A Survey of Indoor Thermal Environments in Rural Dwellings in Cold Regions of China

Tongtong Ji[1], Hiroatsu Fukuda[2]

[1] Doctor student, Faculty of Environmental Engineering, The University of Kitakyushu
[2] Professor, Faculty of Environmental Engineering, The University of Kitakyushu

Abstract

With China's continued investment in the construction of new rural areas, the rural habitat in Shaanxi has been improved to a certain extent. Nevertheless, traditional rural dwellings still face pressing problems such as high energy consumption and poor habitability in the process of living. Therefore, this study takes traditional rural dwellings in Guanzhong region of Shaanxi as the research object, conducts field surveys, categorizes them by type, and analyzes their unique architectural features. In addition, the indoor and outdoor temperatures of different dwellings were measured and comparatively analyzed through field measurements. The results show the persistent challenge of insufficient indoor comfort in the investigated dwellings due to extreme seasonal high energy consumption caused by cracking of building materials and aging of the envelope, which cannot effectively meet the needs of the residents. This study aims to provide valuable insights into the current state of rural dwellings in the Guanzhong region and to analyze the causes of energy consumption. Ultimately, it contributes to improving residential comfort and solving energy-related problems in rural areas.

Keywords: Rural dwelling; Energy consumption; Residential environment; Indoor comfort

1. Introduction

China is the world's largest building country, with more houses built each year than all developed countries combined, and building energy consumption accounts for about 20-30% of the country's total energy consumption [1], because rural dwellings in China account for a large proportion of buildings, and coal consumption for space heating has accounted for approximately 60% of domesic energy consumption for rural residential [2]. Currently, the majority of urban buildings benefit from comprehensive design plans that incorporate energy-saving considerations during the design phase, resulting in relatively low energy consumption. Conversely, many rural buildings lack complete design drawings and typically do not incorporate energy-efficient design principles. These structures are often constructed based on local experience and commonly used building methods, leading to high relative energy consumption, particularly in colder regions [2]. Also due to the limitations of economic conditions, the focus of energy efficiency in rural buildings in China is on how to improve the indoor thermal environment by utilizing low-cost passive technologies to create a comfortable indoor thermal environment suitable for living without increasing energy consumption. Passive technologies in rural dwellings can minimize or eliminate the use of cooling and heating equipment, reducing the economic pressure on residents due to high energy consumption while maintaining indoor comfort [3,4]. The building envelope is the key component that impacts energy consumption and indoor environments [5], and sound is all controlled within the envelope. Building envelope largely determines heat absorption and dissipation [6]. A suitable building envelope should decrease the dissipation of energy and help receive more solar radiation heat through transparent interfaces in the winter. Similarly, it keeps the cooled air inside and the hot air outside during the summer months. Therefore, this paper provides a comprehensive understanding of the current situation of rural dwellings in Guanzhong through field research, measurement, and analysis of rural dwellings in Guanzhong, on the basis of which we propose passive energy-saving measures and the building envelope suitable for the local area to improve the indoor thermal environments of dwellings, and we hope to provide references for the future construction of new rural areas in similar areas.

2. Material and Methods

2.1. Location

Guanzhong is located in the central part of Shaanxi Province and includes Xi'an, Tongchuan, Baoji, Xianyang, Weinan, and Yangling, with 54 districts and counties covering an area of 55,500 square kilometers. It is a typical city in the cold climate zone of China [7]. The average annual temperature ranges from 11℃

Contact Author: Tongtong Ji, Doctor student, Faculty of Environmental Engineering, The University of Kitakyushu
Address Hibikino 1-1, Wakamatsu-ku, Kitakyushu, Fukuoka 808-0135, Japan
Tel: 080-7903-8584
e-mail: jitongtong94@gmail.com

to 13℃, with the coldest and hottest winter months being January and July, respectively.

2.2. Research and Objects

The rural areas of Guanzhong have a rich variety of dwellings, which can be broadly categorized into traditional Guanzhong dwellings, self-built dwellings and unified dwellings according to the age of construction.

