worth noting that the technical paths of the existing researches are obviously divided: on the one hand, a large number of results are concentrated in the traditional fields such as optimization of the thermal conductivity of materials and improvement of the thermal resistance of the sunshading layer; On the other hand, although there are individual researches on the overall structural improvement such as overhead decking or double-ply roofing, the research on the active design of structural form is still in the primary stage, especially on the basic component - the structural innovation of roof tiles. This research gap has led to obvious limitations in the existing technical solutions: although the overall structural improvement can improve thermal performance, it is often accompanied by increased construction difficulties, maintenance costs and other issues; and the entity structure of the traditional roof tiles is difficult to take into account the thermal insulation performance and structural feasibility. This contradiction is particularly prominent in high temperature and high humidity climate zones, and there is an urgent need to realize technological breakthroughs through component level innovation.

In this context, the double-layer overhead tile roofing of traditional houses in South China provides important technical insights. The 50-280 mm ventilated cavity layer formed by buckling the upper and lower tiles [5], although not able to fully utilize the thermal potential due to the traditional process, points out the direction for the structural innovation of modern roof tiles. In this study, a double-layer hollow topological interlocking roof tile construction system is innovatively proposed, combining architectural morphology and computational fluid dynamics, and the mechanism of the height of the hollow layer is investigated through the synergistic application of parametric modeling of Phoenics software and Ladybug + Honeybee thermal simulation platform, and the research results provide a quantitative design basis for high-performance roofing systems.

2. Research Basis for Double Hollow Roof Tiles

The construction practice of double-layer hollow tile roofing can be traced back to the traditional double-layer overhead tile roofing system in South China. In this system, the upper and lower tiles are stacked to form ventilated cavities with heights ranging from 50 to 280 mm (Figure 1). However, due to the lack of structural support in the traditional process, the overall thermal resistance and inertness of this type of roof are low, and there is significant room for improvement in thermal insulation performance. In modern ventilated sloped roof systems, the ventilated layer is mostly formed by the natural cavity between the parapet strips, and the airflow is introduced through gable openings or ventilation louvers, and in some cases, the air exchange is enhanced by ventilation tiles. However, this practice still stays in the relatively primitive buckling and stacking method, the cavity is formed naturally during the laying process, and its overall performance is low. Therefore, this study proposes a double-layer hollow topology interlocking roof tile system, aiming to realize the active regulation of thermal performance through the structural construction innovation.

