博士論文

RESEARCH ON IMPROVING THE WINTER ENVIRONMENT WITH STRAW-FILLED BRICKS AND SUNROOMS IN RURAL HOUSES IN COASTAL AREA OF QINGDAO, CHINA

中国青島沿岸部の農村住宅における藁等充填煉瓦及びサンルームによる冬季環境改善に関する研究

北九州市立大学国際環境工学研究科

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RESEARCH ON IMPROVING THE WINTER ENVIRONMENT WITH STRAW-FILLED BRICKS AND SUNROOMS IN RURAL HOUSES IN COASTAL AREA OF QINGDAO, CHINA

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Preface

This study was conducted at the Department of Architecture at the University of Kitakyushu. This research relies on the Natural Science Foundation of Shandong Province project (ZR2020ME218), "Research on Carbon Emission Control Mechanism and Low Carbon Strategy of Rural Housing Renovation in Shandong Based on Thermal Environment Performance Improvement". This study combined with policy, technical and methodological research in the field of energy-saving renovation of rural houses, focusing on renovation strategies to improve the environment of rural houses in winter.

Acknowledgements

With completing my thesis just around the corner, I look back on my doctorate journey with a lot of emotion. I am very grateful to my supervisor, colleagues, classmates and family members who have provided me with so much help in my studies and life over the past three years. Without their support, guidance and assistance, this thesis would not have been completed.

First of all, I would like to express my sincere gratitude to my supervisor, Professor Weijun Gao from Kitakyushu University, who has given me a lot of guidance and help in my thesis writing, which has made it possible to proceed smoothly. His vast academic knowledge and rigorous approach to science have influenced my research work all the time. Moreover, he also gave me a lot of encouragement and support in my daily life.

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Furthermore, I would like to thank all the students in my project team for the many hours of hard work and sweat they put into the research. Because of their help, I was able to overcome one difficulty after another in my thesis. I would also like to thank the farmers who actively cooperated during the research process. Without their help, I would not have obtained detailed information and data for my research.

Finally, I am very grateful to my family for their endless love, encouragement and moral support in my life, which gave me enough confidence to overcome the difficulties.

RESEARCH ON IMPROVING THE WINTER ENVIRONMENT WITH STRAW-FILLED BRICKS AND SUNROOMS IN RURAL HOUSES IN COASTAL AREA OF QINGDAO, CHINA

Abstract

This study investigated and optimized the energy-saving and environmental conditions of coastal rural houses in Qingdao during winter. Through in-field survey and experimental simulation, the characteristics of rural houses, the indoor thermal environment and the status of air quality were analysed. The renovation method of winter energy-saving and environmental improvement of Qingdao coastal rural houses was carried out from two aspects of envelope renovation and sunroom design by the realistic problems.

In chapter one, Background and Purpose of This Study, the development opportunities and status issues of rural houses in China and the coastal rural areas of Qingdao were introduced, and the purpose and significance of this study were proposed.

In chapter two, Literature Review of Energy-saving and Environmental Improvement in Rural Houses, the research status of energy-saving and environmental improvement in rural houses during winter was reviewed in terms of thermal comfort, air quality, and energy-saving design of rural houses in various countries.

In chapter three, Methodology of In-site Survey, Experiments, and Simulations, mainly included: methodology of survey and measurement, experimental principles of building envelope thermal improvement and numerical simulation software and principles of building thermal environment, which provide the theoretical and methodological basis for the improvement of winter indoor thermal environment and energy-saving design of rural houses in the following chapters.

In chapter four, Status of Coastal Rural Houses and Indoor Environment in Qingdao, through field measurements and questionnaires, the construction of rural houses in Qingdao was investigated to identify the current heating methods and envelope forms of rural houses, and to find out the problems in indoor thermal environment and air quality, which will provide first-hand basic research information for the subsequent creation of suitable human living environment and energy-saving houses.

In chapter five, Thermal Performance Enhancement of Building Envelopes by Using Crop Straw, five different straw materials filled with hollow bricks were selected for controlled tests to investigate the application and efficiency of different straw materials on the thermal performance improvement of envelopes. It aimed to select the optimal straw material which will provide data support for the next envelope modification.

In chapter six, The Energy-saving Improvement for The Rural Houses by Numerical Simulation, a model of a typical rural house in Qingdao was established. The energy-saving renovation options for envelopes were explored in combination with the energy-saving materials identified through experiments in chapter five. The energy insulation and energy efficiency of the external walls, roofs and external windows of different solutions were simulated and analysed by EnergyPlus software. Following the simulation, suitable energy-saving renovation options for envelopes were proposed.

In chapter seven, Application of Sunroom to Improve Indoor Thermal Environment in Winter, the design strategy of the additional sunroom was proposed in relation to the status of rural houses. Additionally, the thermal insulation and energy efficiency of the additional sunroom were simulated and analysed by EnergyPlus software in order to select a cost-effective design option for the sunroom.

In chapter eight, the whole summaries of each chapter and the future prospects were presented.

Keywords: coastal rural houses; winter environment; straw-filled bricks; sunrooms.

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Chapter 1. Background and Purpose of This Study

1.1.Introduction

In recent years, with the rapid advancement of social development and urbanization, China has been paying more and more attention to the development of rural areas, striving to change the living conditions of traditional houses in rural areas, and has successively put forward a series of development strategies such as "the Construction of New Socialist Rural Area", "the Construction of Beautiful Village" and "Rural Revitalization". Improving the living environment in rural areas and building beautiful and habitable villages is essential in implementing the rural revitalisation strategy [1]. As the foundation for improving the living environment, energy-saving of buildings has a significant meaning in reducing energy consumption, improving the quality of life, and promoting the achievement of carbon peak and carbon-neutral targets as well as the green and sustainable development of the countryside.

Owing to the particular geographical environment and climatic conditions of rural houses in the cold regions of China, local rural houses need to meet the requirements of winter insulation. At present, most traditional rural houses in China adopt a rough self-built production model, and the building envelope is generally unsatisfactory in terms of thermal performance and environmental performance of materials. During the winter heating season, rural houses in colder areas are still using more backward heating methods, which cause a large amount of energy consumption and generate plenty of pollutants, causing irreversible damage to the environment and the human body. The increasing standard of living in the rural areas of China is in marked contradiction to the poor indoor thermal comfort that the rural houses can provide at this stage.

Shandong Province is a central traditional agricultural province in China. Large numbers of traditional rural houses exist in rural areas of Shandong, which are functionally homogeneous and poorly insulated, and no longer meet the increasingly diverse housing needs of contemporary farmers. Qingdao has certain representative features in creating rural houses and climate characteristics as an important coastal area in the north. This study selects the coastal rural houses in Qingdao as the object of research. It proposes theories and methods for its energy-saving renovation and environmental improvement, which will help create a comfortable indoor thermal environment, reduce heating energy consumption in winter, promote the construction of green countryside, and enhance the livability of the rural environment.

1.2.Subject source and research background

1.2.1.Subject source

This topic is derived from the Natural Science Foundation of Shandong Province (ZR2020ME218) *"Research on Carbon Emission Control Mechanism and Low Carbon Strategy of Rural Housing Renovation in Shandong Based on Thermal Environment Performance Improvement"*.

