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 six types based on their structural forms and spatial layouts. The next step is to simulate the energy consumption and comfort of the abovementioned building types using the software 'Ladybug Tools'. Through the analysis of the simulation results, it is found that the performance of the gable roof and the equal plane building is better, and suggestions are put forward for the design and renovation of buildings.

Keywords: urban renewal, rural residences, indoor thermal environment, energy consumption simulation

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. 1 Therefore, the methods for designing and renovating urban boundary buildings are an important part that needs to be studied. This paper takes the existing rural residences in the Hohhot region as the research object, explore the relationship between low-energy, high-comfort buildings and space types, aiming to provide insights for the urban renewal. 2

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2 Existing Types of Rural Residences in the Hohhot Region

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. 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. In the early 1990s, brick-wood structures began to see widespread adoption. 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.

At the beginning of this century. Against the backdrop of rapid urbanization, brick-concrete structure walls primarily consist of clay bricks or blocks, which are currently the main structural forms used in new residential construction. In terms of architectural form design, the flat roof is gradually replacing the traditional pitched roof in the local area. Flat roofs increase construction efficiency, reduce building costs, and maintenance costs. 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.

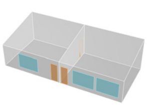
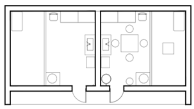
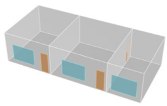
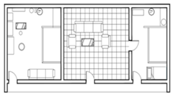
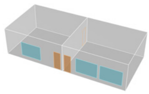
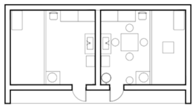
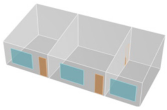
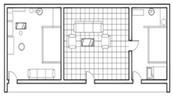
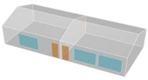
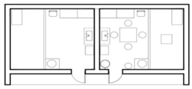
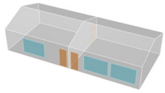
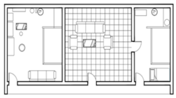
3 Spatial Form Simulation Analysis

Ladybug Tools is a software that uses computer simulations to evaluate the performance of buildings under different climatic conditions and is extremely reliable in predicting the energy consumption and comfort of buildings. 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, 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. These classification methods are combined pairwise to form the following six simulated models (See Table 1):

Table 1. Statistical table of six simulation models (Image source: Self-drawn by the author)

	Model	Floor Plan	Roof	Model	Floor Plan
Condition 1 and Condition 4			Sin-gle slope		
Condition 2 and Condition 5			Flat		
Condition 3 and Condition 6			Ga-bled		

3.2 Experimental Procedure

First, establish an HB-model with material information and classify the interior and exterior walls of the model. Then, insert doors and windows. Import meteorological data into the simulation environment. Finally, set the occupancy density to 0.1 person/square meter and the utilization 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. 4

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/㎡/year, and the total energy consumption is measured in kWh. The visualization of energy consumption for the six conditions is shown in the following figure (See Figure 1):

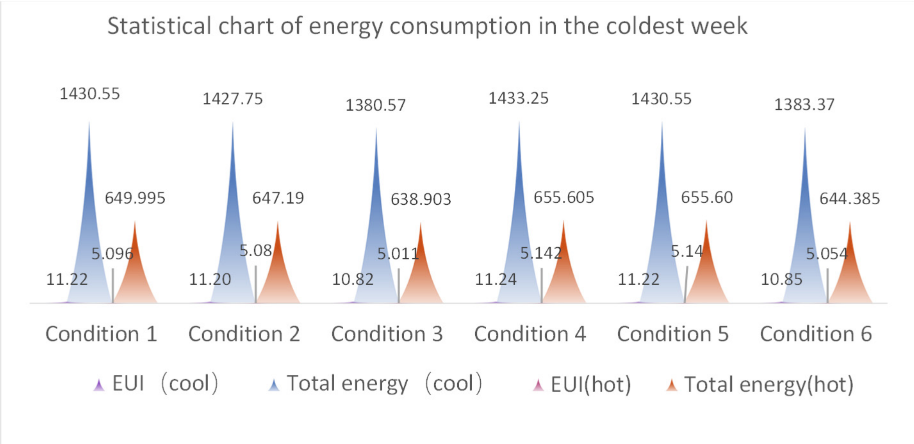


Fig. 1. Statistical chart of energy consumption in the coldest week (Image source: Self-drawn by the author)

By comparing the six 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, with the flat roof being intermediate and the gabled roof having the lowest energy consumption.

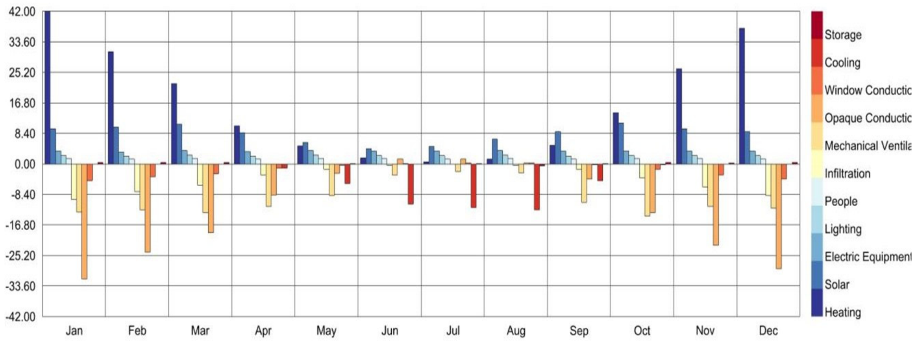


Fig. 2. Energy balance diagram for Condition 1 throughout the year (Self-drawn by the author)

The annual energy consumption for the six conditions is shown in the above figure. (See Figure 2) 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, 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, the heating energy consumption for rooms on the west side is lower than those on the east side.

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 (See Figure 3) 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:

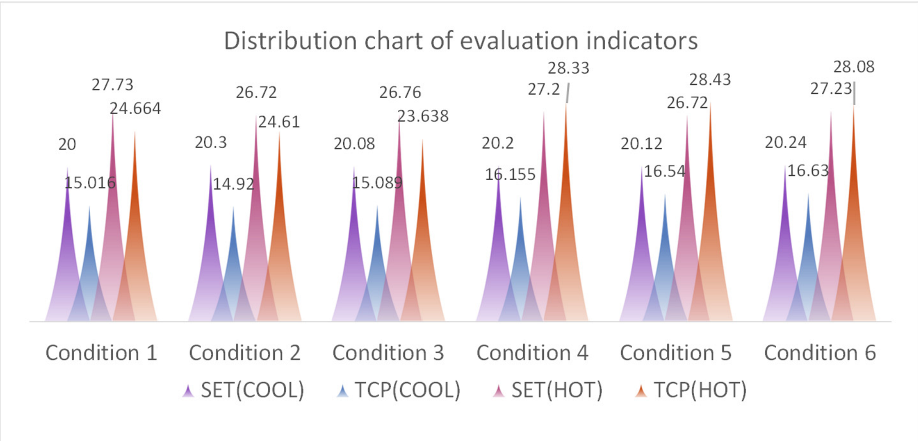


Fig. 3. SET and TCP statistics table (Image source: Self-drawn by the author).

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 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. 5Secondly, 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. 6

In conclusion, these conclusions are crucial for understanding the economic impacts in urban renewal and driving sustainable development. They can help reduce energy expenses while optimizing indoor environments and improving quality of life. Additionally, promoting energy-efficient building design may also spur the development of new technologies, materials, and solutions, thereby advancing the entire industry. 7

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