The first category of dwellings refers to traditional Guanzhong dwellings constructed before the 1970s, characterized by narrow courtyards and courtyard-style layouts. The primary issues associated with these dwellings, which still exist today, stem from their prolonged usage. The protective structures such as doors and windows have deformed or become damaged over time, leading to poor interior sealing. Particularly during the winter season, there is a tendency for heat loss due to the effects of air convection, resulting in reduced comfort within the indoor space. Additionally, these dwellings exhibit subpar indoor lighting performance and a lack of harmony between spatial dimensions and the requirements of modern lifestyles.

The second category consists of self-built dwelling structures constructed from the 1980s to the early 21st century. These dwellings exhibit significant differences in form compared to traditional Guanzhong dwellings. Residents construct such dwellings based on their economic conditions and site constraints, often lacking technical support. In pursuit of spacious and well-lit indoor spaces, these dwellings frequently feature large windows on the north and south walls, with ceiling heights reaching around 3.2 meters. As a result, these dwellings tend to experience overheating in the summer and cold indoor temperatures in the winter. To mitigate this discomfort, residents often resort to using supplementary electrical appliances.

With the development of urbanization and the construction of new rural areas, a third category of dwellings, known as collectively-built dwellings, has emerged in rural areas. These dwellings are primarily led by local governments and involve unified planning and construction. They are often subject to budget constraints and limitations in land size. Measures to improve energy efficiency in construction are typically limited, and the construction model often directly replicates urban residential development, with inadequate consideration for local climate conditions and infrastructure. The main characteristics of these buildings include the use of brick walls and precast concrete panels as the primary load-bearing and enclosure systems. Due to the poor thermal insulation of concrete panels and a lack of ventilation design indoors, these dwellings exhibit a situation of cold winters and hot summers. This also contributes to increased energy consumption in the later stages of building use.

2.3. Methods

The article conducted on-site research and monitoring on three typical residential buildings, employing the following two research and analysis methods: (1) Collection and determination of relevant literature and data pertaining to traditional Guanzhong residential buildings; (2) Building upon the study of the current status of Guanzhong residential buildings, typical representatives from different categories of residences were tested to analyze the indoor thermal comfort of each type. Through survey questionnaires and on-site testing, the annual energy consumption of these residences was also investigated. These two indicators were used as a basis for comparative analysis among the various types of residences, guiding the direction of subsequent renovation and design of residential buildings.

3. Results and Discussion

3.1. Current Status of Dwellings

(1) Traditional dwellings

Traditional dwellings (Fig.1) are often characterized by single-entry courtyards, which have relatively spacious interiors. The exterior walls are constructed with "Huji" walls, consisting of an outer layer of brick masonry over a base of rammed earth, with a thickness of approximately 370mm and a height of about 1 meter. Above the "Huji" wall, the upper section typically comprises rammed earth walls with a thickness of around 300mm, extending up to the eave level where wooden columns are embedded within the wall, serving as the load-bearing structure of the house. Internal partition walls are made of 240mm-thick adobe walls, and the exterior surface of the rammed earth wall is typically smoothed for wall finishing. The interior flooring is constructed using compacted raw earth, overlaid with blue bricks. The roof is a sloped roof composed of a load-bearing structure and roofing materials. Windows are typically single-layer wooden frame windows with glass, and the entrance door is a wooden panel door.

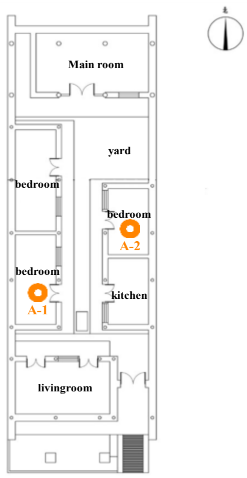

Fig.1. Traditional dwelling plan and test rooms

(2) Self-built dwellings

The land utilization in self-built dwelling (Fig.2) continues the traditional characteristics of the Guanzhong region, which are characterized by narrow and elongated layouts. The primary usage spaces are concentrated and oriented towards the optimal southern direction. The courtyard is enclosed by the main usage space and auxiliary wing rooms to the west, resulting in a narrow and elongated courtyard design.