1.2.2.Research background

(1) Global climate change and the state of energy consumption

With the background of global climate change and rapid urbanization, the deterioration of the human environment and energy shortage has become hot issues of the world. In recent years, environmental damage has become increasingly severe, with carbon emissions exceeding the limit, leading to rising global temperatures and sea levels and extreme temperature events occurring frequently. Continuing the planet's long-term warming trend, the globally averaged temperature in 2020 was 1.02 °C (1.84 °F) warmer than the baseline 1951–1980 mean (Figure 1.1-1.2), according to scientists at NASA's Goddard Institute for Space Studies (GISS) [2]. As of 2020, the average surface temperature has reached a historical maximum. The Fifth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC) points out that the global climate system continues to warm, posing a significant threat to natural ecosystems and human societies [3]. Therefore, climate change has become a hot issue in the field of environment and health internationally. Energy-saving and emission reduction have become urgent issues to be solved worldwide.

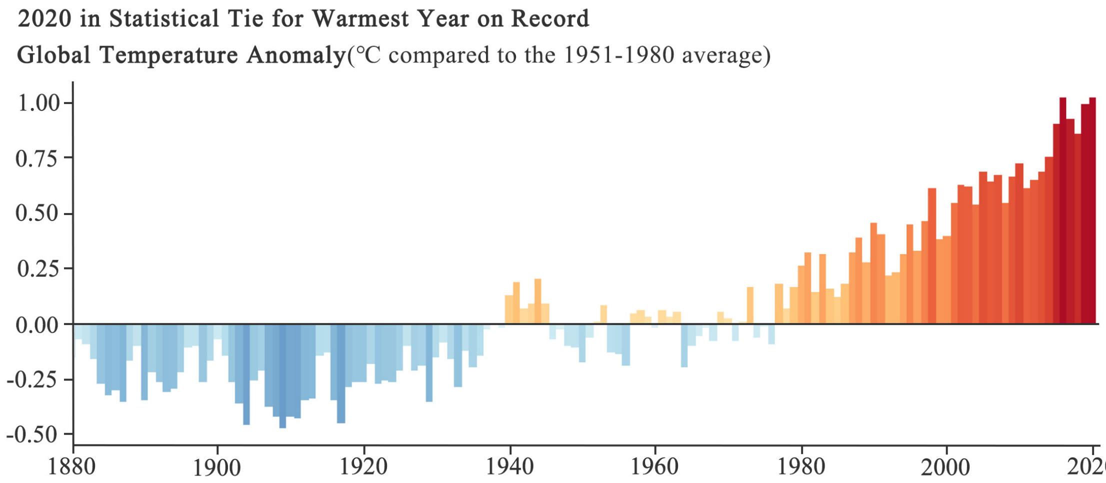

Figure 1.1. Global Temperature Anomaly Statistics (1880-2020) [2]

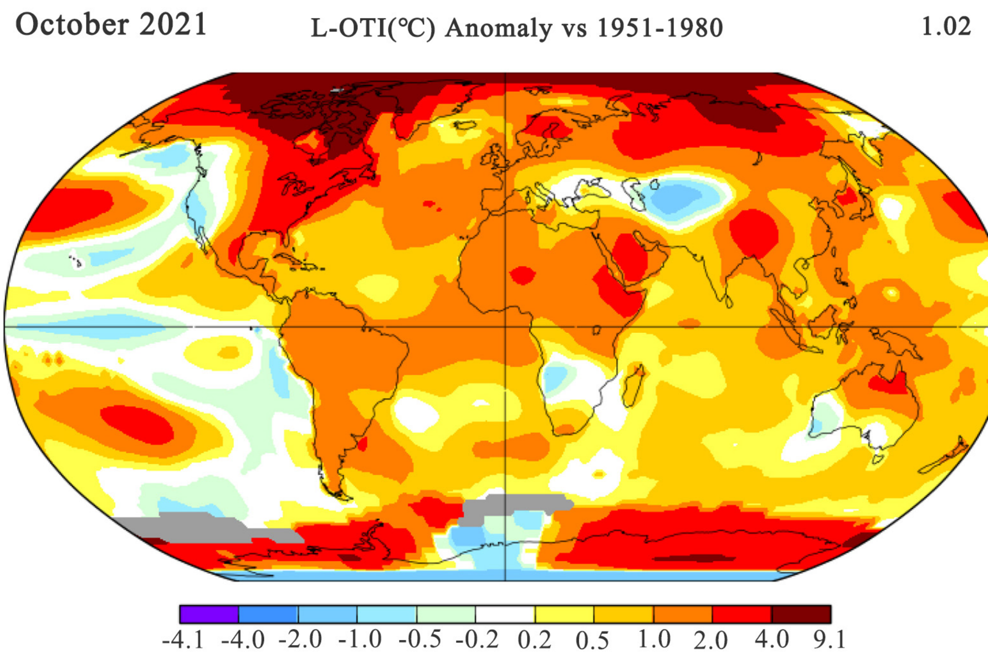

Figure 1.2. Graph of global surface temperature change in winter 2021 compared to the same period in 1980 [2]

According to the *Statistical Review of World Energy 2019*, Total global primary energy consumption has been upward from 2009-2019, but growth has slowed significantly. In 2019, total global primary energy consumption was 583.9 EJ, an increase of 7.7 EJ from 2018, slowing to an average annual growth rate of 1.3% (Figure 1.3) [4]. According to the results of the Global Energy Use and Emissions in Buildings accounting by the International Energy Agency (Figure 1.4), in 2018, the global construction industry and end-use energy related to building operations accounted for 36% of global energy consumption and 39% of total global CO_2 emissions [5]. Building energy consumption remains a significant constraint on global climate issues, and reducing building energy consumption and carbon emissions remains urgent.

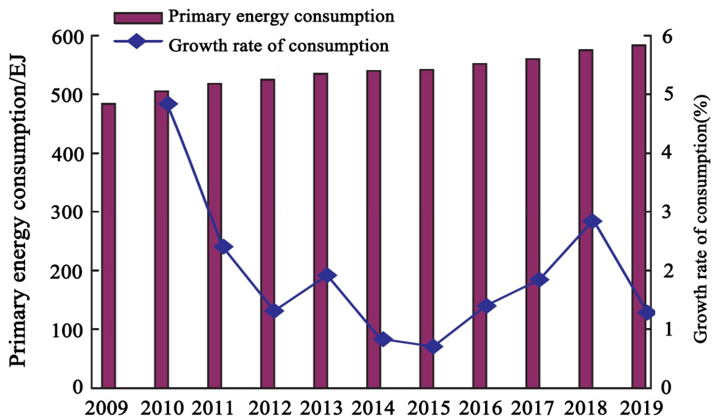

Figure 1.3. Global primary energy consumption and growth rate graph 2009-2019 [4]

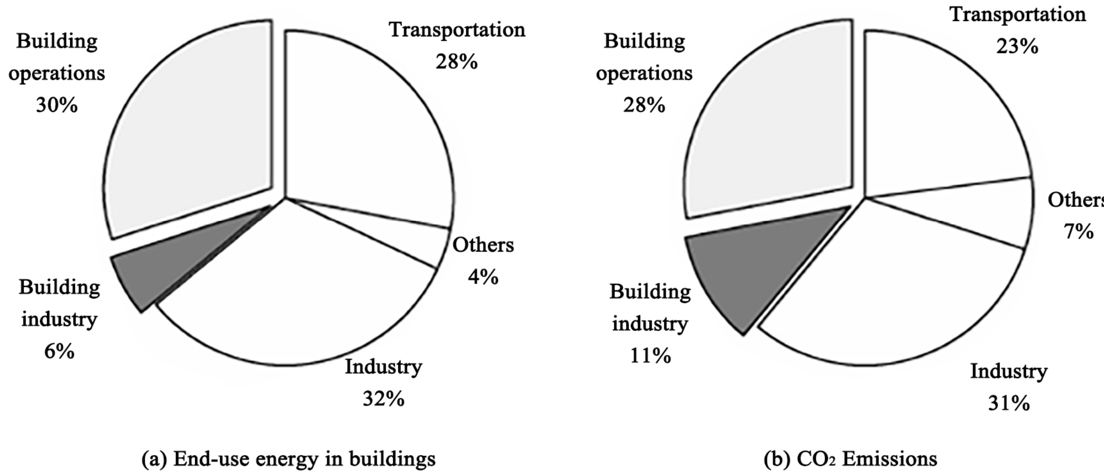

Figure 1.4.2018 Global end-use energy in buildings and CO_2 emissions[5]

