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Indoor Thermal Environment and Energy-Saving Design of Existing Rural Residences in Hohhot Region

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Abstract: China is presently undergoing a transition in urban development, aiming to facilitate the high-quality advancement of urban buildings during the renewal phase. In this regard, this paper focuses on the existing rural residences in the suburban areas of Hohhot, Inner Mongolia, conducting field surveys and categorizing them into three types based on their structural forms, construction materials, and spatial layouts. Spatial form simulation analysis is then carried out to explore the differences in indoor thermal environments and energy consumption among different types of residences.

1. Introduction

Song Chunhua, former Vice Minister of the Ministry of Construction and former Chairman of the Architectural Society of China, clearly pointed out that urban renewal is part of the "Carbon Peaking and Carbon Neutrality" project, and energy consumption is an important aspect of urban living environment construction. Currently, China's urban development has shifted from extensive development characterized by large-scale new districts and new towns to intensive development focusing on the improvement of existing urban areas within the city boundaries. Therefore, this paper takes the existing rural residences in the Hohhot region as the research object, exploring the differences in energy consumption and thermal performance among different types, aiming to provide insights for the renovation and improvement of buildings at the urban boundary.

2. Existing Types of Rural Residences in the Hohhot Region

2.1 Civil Engineering Structures

Before the 1990s, civil engineering structures were the main form of rural residences in the Hohhot region. This type of residence exhibits characteristics such as poor durability, susceptibility to deformation, vulnerability to moisture, and small volume. Against the backdrop of relatively scarce resources, local residents creatively utilized local resources, demonstrating their ability to adapt to and modify the natural environment. Therefore the civil engineering structures in this region carry unique regional characteristics and historical value.

These residences primarily consist of wooden frames as the main structural components, with adobe brick walls serving as maintenance components. Due to limitations in construction materials, the spatial layout generally satisfies only basic functional needs. This approach avoids excessive reliance on timber resources while providing users with a more comfortable living experience.

In terms of architectural form design, iterative experimentation, informed by past experience, has led to the development of relatively optimal residential forms. Typically featuring a single-slope roof, this architectural form can enlarge the area of sunlight exposure and increase indoor heating during winter. Moreover, by utilizing the air cavity structure between the single-slope roof and the interior space, the release of heat from the temporal space is delayed, providing longer auxiliary heating during the night. Additionally, it exhibits excellent heat insulation effects in summer, achieving efficient energy utilization and indoor environment optimization.

2.2 Brick-Wood Structures

In the early 1990s, brick-wood structures began to see widespread adoption. With the comprehensive implementation of the household responsibility system for collective farming and the continuous release of reform dividends, rural economies embraced unprecedented development opportunities. Policy incentives spurred the rapid development of the private economy, providing relatively ample material resources for local construction. As rural incomes steadily increased, the demand for better housing conditions among farmers gradually rose, triggering a wave of residential construction in rural areas.

Brick-wood structure residences utilize walls constructed of clay bricks and wooden purlins as the main supporting components, characterized by vertical load-bearing walls directly supported by purlins. This type of residence not only reduces reliance on large-sized timber but also enhances the stability and reliability of the structure. Some residences adopt steel purlins, while the roof employs lightweight sandwich color steel plates. In terms of spatial layout, to ensure sufficient daylight and illumination indoors, some residences install tall windows on the northern side to enhance lighting and ventilation.

Regarding architectural form design, the form factor is similar to civil engineering structures. A notable change with increased depth is the transformation of the roof from a single slope to a "gabled" slope. This alteration aims to meet the depth requirements while extending the south-facing sloping roof as much as possible to enlarge the coverage area of sunlight exposure. The underlying principle behind this alteration still adheres to the form of civil engineering structure residences.

2.3 Brick-Concrete Structures

At the beginning of this century, brick-concrete structure residences gradually gained popularity. Against the backdrop of rapid urbanization[1], the urban-rural gap and disparities between villages have become increasingly pronounced. The outflow of population and aging trends have become increasingly severe, with many families leasing their farmland to agricultural enterprises or companies, collecting rent themselves. Rural areas are gradually tilting towards non-agricultural activities, and there is a noticeable increase in demand among farmers for improved comfort and functionality of residences.

Brick-concrete structure walls primarily consist of clay bricks or blocks, with roofs made of prefabricated concrete slabs or cast-in-place concrete slabs, which are currently the main structural forms used in new residential construction. In terms of spatial layout, the floor plan is more flexible, and interior space functions are increasingly improved, essentially meeting various functional needs in daily life, and tending towards standardized spatial layouts similar to urban areas.

In terms of architectural form design, simplicity becomes paramount, with notable deviations from both civil engineering structures and brick-wood structures evident in the form factor. With the widespread use of high molecular polymer insulation materials such as polystyrene and polyurethane, channels for heat transfer are effectively reduced, thereby enhancing the building's thermal insulation performance. Flat roofs increase construction efficiency, reduce building costs, and maintenance costs, gradually replacing traditional sloped roofs in the locality.