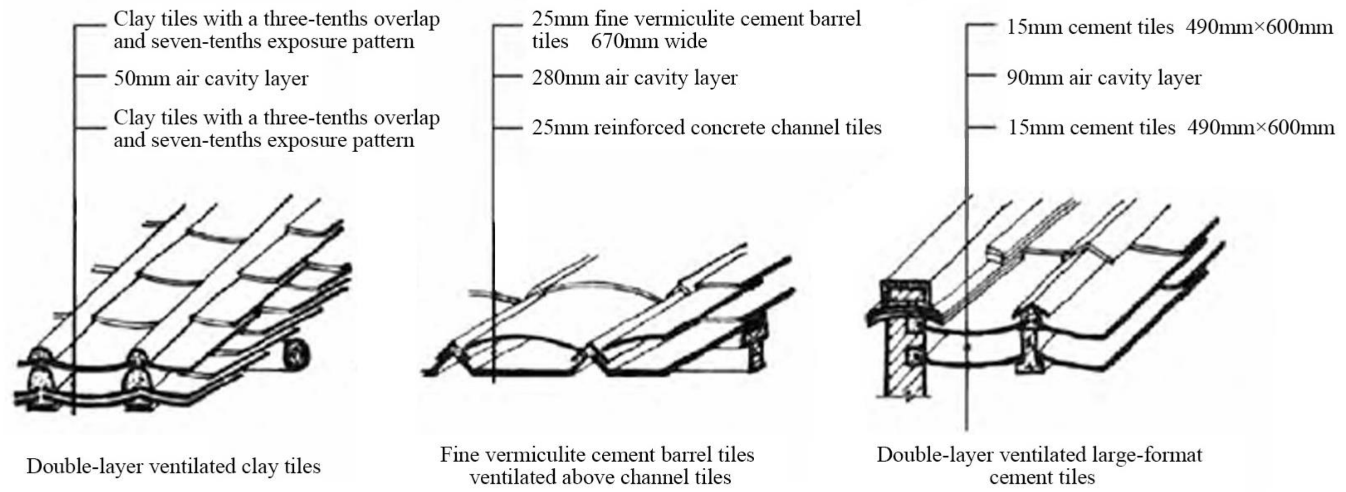

Figure 1: Conventional double-layer overhead tile roofing system

3. Structural System of Double-layer Hollow Topology Interlocking Roof Tiles

The roofing system consists of five core components (Figure 2), including ridge waterproofing vents, roof tile interlocking structure, roof tile strips, downspout strips, and roof structural base. Its structural logic is expressed as follows: the water-conducting strips are equally spaced and parallel distributed along the roof slope to form a longitudinal water-conducting channel, and the roof tile strips are orthogonally arranged to form a support grid; the roof tiles are anchored and connected to the strips through the hooks to form a three-stage bottom-to-top force-transferring system (base layer → water-conducting strips → roof tile strips → roof tiles). The structural unit of a single roof tile contains an upper plate, a lower plate, a hollow layer, a connecting column and a hook (Figure 3), in which the double-layer plate forms a precision-controlled hollow layer through the connecting column, and an interlocking structure is set up around the perimeter to form a continuous coverage with the neighboring tiles (Figure 3).

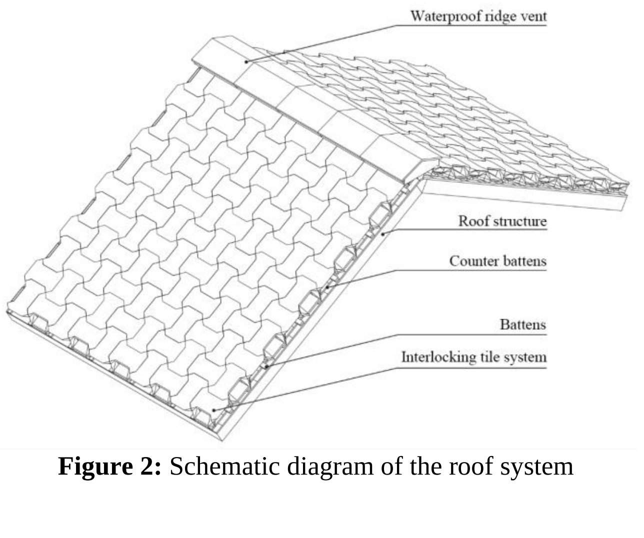

Figure 2: Schematic diagram of the roof system

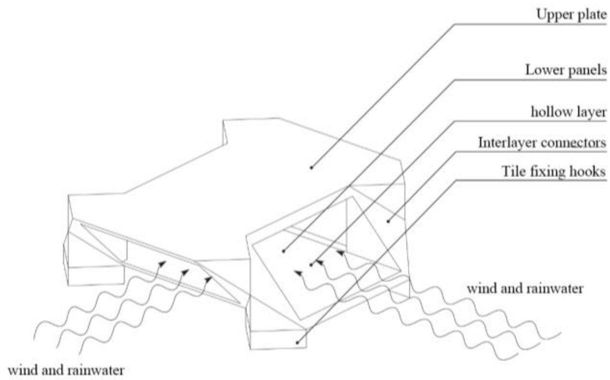

Figure 3: Structural double-layer hollow topology interlocking roof tiles

The core innovation of the system is in reflected three aspects: 1) double-layer plate synergistic construction: the rigid connection of upper and lower plates is established through connecting columns, forming precisely adjustable geometric parameters of the hollow layer; 2) composite interlocking mechanism: the dual locking system of dovetail and spring clamp is adopted to ensure the structural stability while realizing the climate-responsive construction; 3) modular integrated design: the standardized interface between the hooks and the supporting system is designed to take into account the industrial production and on-site construction efficiency.

3.1 Upper Plate

As the outer covering of the roof, the upper layer of the board assumes the functions of sun shading, rain protection and partial heat insulation. The upper plate is composed of lightweight non-transparent materials, such as steel sheet iron, thin earth tiles, tile tiles, etc., which is characterized by high reflectivity of the outer surface, which can effectively reduce the outer surface of the solar radiation heat gain, and due to its poor thermal storage properties, the thermal response time of the upper plate is shorter, and when the intensity of the solar radiation is gradually increased, it can also synchronize the warming of the ventilation layer of the upper side of the airflow, thus enhancing the role of the cavity heat pressure, increase the cavity airflow flow and take away more heat. In order to avoid the high temperature rise of the upper plate to the lower plate and the roof to produce a large thermal radiation effect, you can set up a radiation barrier on the lower surface of the upper plate, such as aluminum foil, in order to reduce the heat gain [6].