The outer perimeter features load-bearing walls constructed using solid red clay bricks with a thickness of 370mm, while partition walls separating rooms are built using solid red clay bricks with a thickness of 240mm. The ground is prepared using compacted raw earth, covered with a 50mm layer of cement mortar, and topped with ceramic tiles. Outdoor ground areas such as the front yard and backyard are treated with a cement mortar finish for added durability.

Windows are typically single-layer aluminum alloy frames with white glass, and the entrance doors are relatively large, often composed of aluminum alloy and single-layer glass composites. Interior doors are typically standard wooden doors.

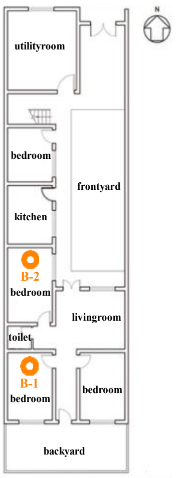

Fig.2. Self-built dwelling plan and test rooms

(3) Collectively-built dwellings.

The collective-built dwelling (Fig.3) buildings are mostly two-story structures, arranged in a front-house-back-yard or front-yard-back-house layout. The building areas range from 160 square meters to 250 square meters, with each household having a backyard. The second floor typically includes a room set aside as a sun terrace.

The exterior walls are constructed using regular solid clay bricks (load-bearing walls) with a thickness of 370mm, while internal partition walls come in two types: 240mm and 120mm (non-load-bearing walls). The ground is prepared in a bottom-up manner, with compacted raw earth followed by a 50mm layer of cement mortar and ceramic tiles on top. Windows are double-layer white glass windows made of aluminum alloy, and the entrance doors are constructed with aluminum alloy frames. The doors inside the residential units are typically wooden hollow-core doors.

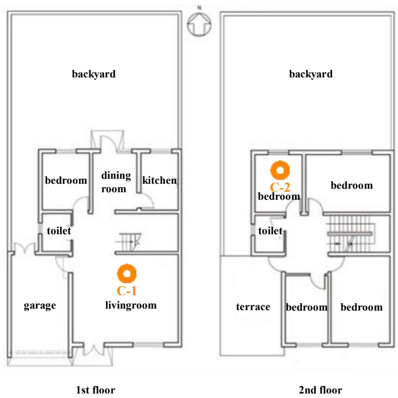

Fig.3. Collectively-built dwelling plan and test rooms

3.2. Measurement

The testing experiments were conducted during two seasons, winter and summer, spanning from January 2016 to January 2018, encompassing a total of four test sessions. Building upon the survey and mapping of village residences, indoor and outdoor temperature and humidity tests were carried out during typical seasons. Simultaneously, to compare the impact of human factors on indoor thermal environments, two rooms within each test residence were selected for comparative testing. Throughout the testing period, all rooms without any human interference remained in a state of closed doors and windows.

(1) Traditional dwellings

During the winter testing period, the indoor average temperature of the traditional residence (A-2) (Fig.1) without the influence of human activities and supplementary heating was approximately -0.65°C, with a temperature fluctuation range of 3.3°C. In contrast, the indoor air temperature of the traditional residence (A-1) (Fig.1) with the influence of human activities and supplementary heating averaged 5.22°C, with a temperature fluctuation range of approximately 7.9°C (Fig.4). Even with the use of coal stoves for heating, the indoor average temperature of traditional residences in winter remains within the discomfort range for humans. This situation can be attributed to two main factors: first, the aging of building components such as doors and windows due to the long construction period and lack of effective maintenance, leading to reduced indoor sealing and increased indoor convective heat exchange; second, the use of traditional wooden lattice paper-pasted windows, which have poor thermal insulation properties.