3. Spatial Form Simulation Analysis

This study focuses on the rural residential forms in the suburbs of Hohhot, Inner Mongolia Autonomous Region, aiming to explore the differences in energy consumption among different types of residences in the same area. Ladybug Tools is employed for analysis, investigating the relationship between six different types of rural residences and the environment to optimize building design and enhance energy efficiency.

In this research, parameterized models are primarily established using Grasshopper, with material assignment, importing of building occupancy schedules, and placement of sensor points executed through Honeybee. HB-Energy is then utilized to compute the energy consumption required. Finally, simulation data is inputted into Ladybug for visual analysis of temperature, humidity, comfort, and other factors. Based on the spatial forms of traditional rural residences in Hohhot, basic models of different types of residences are extracted separately.

3.1 Basic Architectural Models

In this simulation, factors affecting energy consumption are explored by controlling volume, and the relationship between mean radiant temperature (MRT) and predicted mean vote (PMV) is investigated by controlling the number and area of doors and windows. Therefore, the simulated houses have the same base and height, with windows facing the same direction. The floor plan is divided into two types: equally divided binary and unequally divided ternary. The roof forms include single-slope, flat, and gabled roofs.

3.2 Experimental Procedure

3.2.1 Meteorological Data

Meteorological data are crucial foundational data for simulating building wind, light, and thermal environments. In this study, meteorological data files for Hohhot are downloaded through Ladybug Tools EPW Map. The files contain various data formats including Energy Plus weather files (.epw), standard design day weather files (.ddy), weather statistics files (.stat), Daysim weather files (.wea), precipitation files (.rain), and others.

3.3.2 Model Establishment

(1) Parameterized models are established based on the condition data, distinguishing between internal and external walls in Honeybee. Doors and windows are defined, and shading is applied. Weather data are imported into the simulation environment, and the HB-MODEL is used to progressively approximate the real building to obtain accurate simulation results.(Figure 1).

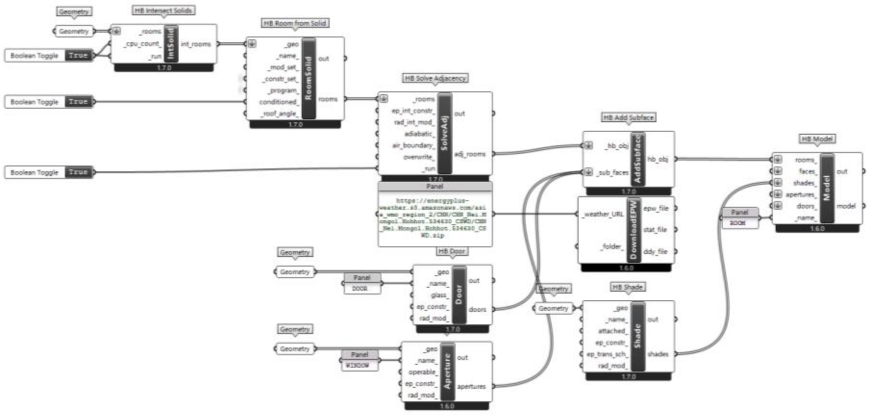

Figure 1: Process of establishing the Honeybee model

(2) Setting the physical properties of the building. When inputting the thermal resistance of the building envelope, the formula used is: K=1/∑R. However, when calculating different parts, besides the issues related to the materials themselves, there are also environmental factors to consider. Therefore, a modified formula is adopted here: K=1/(0.15+∑R) for calculating the thermal resistance of external walls, and K=1/(0.22+∑R) for calculating the thermal resistance of internal walls to further reduce simulation errors.(Figure 2).

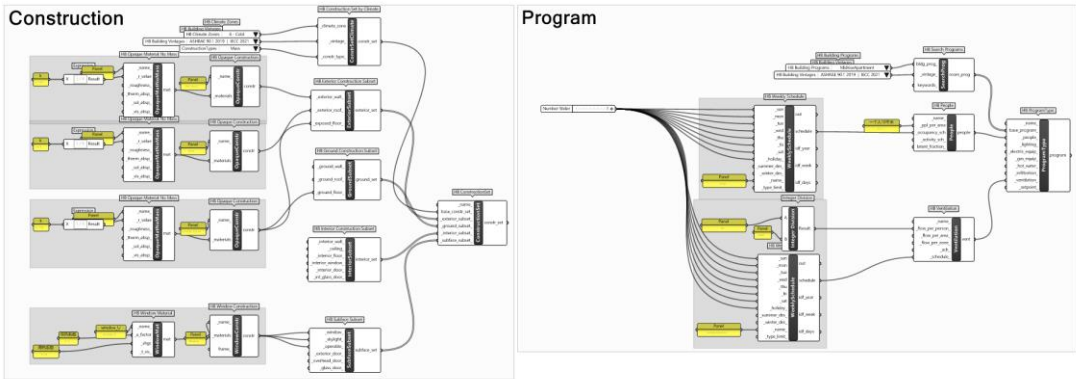

Figure 2: Setting building parameters and simulation parameters

(3) Setting occupancy data, since the tested building is a residential dwelling, continuous ventilation is set throughout the day. The occupancy density is set to 0.1 people/m² and the utilization rate is set to full-day usage.