3.2 Hollow Layer

The hollow layer serves as a ventilation layer and plays the role of forming a heat-insulating barrier to reduce heat transfer. The airflow enters from the hollow part and carries away the heat from the roof surface, and flows out from the ridge, effectively releasing the heat from the roof surface to the outside world and enhancing the thermal insulation performance of the roof.

3.3 Lower Panels

The lower panel serves as the load-bearing layer of the roof and as an inner thermal barrier. It has excellent load-bearing capacity and corrosion resistance. It not only has to bear the weight of the tiles themselves and the external forces that may be applied, but also ensures the stability and safety of the roof structure. At the same time, the underlayment also provides a certain degree of thermal insulation to further minimize the transfer of heat to the interior.

3.4 Interlocking Structure

The topological interlocking structure realizes close connection and locking between roof panel elements through precise geometrical matching, which improves the overall structural strength of the roof. The interlocking structure effectively disperses stresses under external forces such as wind pressure and snow load, ensuring the safety and stability of the roof structure. In the x - y plane, the interlocking structure has a unique geometry with the lower surface of the hook facing inward and the upper surface facing outward. From the x-axis, the hook extends along the length of the roof slope, with the inward-facing part of the hook fitting tightly into the substructure to form a relatively closed interlocking space, and the outward-facing part of the hook making effective contact with the superstructure sheet or other covering materials. Observed from the y-axis direction, the hanging tile hook has a certain width, and the part of the lower surface facing inward can be embedded corresponding to of the lower structure in this direction in the slot to enhance the lateral connection stability. When the weight of the sheet is applied to the hook, the gravity of the sheet can be evenly distributed on the upper surface of the hook. Then, through the structure of the shingle hook itself, the force is conducted downward along the main part of the shingle hook. Because the lower surface of the hook faces inward and interlocks with the substructure, this portion of the structure is able to efficiently transfer the force to the substrate or the main structure of the building.

4. Thermal Performance Influencing Factors and Research Hypotheses

4.1 Principle of Ventilation and Thermal Insulation of Double-layer Hollow Topological Interlocking Roof Tiles

The thermal insulation efficiency of double-layer hollow tile originates from the heat pressure - wind pressure composite driving mechanism, when the solar radiation acts on the upper plate, its surface temperature rises rapidly and heats the air at the top of the cavity, and the resulting thermal pressure difference drives the airflow in the cavity from the eave to the ridge. At the same time, the external wind field forms positive and negative pressure zones on the building surface, accelerating the air replacement in the interlayer through wind pressure. The wind pressure and thermal pressure action will continuously take away the hot air in the hollow layer, lowering the peak internal surface temperature by up to 7.2°C compared with the traditional solid tile roof, and significantly weakening the heat flow transfer [7].

The air flow rate of the is a key parameter affecting the thermal insulation effect, hollow layer in the case of the same area of the roof receiving solar radiation, the faster the wind speed of the hollow layer, the more heat is taken away from the roof. And the size of wind speed and the height of the hollow layer (H) has a close relationship, experimental data show that, with the increase of the height of the, the thermal insulation effect is a rising trend, but more than a certain value, the thermal insulation effect has risen insignificantly, while the cost and load but continued to increasehollow layer [8]. Therefore, by changing the height of the interlayer to study the wind speed in the interlayer, it is possible to know the effect of the tile on the thermal insulation of the roof. This study will analyze and calculate the appropriate through an effective method layer height of the to achieve the best thermal insulation effect and can control the cost to achieve the goal of energy efficiency in the building interlayer.

4.2 Factors Affecting the Thermal Performance of Roofs

The thermal performance of the roof is related to many factors, which mainly include material properties (such as thermal conductivity, emissivity, etc.), environmental parameters (such as wind speed, solar radiation intensity, etc.) and structural parameters (such as roof inclination, interlayer height, etc.). These factors are intertwined and together determine the performance of the roof in response to the external thermal environment. For example, the thermal conductivity of the material directly affects the conduction velocity of heat in the roof, and the solar radiation intensity determines the amount of heat absorbed by the roof. The structural parameters such as roof inclination and interlayer height will affect the ventilation effect, which in turn affects the thermal insulation performance of the roof.