(2) Development and energy consumption status in the rural areas of China

China is a traditionally largely agricultural country, and the rural population and the construction area of rural houses account for a significant proportion of the total population and construction area. Since the reform and opening up, with the continuous growth of the economic level in China and the steady improvement of the living standard of rural residents, the construction of rural houses has entered a peak period of renewal [6]. According to the *China Statistical Yearbook 2020* published by the National Bureau of Statistics of China, the rural population of China was approximately 552 million by the end of 2019, accounting for 39.4% of the total national population. The per disposable capita income of rural households reached RMB 16,021, and the per capita consumption expenditure of rural households reached RMB 13,328. GDP per capita increased from RMB 7,846 in 2000 to RMB 70,725 in 2019 [7]. According to the *China Urban-Rural Construction Statistical Yearbook 2019* published by the Ministry of Housing and Urban-Rural Development of China, in 2019, the total building area of China was about 64.12 billion m^2, of which rural houses building area was about 25.53 billion m^2 [8], accounting for 39.8% of the total building area of China. From 2010 to 2019, China added an average of 610 million m^2 of new rural houses each year, showing a rising trend (Figure 1.5). In addition, the per capita residential building area in rural areas has increased from 24.3m^2 in 2010 to 32.9m^2 in 2019 [8]. At present, the rural houses in China suffer from a large building base and a great deal of incremental growth, and with the steady increase in the construction of rural housing in China, land, resources, energy, and ecological environments are under enormous pressure everywhere owing to the high-input crude economic model [9].

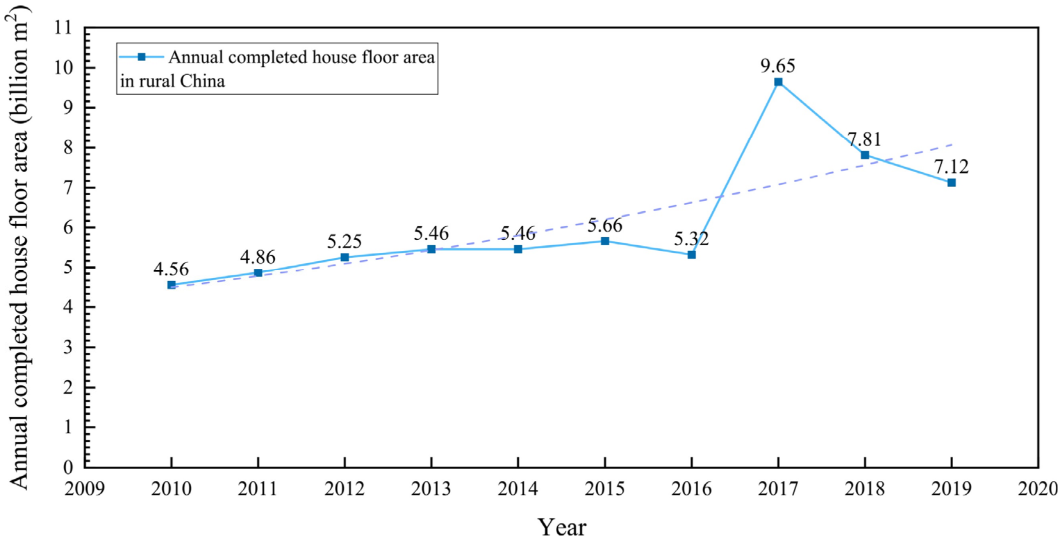

Figure 1.5. Statistics on the newly-increased residential construction area in rural areas of China each year

With the rapid development of the economy, farmers have become increasingly demanding in terms of quality of life, which has led to a significant increase in energy consumption in rural houses. Existing rural houses generate a large amount of energy consumption, which mainly includes energy consumption for heating in the north and daily energy consumption for lighting, cooking, domestic hot water, home appliances and air conditioning during their daily use. As a result, enormous pressure is placed on our energy supply. In 2020, the Special Commission on Energy Consumption Statistics of the China Association of Building Energy Efficiency issued the *China Building Energy Consumption Research Report (2020)* in Shanghai. According to the statistical results of the data in this report, from 2005 to 2018, the total energy consumption of the whole building process in China had increased from 934 million tce to 2,141 million tce (Figure 1.6). Its share in the total social terminal energy consumption had increased from 36% to 46%, with an increased proportion. Furthermore, as the floor space per person increases, the energy consumption and carbon emissions of building operations also tend to rise. In 2018, the per capita residential building area in urban areas of China reached 37 m^2. During the building operation phase, the total building energy consumption in China was about 1 billion tec, accounting for 21.7% of the national energy consumption, and the total carbon emissions were about 2.11 billion tCO_2, accounting for 21.9% of the national total carbon emissions (Figure 1.7). The energy consumption of rural houses was about 238 million tons of standard coal, accounting for 24% of the national energy consumption of buildings [10]. According to the *2020 Annual Report on China Building Energy Efficiency - Rural Housing Topics* compiled by the Building Energy Efficiency Research Centre of Tsinghua University, the most significant proportion of energy consumption in rural buildings is coal, accounting for 113 million tec, the next largest is non-commodity biomass energy (including fuelwood and straw) at 94 million tec [11]. To sum up, it is urgent to reduce energy consumption and emissions in rural China.

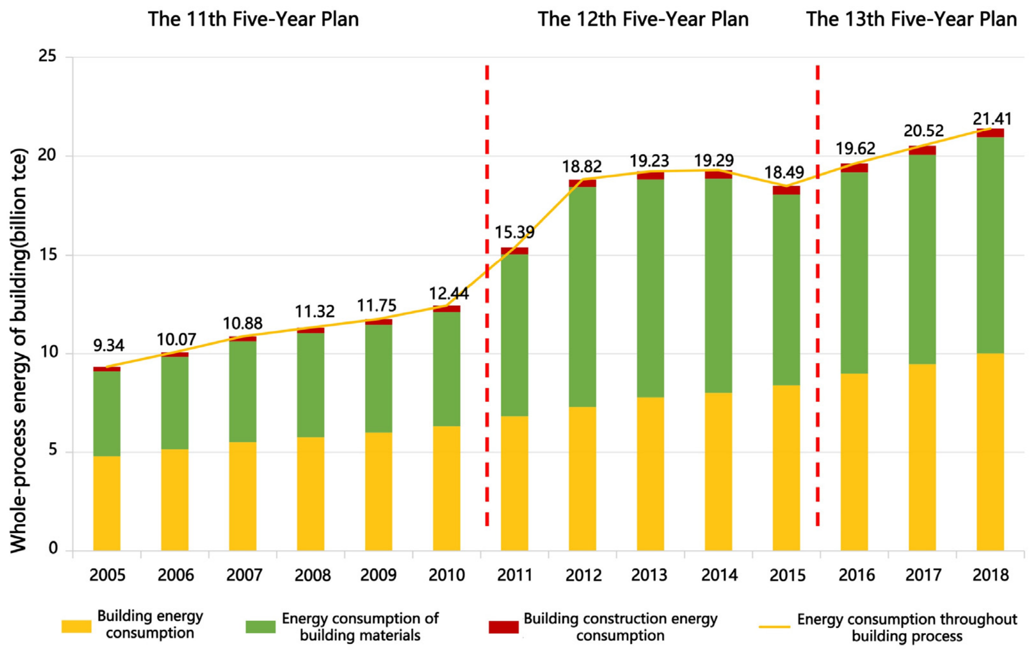

Figure 1.6. Trends of energy consumption in the whole building process in China (2005-2018)[10]