In the summer, according to Fig.4 the indoor average temperature of the traditional residence (A-2) without the influence of human activities and supplementary cooling was approximately 27.5°C, with a temperature fluctuation range of 2°C. Conversely, the indoor air temperature of the traditional residence (A-1) with the influence of human activities and supplementary cooling averaged 25.8°C, with a temperature fluctuation range of approximately 2.9°C. Both room

A-1 and room A-2 had indoor temperatures lower than outdoor temperatures during the daytime. This is attributed to the maintenance structure of traditional residences primarily being made of rammed earth walls, which have high thermal resistance, slowing down the transfer of outdoor heat into the interior when temperatures are high during the day. However, room A-2 had temperatures about 1°C higher than outdoor temperatures during the night, a phenomenon caused by the release of heat absorbed by the rammed earth wall during the day.

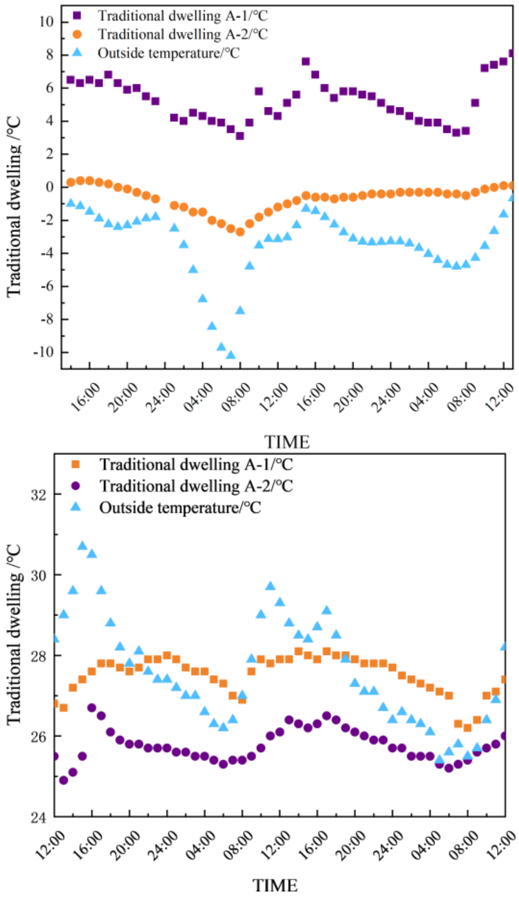

Fig.4. Winter & Summer temperature of traditional dwelling

In traditional residences, indoor relative humidity is generally higher than outdoor air relative humidity, and humidity fluctuations are less affected by outdoor conditions. This is primarily due to the use of rammed earth in the wall enclosure structure, which has good insulation and moisture retention properties, along with self-sustaining characteristics.

(2) Self-built dwellings

During the winter testing period, the indoor average temperature of the self-built residence (B-2) (Fig.2) without the influence of human activities and supplementary heating was approximately 2.95°C, with a temperature fluctuation range of 3.3°C (Fig.5). In contrast, the indoor average temperature of the self-built residence (B-1) (Fig.2) with the influence of human activities and supplementary heating averaged 16.7°C, with a temperature fluctuation range of approximately 4.8°C. In summer, self-built residence (B-2) with no human activity and supplementary cooling had an indoor average temperature of 26.6°C, with a temperature fluctuation range of 2.1°C. Meanwhile, the self-built residence (B-1) with the influence of human activities and supplementary heating had an indoor average temperature of 23.8°C, with a temperature fluctuation range of approximately 4.1°C. Room B-2 used air conditioning as supplementary cooling equipment, leading to a rapid decrease in indoor temperature followed by a recovery to the desired temperature range. Such abrupt temperature changes can reduce human comfort and may also increase the risk of illnesses such as colds.