This study focuses on the problem of optimizing the height of the hollow layer in the tectonic features of double hollow tiles. Although the roof length and roof pitch angle have some influence on the ventilation thermal performance, and there are different inter-air layer thicknesses for double-ply roofs with different roof lengths, the double-ply hollow tiles proposed in this study follow a certain modulus criterion in design. This means that does not need to produce diverse samples for different situations, but is committed to seeking a universal thickness of the inter-air layer to meet the thermal insulation needs in practical applications. Based on this, after considering various factors such as production feasibility, thermal insulation performance expectation and cost budget, selected the thickness of both to be upper and lower layers 10mm, the horizontal inclination angle of the roof to be 35° [9], and through the combination of theoretical analysis and experimental testing, the mechanism of the height of the inter-air layer on the regulation of the thermal insulation performance was explored in depth.

4.3 Research Hypothesis and Significance

Based on the above analysis, the following hypotheses are put forward in this study: 1) the topological interlocking structure can improve the ventilation efficiency through structured cavities, which has significant performance advantages compared with the traditional buckled roof; 2) there exists an optimal value domain of the height of the hollow layer, which can realize the optimal balance between the thermal insulation performance and the construction cost. The subsequent research will focus on these assumptions, establish the quantitative relationship between key structural parameters and thermal performance through numerical simulation, and provide theoretical basis for the engineering application of the new roofing system.

5. Experimental

5.1 Experimental Conceptualization

Based on the composite driving mechanism of heat pressure and wind pressure, this study adopted a hybrid research method to verify the quantitative relationship between the height (H) of the hollow layer and the thermal insulation performance. The experimental design focused on the thermal insulation performance of double-layer hollow topology interlocking roof tiles, and employed a technical route combining computational fluid dynamics (CFD) simulation with dynamic thermal performance simulation verification.

First, the parametric volume model of the building was established in Rhino. Second, wind environment simulation analysis was conducted using Phoenics software for buildings with different hollow layer heights, comparing the wind speeds at the eave, mid-roof, and ridge to determine appropriate hollow layer heights. Finally, the thermal performance of the roofing system was verified using the Ladybug + Honeybee platform with typical meteorological data from Haikou area under non-air-conditioned conditions.

The experimental procedure followed a three-step progressive structure: "geometric modeling - wind environment simulation - thermal verification".

5.2 Experimental Platform Construction

The experimental platform consisted of three major modules: 3D modeling, fluid dynamics simulation, and thermal performance verification. Rhino was used to construct the physical model, while Phoenics and Ladybug + Honeybee were employed to establish the simulation platform for the built environment. Rhino was a NURBS-based 3D modeling software that could quickly create complex geometries. Phoenics software (Parabolic Hyperbolic Or Elliptic Numerical Integration Code Series) was a powerful Computational Fluid Dynamics (CFD) simulation tool that simulated the flow field of buildings. Ladybug + Honeybee were two open-source plug-ins for building environment analysis, which could be used in Rhino software to perform simulation experiments including solar radiation analysis, sunshine duration calculations, energy consumption simulation, and related tests.

5.3 Experimental Condition Setting

Haikou City, Hainan Province, a habitable hot city, was selected as the study site. Haikou city is located in the hot and rainy tropical monsoon climate zone, with hot and humid summers, warm and dry winters, and abundant precipitation throughout the year, which is concentrated in summer. Haikou area has a large solar altitude angle and strong radiation, and the thermal insulation performance of the roof is particularly important to the overall thermal insulation performance of the building. In order to avoid the interference of site shape and site environment, these two are not set for the time being, and only the meteorological parameters of Haikou City are determined for horizontal comparison.

5.4 Physical Modeling

In order to simplify the calculation, the whole building is simplified as a rectangular block when modeling, and the building elevation is always consistent. In rhino to establish the main model of the building, north-south orientation, the model is 3m long, 6m wide, 6m high; The roof adopts a double-layer hollow topology interlocking roof tiles structural system, the size of the roof tile unit is 350×250mm, the upper and lower layers of the plate thickness are 10mm, the height of the hollow layer is incremented according to a gradient of 20mm (20-140mm), and the connecting columns have a diameter of 40mm, whose height is the same as the height of the hollow layer.