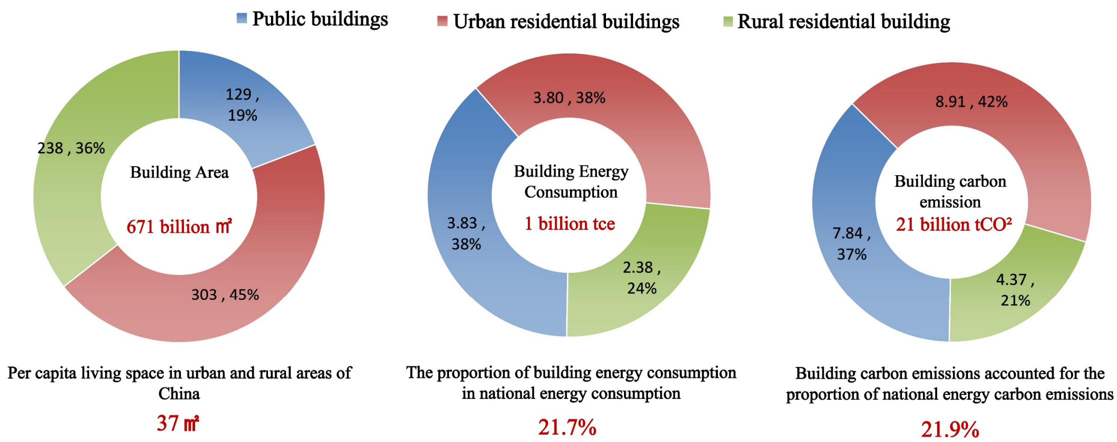

Figure 1.7. Energy consumption during building operation in China, 2018[10]

Furthermore, farmers are putting forward higher requirements for their living environment, and the comfort and livability of buildings are gradually becoming increasingly important. The indoor temperature environment and air quality of a building are essential indicators of building comfort [12]. The climate in northern regions is cold and long in winter, with the average outdoor temperature in January below 0°C. Heating insulation is one of the main means of improving indoor thermal comfort. However, traditional rural houses are mostly self-built by residents, which have poor insulation performance of the building envelope [13]. In winter, the indoor heating temperature is far below the national standard, thus resulting in poor indoor thermal comfort. In addition, the rural lifestyle in northern areas is still relatively backward, and the energy for heating and insulation mainly comes from biomass fuels such as coal and straw. The total time spent on combustion activities in winter houses is long and primitive stoves such as traditional coal stoves, and Kang are used. Straw and coal are not burned sufficiently during the combustion process, and many pollutants are produced, such as indoor $PM_{2.5}$, PM_{10}, CO, CO_2, SO_2 and NO_x, which are exceeded to varying degrees [14]. This sloppy combustion method produces a significant waste of resources and causes air pollution, and brings serious health problems to rural residents. The World Health Organization in the *World Health Report 2002* states that "indoor smoke from solid fuels is one of the top 10 global risk factors in terms of burden of disease" [15].

With the rapid growth in the construction of rural houses, China is paying increasing attention to the three rural issues and have published a series of policy documents to promote the comprehensive and rapid development of rural areas. In 2005, the Fifth Plenum of the 16th Central Committee of the Communist Party of China put forward the strategic task of constructing a new socialist rural area, and the construction of rural housing became an essential part of the national effort. In 2012, the 18th National Congress of the Communist Party of China proposed vigorously promoting ecological civilisation and steadily promoting the energy-saving and green transformation of agricultural housing combined with the renovation of unstable housing in rural areas. In 2013, China decided to carry out the construction of Beautiful Village, which has promoted ecological construction and environmental protection in China. In 2017, the report of the 19th National Congress of the Communist Party of China proposed the strategy of rural revitalization, suggesting that the sustainable development of rural houses should be placed on the same level of importance as that of urban housing. In addition, the report also proposes that green housing is bound to become a significant trend in the construction and development of rural houses. In 2018, China released the *Strategic Plan for the Rural Revitalization (2018-2022)*, in which the creation of habitable and suitable living spaces became an essential element in the optimization of the rural development plan. In 2019, *Document No. 1 of the Central Government* proposed to arrange special funding to support the improvement of the human habitation environment in rural areas and promote the improvement of essential public service standards in rural areas.

(3) Development status overview of rural houses in Qingdao

Shandong has always been one of the largest population and agricultural provinces in China. The agricultural population accounted for around 50.4% of the population in the province. Qingdao has the second largest total population in Shandong Province. According to the Qingdao Statistical

Yearbook 2020, the total resident population of Qingdao was 9,499,800 at the end of 2019, which includes a rural population of 2,458,500, accounting for 25.88% of the total population of the city [17]. The income and expenditure of rural residents in Qingdao have improved significantly since 2000, with an increasing trend in the per capita disposable income of rural residents from 2000 to 2019 (Figure 1.8). At the end of 2019, the rural per capita disposable income in Qingdao reached RMB 22,573 and per capita consumption expenditure RMB 14,899, both of which exceeded the national per capita level. In 2019, the rural residential area in Qingdao reached 90,964,500 m^2, and the per capita current housing floor area of rural residents reached 37.0 m^2, with an increase of 3.1% compared to 2018 [18]. The huge rural houses base means that there is huge energy-saving potential and great research value.

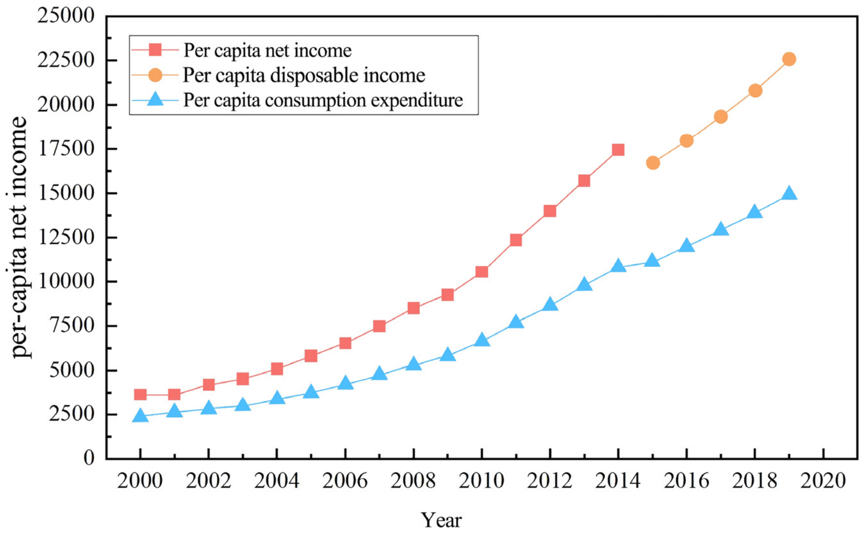

Figure 1.8. Per capita income and expenditure of rural residents in Qingdao (2000-2019)