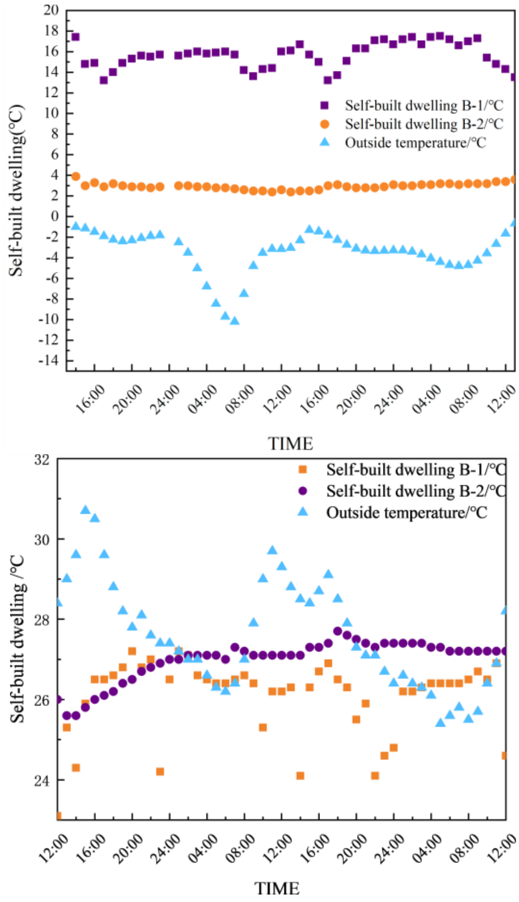

Fig.5. Winter & Summer temperature of self-built dwelling

During the winter testing period, the indoor average humidity of the self-built residence (B-2) without the influence of human activities and supplementary heating was approximately 46.22%, while the self-built residence (B-1) with the influence of human activities and supplementary heating had an indoor average humidity of approximately 32.15%. According to the

"Annual Research Report on Energy Efficiency in Chinese Buildings"[2] in conditions with higher indoor comfort levels in rural residences, indoor relative humidity should ideally fall within the range of 30% to 70%. However, the indoor relative humidity in self-built residences did not reach a level conducive to human comfort during the winter. Therefore, measures should be taken in self-built residences during the winter to increase indoor relative humidity and maintain a suitable indoor environment for occupants.

(3) Collectively-built dwellings.

Within the collectively-built residence, testing was conducted on the ground floor at point C-1 and on the second floor at point C-2 (Fig.3). During the winter testing period, the indoor average temperature of the collectively-built residence (C-2) without the influence of human activities and supplementary heating was approximately 5.3°C, with a temperature fluctuation range of 4.8°C (Fig.6). In contrast, within the collectively-built residence (C-1) with the influence of human activities and supplementary heating, the average room temperature was 6.7°C, with an indoor temperature fluctuation range of approximately 4.9°C. During daylight hours, room C-2 had a higher indoor temperature than room C-1, primarily because C-1 benefited from better sunlight exposure facing south. However, during other time periods when solar radiation intensity decreased, room C-1 gradually had higher temperatures than C-2. This was due to factors such as human activity and the use of electric heaters in room C-1, leading to significant temperature fluctuations and higher average temperatures in room C-1.

During the summer testing period, the indoor average temperature of the collectively-built residence (C-2) without the influence of human activities and supplementary cooling was approximately 29.5°C, with a temperature fluctuation range of 2.6°C. Conversely, the indoor average temperature of the collectively-built residence (C-1) with the influence of human activities and supplementary cooling was 28.2°C, with a temperature fluctuation range of approximately 3.6°C. Based on the graphs, it can be observed that the indoor temperature in room C-2 was consistently higher than room C-1 and outdoor temperatures. This situation primarily occurred because room C-2 was located on the second floor, and the upper portion of the roof used precast concrete panels without an air thermal insulation layer. This allowed the daytime radiated heat to be directly transferred indoors through the floor. Although room C-1 was on the ground floor and had the second floor space as an air thermal insulation layer, its indoor layout was compact, and it lacked proper ventilation, resulting in its temperature remaining higher than outdoor temperatures. Additionally, indoor relative humidity in the collectively-built residence showed an inverse relationship with temperature; as temperature increased, indoor relative humidity decreased.