5.5 Wind Environment Simulation Analysis

In view of the limitations of wind tunnel tests in terms of long cycle time and high cost, CFD numerical simulation method is used in this study.

5.5.1 Calculation Parameterization

The wind field is calculated according to the following principles: the height of the calculation area is 3 times the height of the building and the width of the calculation area is 6 times the width of the building [7]. The height of the calculation area is 18 m, and the width of the calculation area is 18 m. In this study, the boundary conditions are set based on the dominant summer winds in Haikou. In this study, the boundary conditions are set based on the dominant summer wind direction in the Haikou area: south wind 10 m/s, material option is set to 1.013×105 Pa, the ambient temperature is taken to be 35℃, the direction of gravity is -9.8 m2/s in the Z-direction, and the flow type is selected to be turbulent type (turbulent type). The mesh was chosen to be freely divided. The turbulence model was chosen as K-E (k-ε two-equation model), and the number of iterations was chosen as 1500 times.The aerodynamic flow patterns obtained from the computational fluid dynamics (CFD) simulation are visualized in the Figure.

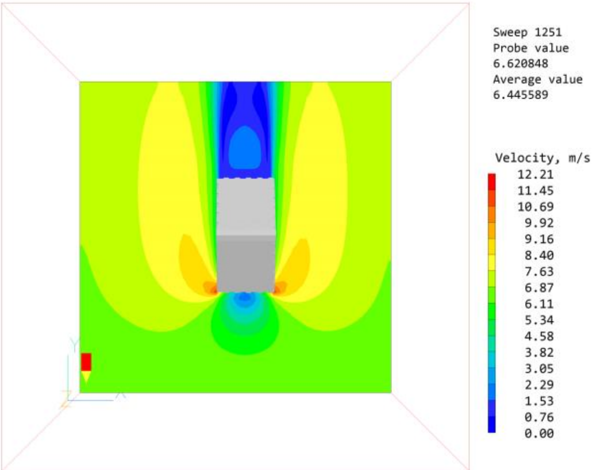

Figure 4: Ground-level wind flow field with 80mm hollow layer

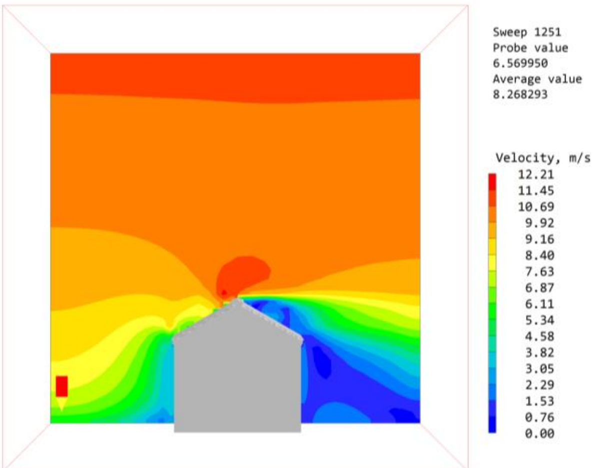

Figure 5: Cross-sectional wind flow field with 80mm hollow layer

5.5.2 Wind Environment Simulation Results

The results simulation show (Figure 6) that the height of the hollow layer shows a significant gradient effect on the flow field of the roof. The difference of wind speed at the eaves of is not significant, the wind speed at the middle section of the roof and the ridge of the roof shows the trend of increasing and then decreasing with the value of H, and the inflection point appears uniformly at H=80mm, when H=80mm, the maximum wind speed peaks at the ridge of the roof at 9.596m/s, and the maximum wind speed at the middle section of the roof at 8.994m/s. Therefore, the maximum wind speed is found at the height of the height of the hollow hollow layer of when the layer is 80mm, and it carries away the most, and its. heatinsulation effect is verified subsequently through the heat engineering simulation The heat insulation effect is verified by thermal simulation.