According to the *Standard of Climatic Regionalization for Architecture (GB 50178-93)* (Figure. 1.9), Qingdao belongs to the cold climate zone [19]. It has a typical warm temperate continental monsoon climate and maritime climate characteristics. During the winter Qingdao is cold, dry and windy, while the summer is warm, humid and rainy. According to the climate statistics data of Qingdao from 2010-2019 provided by Qingdao Statistics Bureau, the annual average temperature of Qingdao was 13.39°C in 2010-2019, while the minimum monthly average temperature was -2.9°C and the maximum monthly average temperature was 26.4°C during the last ten years [18]. The average number of days with daily maximum temperatures above 30°C is 11.4 days per year, and the average number of days with daily minimum temperatures below -5°C is 22 days per year [20]. According to Figure 1.10 annual climate data of Qingdao from 2010 to 2019, the lowest temperature in Qingdao was -12°C in December, and the highest temperature was 35°C in August. The annual average relative humidity in Qingdao is 73%, with a maximum of 89% in July and a minimum of 68% in December. Qingdao has a minimum average winter wind speed of 4.7m/s and a maximum average wind speed of 5.3m/s, while the maximum average winter wind speed in Jinan, an inland area at the same latitude, is 4.5m/s. Compared with the inland areas, the wind speed in the coastal areas is faster in winter and traditional rural houses are more breathable and heat is more easily dissipated. The number of sunshine hours in Qingdao is generally high in all seasons, with a sunshine percentage of 58%, and the total daily solar intensity can reach 3.8-4.5 KW·h/m^2, which is equivalent to the heat released by burning 170-200 kg of coal. Therefore, Qingdao is relatively rich in solar energy resources. Overall, Qingdao has a short duration of high-temperature periods in summer, and the average temperature meets the thermal comfort requirements of the human body. The temperature change between indoor and outdoor is not significant, and the relative humidity is about 89%, making the environment more comfortable. However, Qingdao has cold and dry winters and high outdoor wind speeds in the coastal areas, which results in lower body temperatures and poorer thermal comfort than inland areas. During the winter heating period, the average outdoor temperature in January is about 0.37°C, while the average indoor temperature is below 10°C in rural Qingdao, which is far below the energy-saving standard of 18°C in China. According to the survey of rural houses in Qingdao, in winter, 95% of houses are heated, and residents feel cold indoors without heating. Local residents mostly use "fire Kang" or stove for heating in winter. The coal consumption of each household in winter is about one ton, and the heating cost is about 1000 yuan for each family. In general, rural residents have a more vital need for heating in winter, and more energy is consumed for heating in winter. In addition, the use of traditional Kang and stoves for heating in the winter produces air pollution issues. As a result, there is an urgent need to improve the living environment in rural areas.

Figure 1.9. Architectural climate zone map of China

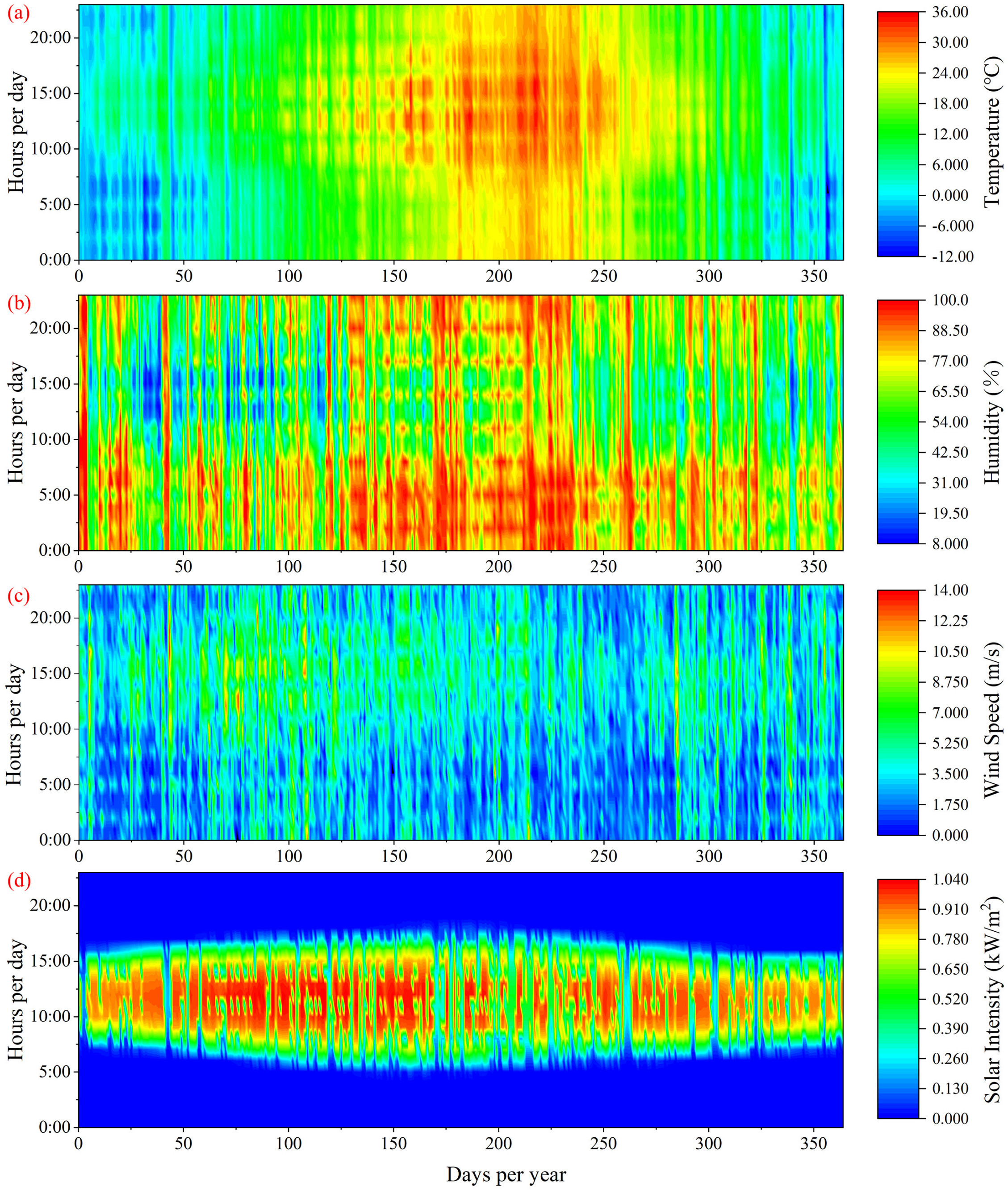

Figure 1.10. Annual climatological data of Qingdao 2010-2019

1.3.Research purpose and significance

1.3.1.Research purposes

This paper combines the characteristics of the regional environment and takes the rural houses in the coastal area of Qingdao City, Shandong Province, as the research object. Through field research, experimental simulations and numerical simulations by EnergyPlus software, a series of problems such as high energy consumption, poor insulation performance, poor indoor thermal environment and air quality conditions are found to exist in rural houses in general. The theory and methods of energy-saving renovation and environmental improvement of rural houses in the coastal area of Qingdao are explored. The objectives of this study are as follows.

(1) To study the development status of rural houses in Qingdao and identify indoor environmental problems in typical coastal rural houses in Qingdao

To investigate the construction of rural houses in Qingdao, systematically understand the heating methods and the form of envelope of the rural houses, and identify the indoor thermal environment and air quality problems through field measurements and questionnaire surveys.