3.3.3 Setting Simulation Period

To comprehensively study the energy consumption of the building throughout the year, this study will calculate the energy consumption for the coldest and hottest weeks in Hohhot separately. As previously noted, analysis of the annual dry bulb temperature distribution in Hohhot determines the coldest week to be from January 11th to January 17th, and the hottest week to be from June 19th to June 25th.

This study simulation is divided into two parts, the first part calculates the energy consumption generated by the actual use of the building during the temperature peak weeks, and the other part estimates the required loads for heating, cooling, lighting, and electricity throughout the year. The former is more accurate for analyzing overall energy consumption changes, while the latter has a longer time frame and is used to identify patterns of energy consumption changes.

4. Spatial Form Simulation Results

4.1 Analysis of Energy Consumption Results

In this study, the energy use intensity of the buildings is converted into the standard unit of $kWh/m^2/yr$, and the total energy consumption is measured in kWh.

By comparing the conditions, it is evident that the energy consumption produced by the single-slope roof during the coldest week is significantly higher than the other two roof types[2], with the flat roof being intermediate and the gabled roof having the lowest energy consumption. Regardless of changes in the floor plan, the same pattern exists, and the energy consumption of the equally divided floor plan is consistently lower than that of the unequally divided floor plan.

During the hottest week, the energy consumption for the six conditions shows little difference. Therefore, it can be inferred that residential energy consumption in the research area during the summer months is not significantly affected by spatial form.[3]

Energy consumption increases month by month before and after the hottest month (June), reaching its peak in the coldest month. Therefore, energy-saving measures in the research area should primarily focus on cold months, especially considering the significant energy consumption for heating.

Another observation made during the study is that, for Conditions 1, 2, and 3 (i.e., the equally divided floor plan), the heating energy consumption for rooms on the west side is higher than those on the east side. However, for Conditions 4, 5, and 6 (i.e., the unequally divided floor plan), the heating energy consumption for rooms on the west side is lower than those on the east side.[4]

4.2 Analysis of Indoor Environmental Evaluation Results

The figures below show the statistical graphs of the standard effective temperature (SET) and the thermal comfort percentage (TCP) for the six conditions. Combining the data, it is found that during the coldest week, the gabled roof provides the highest comfort level, while during the hottest week, the flat roof with the unequally divided floor plan offers the highest comfort level. However, there is not a significant difference between them. Overall, throughout the year, the comfort percentage for houses with an equally divided floor plan is lower than those with an unequally divided floor plan.

The specific spatial distribution of MRT and TCP is shown in the table below. Both MRT and TCP are greatly influenced by doors, windows, and internal walls. In the simulation report for the coldest week, the temperature around the windows gradually decreases, while the comfort level gradually increases.

As mentioned earlier, in houses with an equally divided floor plan, the energy consumption is higher on the west side than on the east side. In houses with a floor plan divided into thirds, the energy consumption is lower on the west side than on the east side. Additionally, it is worth noting that in houses with an equally divided floor plan, the comfort level is higher on the west side than on the east side, whereas in houses with a floor plan divided into thirds, the comfort level is lower on the west side than on the east side.[5]

5. Conclusion

Through the analysis and comparison of energy consumption and comfort levels of three different types of buildings in Hohhot, it is found that in terms of spatial energy consumption, the gabled roof performs better than the single-slope roof and flat roof, with the single-slope roof having the highest energy consumption. Spatial partitioning increases energy consumption, but its impact is lower than that of roof form changes. In the analysis of indoor comfort evaluation results, the gabled roof also exhibits the best performance, followed by the flat roof, while the single-slope roof has the lowest comfort level. Additionally, spatial partitioning is conducive to improving comfort levels.

Based on these findings, further exploration on how to effectively utilize these conclusions to reduce energy consumption and improve comfort levels in building design and renovation can be discussed. Firstly, considering the climatic characteristics of Hohhot, it is recommended to prioritize the use of gabled roofs in building design to better adapt to the local climate conditions and reduce spatial energy consumption. Secondly, considering that spatial partitioning increases energy consumption, it is essential to allocate space reasonably in building planning, avoiding excessive placement of internal walls, making building use more efficient, reducing unnecessary energy consumption, and further improving resident comfort.

In conclusion, through the analysis and comparison of energy consumption and comfort levels of different types of buildings in Hohhot, beneficial conclusions and recommendations are drawn. These conclusions and recommendations are of important guidance for building design and renovation, helping to effectively reduce building energy consumption and improve resident comfort.

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