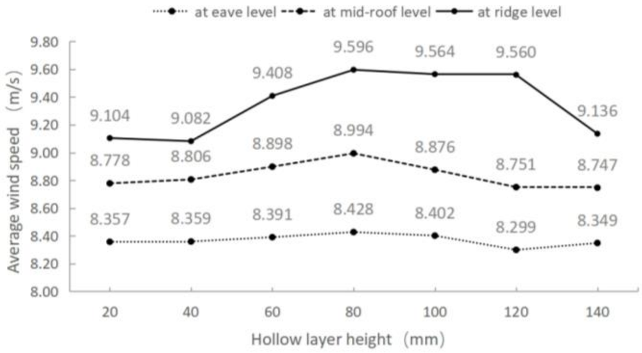

Figure 6: Correspondence between the height of the hollow floor and the wind speed on the roof

5.6 Thermal Simulation Verification

5.6.1 Calculation Parameterization

The main model roof is a structural system of double-layer hollow topological interlocking roof tiles with a hollow layer height of 80 mm, and the control model is a single-layer roof. In order to compare the thermal insulation and energy saving effects of different roof forms under the same conditions, to simplify the model and to eliminate the interference of other factors, it is assumed that the building is airtight and the infiltration rate is set to 0 times/h, during which there is no natural or mechanical ventilation. The two building models keep the same parameters except for the different roof structure forms. The meteorological data are typical meteorological data from Energyplus website, and 8:00 to 17:00 on the summer solstice of Haikou City (June 21) is selected as the time domain for the simulation.

5.6.2 Thermal Simulation Results

In order to study the thermal performance of the roof, the day-by-day average air temperature values of the external surface of the roof and the interior under the no air conditioning condition were simulated, and the results are shown in the following figure. From the figure, it can be seen that the temperature of the building's external envelope does not differ much, with a temperature of 27.1°C, while the average indoor air temperature decreases significantly, from 25.90°C to 20.41°C, with a decrease of 21%, realizing an excellent thermal insulation effect (Figure 7).

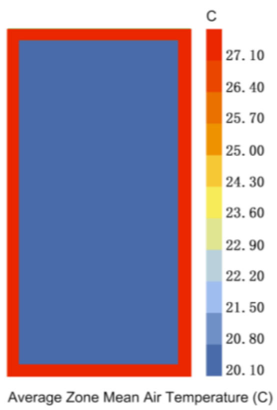

Figure 7: Mean indoor in the air temperature main model

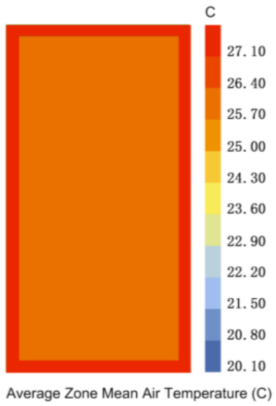

Figure 8: Mean indoor in the air temperature control model

6. Summary and Outlook

In this study, a double-layer hollow topological interlocking roof tile construction system is innovatively proposed, and the climate response mechanism and thermodynamic optimization path of this construction are revealed through a hybrid experimental method of CFD ventilation simulation and dynamic thermal performance verification, and the main conclusions are as follows: 1) Ventilation-insulation synergistic mechanism: there is a critical threshold effect of the height of the hollow layer (H) on the ventilation performance of the roof. When H=80mm, the wind speed at the ridge reaches a peak value of 9.596m/s, forming the optimal chimney effect and convective heat dissipation efficiency, and this parameter can be used as a benchmark value for the design of similar roofs in tropical regions. of the roof tiles 2) Thermal performance advantage: under typical high-temperature day conditions, the optimized roof system can reduce the average indoor air temperature by 21% compared with the traditional roof system, which verifies the multiple barrier effect of the structure on solar radiation heat.

However, this study still has certain limitations, future research can be deepened in the following aspects: 1) climate region limitations: the study of Hainan Island tropical monsoon climate as a single object does not cover the continental climate, Mediterranean climate and other climatic zones such as the radiation intensity spectrum and temperature and humidity of the combination of conditions, which may affect the universality of the design parameters; 2) time dimension singularity: the thermal simulation of the summer solstice using a typical weather data, which fails to reveal the performance fluctuation pattern during the rainy season, extreme high temperature week, etc., and needs to be verified by the dynamic coupling simulation throughout the year; 3) Dynamic Coupling Deficiency: Current research adopts staged CFD and thermal simulations conducted independently, failing to implement real-time coupled computation of ventilation-heat transfer processes. This decoupled approach may underestimate the nonlinear effects arising from their synergistic interactions.

Funding

This research was supported by the Hebei Provincial Department of Housing and Urban-Rural Development Construction Science and Technology Research Project "Research and Application of Non-Standard Module Interlocking Assembled Building Technology" (Project No.: 2024-2032).

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