(2) To explore the application and efficiency of different straw materials in envelope thermal performance improvement

As a widely distributed and renewable natural material, straw has good building insulation properties. However, many straws in rural areas are handled by traditional burning methods, causing severe environmental pollution and wasting resources. Through experimental simulations to explore the efficiency of different types of straw materials as filler materials in improving the thermal performance of building envelopes, and explore the feasibility of applying straw in rural houses renovation.

(3) To explore the ways and efficiency of indoor environment improvement in rural houses during winter from the aspect of building envelopes

Based on the previous experiments, to explore renovation options for the external walls, roofs and external windows of the original houses combined with straw applications as a feature, and to determine their renovation efficiency through simulations with EnergyPlus, and to discuss the effect of different renovation options on the improvement of the indoor thermal environment. The optimal solution is selected to provide a reference for envelope renovation.

(4) To explore the methods and efficiency of indoor environment improvement in rural houses during winter from the aspect of sunrooms

To design the sunrooms in combination with the plan form of a typical rural house. Through

EnergyPlus building energy simulation software, the thermal insulation and energy-saving efficiency of the additional sunrooms are calculated, and the effect of clean solar heating on improving the indoor environment in winter. It provides a reference for the design of additional sunrooms for coastal rural houses in cold regions.

1.3.2.Research significance

(1) To provide data and information for the design of coastal rural houses in the cold northern regions and help promote the development of the optimal design of rural houses.

Currently, the research on energy-saving and environmental improvement of rural houses in China has some regional characteristics, and the quantification of primary data remains lacking. This study enriches and improves the data resources on the status of the envelope and indoor and outdoor thermal environment in cold regions through a large amount of data from surveys and provides first-hand information for constructing sustainable rural houses. The study results can provide a reference for improving the indoor thermal comfort of rural houses and the living environment of coastal rural areas in China.

(2) Through the experiment of straw and hollow brick integrated insulation material, exploring the methods and application of straw in the renovation of the envelope, expanding the application of straw in rural areas and reducing straw pollution to the environment.

Straw building materials have the characteristics of being low carbon, energy-saving and sustainable. This study provides an economical and practical form of insulation and energy-saving for applying straw in the renovation of the envelope through the experiment of integrated straw and hollow brick insulation materials. It expands the application of straw in rural areas, reduces the air pollution caused by burning excess straw, and can provide a reference role for applying straw materials.

(3) Proposing a comprehensive reform plan for the energy-saving renovation and environmental improvement of the external envelope and additional sunrooms of coastal rural houses in Qingdao will improve the indoor environment of rural houses and promote green and sustainable development for the rural areas.

Under the background of global climate change and rapid urbanisation, the deterioration of the human living environment and energy shortage has become a hot issue worldwide. At present, with the steady growth of social and economic development, the material living standard of farmers is improving, and the requirements of residents for the quality of life are also increasing. The traditional rural residential buildings have a single form, serious ageing of the envelope, poor insulation and heat preservation, and severe indoor and outdoor air pollution in the buildings, making it challenging to meet the requirements of the indoor living comfort for people. This study proposes a renovation plan for the energy-saving renovation and environmental improvement of rural houses from two aspects: envelope structure renovation and passive solar house design, which will improve the thermal performance of the envelope, increase the indoor temperature, reduce heating energy consumption, lower carbon emissions and improve the indoor air environment, thus promoting the green and sustainable development of rural houses.

1.4.Research Structure

1.4.1.Research content

Strategies for energy-saving and environmental improvement are investigated concerning the low indoor temperature, high heating energy consumption and poor indoor air quality in winter in coastal rural houses in Qingdao, Shandong Province. The main research elements of this paper are as follows.

In chapter one, the current situation, problems, and opportunities for the development of rural houses in China and Qingdao are reviewed, and the aims and framework of this study are also presented.

In chapter two, the status of research on the thermal environment, indoor air quality and energy-saving design of rural houses in the world are reviewed, and the research trends and advanced experiences of countries in energy-saving renovation and environmental improvement of rural houses are summarized. It provides a theoretical basis for the subsequent research.

In chapter three, the research methodology and simulation theory is introduced. The field survey methods for the status of rural houses in coastal areas of Qingdao in this study include interviews, questionnaires, and actual measurements. Furthermore, the SHB-HFM method using the flat wall steady-state heat transfer principle is introduced to simulate the effect of different straw materials on the thermal performance of hollow bricks. Moreover, the experimental principles and methods for measuring the thermal conductivity of the envelope are presented. Finally, the principles of using the EnergyPlus software developed by the US Department of Energy to simulate and assess the thermal insulation and energy-saving efficiency of typical rural houses in Qingdao for envelope renovation and additional sunrooms are described.

In chapter four, through field measurements and questionnaire surveys of rural houses in coastal areas of Qingdao, the status of the forms for the envelope, heating methods, indoor thermal environment and air quality of rural houses is investigated. Problems such as poor thermal performance of the envelope, outdated heating methods, low indoor temperature and poor air quality are identified, which will provide first-hand data for later research.

In chapter five, experiments on the thermal conductivity of hollow blocks filled with straw are introduced. They are selecting five common straw materials to fill into the hollow blocks bricks and simulating the effect of different straw materials on the thermal performance of the hollow blocks through hot box method experiments. Then, a controlled experiment was conducted to find the lowest straw filling option for heat transfer, which will provide technical support for the energy-saving renovation of the building envelope.

In chapter six, the initial model of a typical rural house in Qingdao is established using EnergyPlus software, with the climate and building envelope characteristics of the coastal area of Qingdao. Based on chapter five, corresponding energy-saving renovation technology measures are selected to simulate and test the thermal insulation and energy-saving efficiency of the house from three aspects: external walls, roof, external doors and windows. The energy consumption of the building and the energy-saving effect of different renovation options for various parts of the envelope were analysed. Then the overall energy-saving efficiency of the renovation of the envelope was comprehensively analysed.

In chapter seven, the design strategy of the additional sunroom is proposed combined with the status of rural houses. The data on the heating energy consumption of the sunroom is analysed using EnergyPlus software simulations to select a cost-effective design solution for the sunroom that will establish the basic model of the additional sunroom.

In chapter eight, the whole summaries of each chapter and the future prospects were presented.