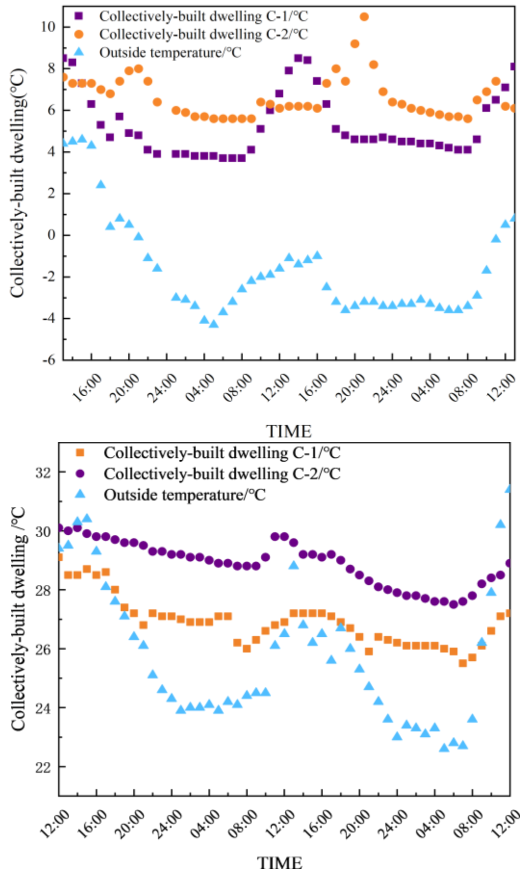

Fig.6. Winter & Summer temperature of collectively-built dwelling

4. Conclusion

From analysis of indoor thermal environments in three types of rural dwellings in the Guanzhong region, leads to the following conclusions: All three categories of dwellings generally face challenges of cold winters and hot summers.

Traditional dwellings, due to their extended history of use, exhibit reduced indoor airtightness primarily caused by aging and damaged building envelope components, particularly doors and windows. This results in easier infiltration of cold air during winter, leading to lower indoor temperatures. Nevertheless, during the summer, traditional dwellings benefit from the thermal inertia of their rammed earth walls, helping to maintain indoor temperatures within a comfortable range.

Self-built and collectively-built dwellings, despite employing 370mm-thick wall structures for insulation, still experience relatively low indoor temperatures in winter due to the absence of well-designed heating systems. In summer, the indoor-outdoor temperature difference is not substantial, but due to high indoor airtightness and a lack of adequate ventilation design, some rooms may even become hotter than the outdoor temperature.

During the winter test period, the indoor airtightness of traditional residences was poor, and the heat loss caused by cold wind penetration was much greater than that of unified residences. However, the average indoor temperature difference between the two was about 1℃.

During the summer test, the indoor temperature of traditional residential buildings differed by about 1.5°C from that of self-built residential buildings that use air-conditioning cooling. The indoor temperature was also within the comfort range of the human body, but the energy consumption was much lower than that of the other two types of residential buildings.

To sum up, it is currently difficult for rural residences to achieve zero energy consumption. How to obtain a better indoor thermal environment on the basis of smaller energy consumption is of great reference for traditional residences.

Considering these issues, improvements for rural dwellings in the Guanzhong region can be approached from the following academic perspectives:

(1) Identifying ecologically sound and cost-effective winter heating methods, such as solar energy and "kang" (heated brick bed) systems, which can serve as ideal supplementary heating sources.

(2) Modifying the roof structure of dwellings, promoting the use of pitched roofs. Pitched roofs create insulation layers beneath the roof structure, offering improved insulation and thermal performance.

(3) Emphasizing the airtightness of building envelopes, particularly doors and windows, during construction. Prioritizing the use of high thermal resistance materials for doors and windows can reduce cold air infiltration during winter and enhance energy efficiency. In regions with abundant solar energy resources, increasing the window-to-wall ratio and incorporating passive solar design features like sunrooms can reduce winter energy consumption.

(4) Enhancing the design and utilization of natural ventilation, particularly during summer. Effective natural ventilation can help lower indoor temperatures and reduce energy consumption.

These improvement measures, considered from an academic perspective, aim to enhance the indoor thermal environment of rural dwellings in the Guanzhong region, improving residents' comfort and reducing energy consumption.

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