1.4.2.Research Flow

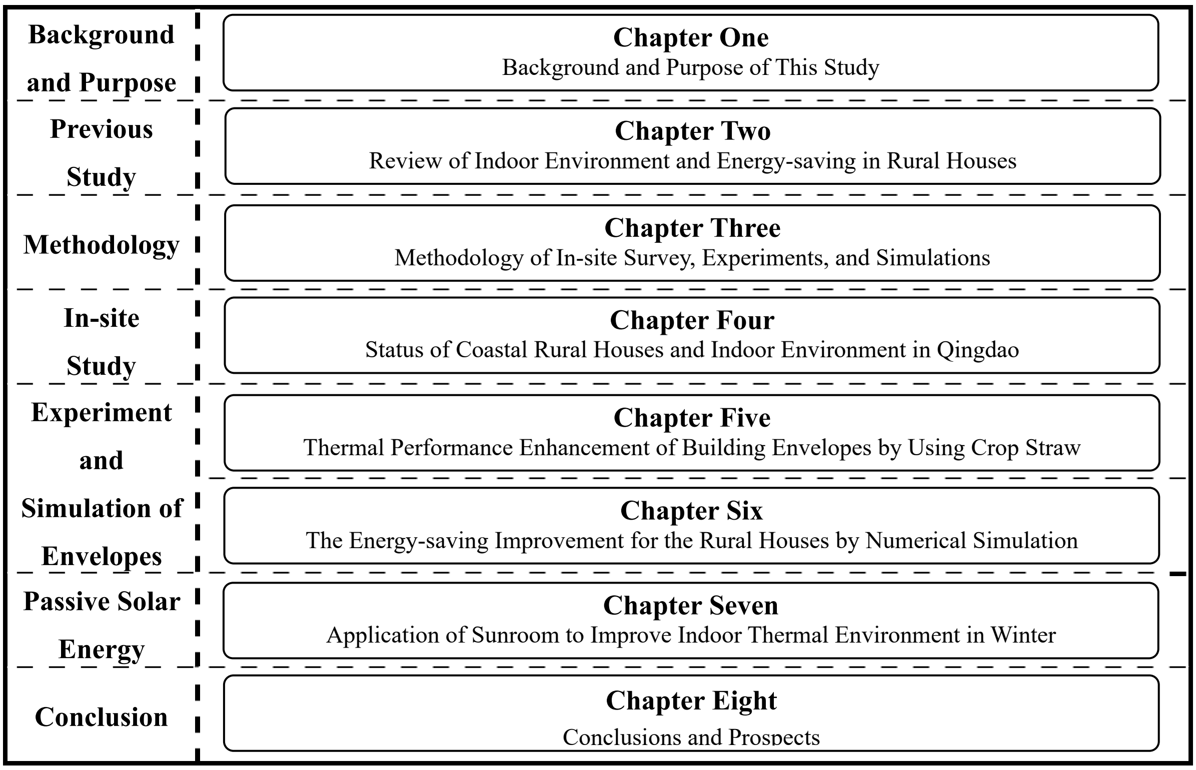

Figure 1.11. Research Flow

Reference

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Chapter 2. Literature review of energy-saving and environmental improvement in rural houses

2.1.Introduction

With the rapid development of urban construction and the further improvement of residents living standards, people have put forward higher requirements for the indoor living environment. Wu Liangyong proposed that the core concern of the study of the habitat environment is the people; an appropriate habitat environment should meet the residential needs of residents as a prerequisite [1]. The environmental quality of rural houses is an essential prerequisite for ensuring a healthy life for farmers. The main factors affecting the comfort of the living environment are light, thermal, ventilation, air quality, Etc. The indoor thermal environment is an essential component of this and directly affects the thermal comfort of the occupants. On the other hand, indoor air quality has a direct impact on the health of the occupants [2]. Therefore, thermal comfort and indoor air quality are considered the main parameters for building environment improvement studies. Energy-saving renovation measures in buildings can enhance indoor thermal comfort, an important measure to optimize the indoor environment and reduce building energy consumption [3].

Since the 1960s and 1970s, some developed countries have started research on the rural living environment. Although the specific approaches vary from country to country, the core idea is similar, i.e., different renewal measures are proposed for each village's different human and geographical conditions and economic status. Specifically, in terms of new construction and renovation of rural housing units, countries have researched several aspects, such as improving the thermal environment of rural houses and the energy-saving renovation of buildings.

In cold regions of China, the indoor thermal environment is essential due to the cold outdoor climate in winter. The research focus of researchers has changed to how to minimize building energy consumption and enhance the habitability of winter Residences while ensuring a comfortable indoor thermal environment.

Combining the research content, this study compares the current research status of energy-saving and environmental improvement of rural houses in different countries. It reviews them in three aspects: thermal comfort on rural houses, air quality on rural houses, and energy-saving design on rural houses.

2.2.Thermal comfort in rural houses

Thermal comfort is an essential indicator of residents' satisfaction with the indoor thermal environment. Research on thermal comfort evaluation of buildings mainly started in the 1920s. Influenced by the energy crisis, the development of thermal comfort became more rapid after the 1960s, and people realized that while pursuing low energy consumption, they should also pay attention to the comfort of the indoor environment.

Research on indoor thermal comfort in China has been conducted at a late stage. It was not until the 1980s that scholars began to pay attention to the issue of the human-environment relationship and carried out relevant research. Studies on indoor thermal comfort in rural houses in winter mainly focus on severe cold areas and cold regions, analysed indoor thermal environment indicators from different perspectives.

The current research on thermal comfort of rural houses can be divided into three main aspects from theory and practice: thermal comfort evaluation index, residential thermal comfort evaluation research, and residential thermal comfort improvement research.

2.2.1.Thermal comfort evaluation index

(1) England

The U.K. was the first country to research thermal comfort evaluation indexes. In 1914, Leonard in the U.K. first proposed the Kata cooling capacity index, which integrates the effects of average radiation temperature, air temperature and airflow rate. In 1932, Dufton proposed the Equivalent temperature index. In 1976, Mcintyre proposed the subjective temperature index and the calculation formula, which separated the human variable from the environmental variable for practical application and was widely accepted [4].

(2) America

The research on thermal comfort evaluation index is also relatively early in the U.S. In 1923, Houghton and Yaglon proposed the effective temperature index E.T. and was widely used in air conditioning room design, but there were defects such as overestimation of the effect of humidity in low-temperature conditions [5]. In 1932, Vernon and Warner used the black sphere temperature instead of the dry sphere temperature to correct the thermal radiation and proposed the Corrected Effective Temperature (CET). In 1936, Bedford made field measurements and questionnaire surveys of the thermal environment of the factory using a kata thermometer and Mark I anthropomorphic apparatus, and obtained an analytical expression for equivalent temperature by regression analysis, and proposed the Bayesian scale, which combined thermal sensation and thermal comfort into one. In

1950, Yaglou modified thermal radiation and proposed the concept of equivalent effective temperature [4]. In 1971, Gagge introduced the concept of skin wettability based on effective temperature E.T. and proposed the concept of E.T.* (New Effective Temperature). After it gained wide application, the standard practical temperature index SET (Standard Effective Temperature) was proposed based on new effective temperature by considering the effects of different activity levels and thermal resistance of clothing [6-7].

(3) Denmark

In 1967, P.O. Fanger proposed the well-known thermal comfort equation based on experimental data. In 1970, he proposed the PMV (Predicted Mean Vote) and PPD (Predicted Percent Dissatisfied) index, which is the most comprehensive thermal environment evaluation index to date and was adopted by the ISO7730 standard published by the International Organization for Standardization (ISO) in 1984. However, the PMV model is often biased in predicting the thermal sensations in the natural environment, especially in naturally ventilated buildings and buildings where people can regulate themselves; the bias will be more significant [8-9].

Table 2.1. Thermal environment evaluation index theory

Country	Authors (Year)	Main indicators	Core Indexes
America	Houghton, Yaglon (1923)	ET (Effective Temperature)	Dry bulb temperature, 100% relative humidity, airflow rate
	Vernon, Warner (1932)	CET (Corrected Effective Temperature)	Black sphere temperature, 100% relative humidity, air flow rate
	Bedford (1936)	Bechtel scale	Air temperature, thermal radiation, airflow rate
	Yaglou (1950)	Equivalent effective temperature	Air temperature, thermal radiation, airflow rate
	Gagge (1971)	ET*(New Effective Temperature) SET (Standard Effective Temperature)	Air temperature, 50% relative humidity, average radiation temperature, true skin temperature, skin moistness

Table 2.1. (Continued)

Country	Authors (Year)	Main indicators	Core Indexes
England	Leonard hill (1914)	Kata cooling capacity index	Average radiation temperature, air temperature, airflow rate
	Dufton (1932)	Equivalent temperature	Air temperature, thermal radiation, airflow rate
	Mcintyre (1976)	Subjective temperature	Air temperature, average radiation temperature, 0.1m/s relative air flow rate, 50% relative humidity
Denmark	P.O. Fanger (1967)	Thermal comfort equation	Average radiation temperature, air temperature, air humidity, human thermal equilibrium state, average skin temperature, human sweating rate
	P.O. Fanger (1970)	PMV（Predicted Mean Vote） PPD（Predicted Percent Dissatisfied）	Average radiation temperature, air temperature, air humidity, human thermal equilibrium state, average skin temperature, human sweating rate, human thermal load

2.2.2.Thermal comfort evaluation in traditional rural houses

With the maturity of the theoretical system of thermal comfort evaluation index, researchers have mainly studied the thermal comfort of buildings in different regions and climates in recent years. The research results are mainly reflected in the evaluation of thermal comfort and improvement of thermal comfort.

Regarding the evaluation of thermal comfort, Rijal and Oikonomou et al. evaluated the thermal comfort of traditional houses in different regions in terms of architecture and climate, including through field visits [10-11]. Nematchoua et al. analysed the thermal comfort adaptability, and the reasons for the differences in thermal comfort evaluations of residents in different climate zones by means of field tests and questionnaires [12-13]. Cao Bin et al. conducted field measurements of indoor thermal environment parameters, including air temperature, wind speed, and relative humidity, in rural houses in different climatic zones and comprehensively considered the effects of different building indoor thermal environment parameters on thermal comfort [14-15]. Wang Zhaojun et al. also studied the thermal adaptation behaviour of residents employing questionnaires and found that residents in traditional buildings are more tolerant of harsh environments and residents will adapt to colder environments through personal behavioural adjustments [16-17]; Hong Jin et al. evaluated indoor thermal sensation in different populations and studied the relationship between population composition and thermal adaptation, which helps to construct a more reasonable thermal comfort evaluation model [18-19].

Table 2.2. Study on the evaluation of thermal comfort of residential buildings

Authors (Year)	Country	Core viewpoints
Rijal (2010)	Nepal	Thermal environment and thermal sensing surveys were conducted in five regions of Nepal for indoor and semi-open spaces of traditional houses, and the results showed that the thermal neutral temperature of semi-open spaces was higher than that of indoor.
Oikonomou （2011）	Greece	The thermal comfort of residences in north-western Greece was assessed in terms of architectural aspects and bio-climatic aspects through literature analysis and fieldwork.
Nematchoua （2014）	Cameroon	Through the questionnaire, analysed the thermal comfort satisfaction of the inhabitants of Cameroon and evaluated the thermal comfort of the residential houses in the area.
Anastasios, et al. （2017）	Holland	Developed methods for measuring quantitative and qualitative parameters affecting thermal comfort in real time and apply them in 30 houses in the Netherlands to further analyse the drawbacks of the PMV model and the reasons for differences in thermal comfort evaluations residence type and subject type.
Bin Cao, et al. （2010）	China	Measured farmhouses' indoor thermal environment parameters in suburban Beijing and recorded the farmers' hot feelings by questionnaire. The results of the study showed that the neutral temperature of farmhouses was 18.4℃, and the lower limit of the acceptable temperature interval was 10.9℃.
Xiping Zhao, et al. （2018）	China	The parameters of indoor and outdoor air temperature, relative humidity and wind speed in a residential district in Qingdao were tested in the field and statistical analysis of questionnaire survey. Applying the climate adaptation model for cold regions, the comfortable summer indoor temperature of naturally ventilated residences in Qingdao was calculated to be 27.57-28.90℃.

Table 2.2. (Continued)

Authors (Year)	**Country**	**Core viewpoints**
Zhaogun Wang, et al. （2014）	China	The average indoor temperature of the farmhouse in winter is 12.3℃, and the inhabitants have 92% acceptable thermal environment; the thermal neutral operating temperature is 14.4℃, the lower limit of the 90% acceptable temperature range is 8.8℃; farmers will adapt to the colder environment through personal behavioural adjustment, resulting in a lower thermal neutral temperature and acceptable temperature.
Jihye Ryu, et al. （2020）	Korea	Conducted On-site monitoring of thermal sensitivity (Griffith's constant) in 11 households in Korea, and it was found that the thermal sensation of residential building occupants was less sensitive to changes in indoor temperature.
Chengcheng Xu, et al. （2018）	China	Residents in traditional houses are more tolerant of harsh environments, with lower thermoneutral temperatures and thermal sensitivity in winter and higher in summer.
Hong Jin, et al. （2017）	China	The resident population of Harbin feels more comfortable in the cold winter months. Men feel more comfortable than women, while older people are better adapted to extreme weather conditions.
Yu Jiao, et al. （2020）	China	To evaluate the indoor thermal comfort sensation of elderly people's homes in winter, the acceptable temperature range for elderly people in Shanghai is 14.1-19.4℃ in winter and 23.8-27.0℃ in summer.

2.2.3.Thermal comfort improvement in traditional rural houses

In the study of thermal comfort improvement, Berkovic et al. investigated the effect of building envelope performance on thermal comfort improvement in different regions using field measurements and software simulations [20-23]. Zhu Dayou found that gypsum phase change materials can effectively regulate indoor temperature and humidity [24]. Huixing Li and Dongji Wang et al. studied the effects of different air supply conditions and heating methods on the indoor thermal environment and thermal comfort of residential houses in rural areas in winter, providing references and suggestions for the improvement of indoor thermal comfort in buildings [25-26].

Table 2.3. Study on the improvement of thermal comfort of residential buildings

Authors (Year)	Country	Core viewpoints
Berkovic (2012)	Israel	Real measurements and simulations investigated the effect of ventilation and shading on the thermal comfort of residential houses in arid regions of Israel.
Üllar (2014)	Northern Europe	Through actual measurements and simulations of the thermal environment of dwellings in Estonia, Finland, Sweden. Investigated the effect of envelope performance on thermal comfort improvement.
Amir, et al. (2018)	United States	Used Whole building energy simulations to estimate the direct and indirect benefits of high albedo roofs on Single-family detached houses at three sites in the Los Angeles, Southern California area. Explore the main determinants of roof effectiveness and the role of climatic conditions on energy use and thermal comfort improvement.
Dinesh, et al. (2021)	Nepal	Field survey in cold, mild and subtropical regions to evaluate the thermal comfort of Nepalese household residents and how it can be improved by strengthening the insulation of houses.
Dayou Zhu (2019)	China	The gypsum-based phase change water storage building material enables efficient temperature and humidity regulation and improves indoor comfort. In hot summer and cold winter regions, the temperature and humidity fluctuations in energy-efficient rooms vary by 0.19°C and 0.4% RH less than those in the standard room.
Huixing Li, Shan Wu (2016)	China	Analysed the influence of different air supply temperatures and speed working conditions on the thermal comfort of the indoor environment. the air supply temperature of 24℃ and air supply speed of 2m/s are determined to meet the requirements of environmental thermal comfort.
Dongji Wang, et al. (2020)	China	Different heating methods have an impact on the indoor environment as well as the thermal comfort of the residents. Under the heater type of air source heat pump, gas wall-hung boiler, biomass boiler and clean coal boiler, the proportion of residents' thermal sensory voting from -1 to +1 are 73%, 66%, 74% and 76%, respectively; the thermal neutral temperature is 18.48℃, 18.21℃, 18.24℃ and 18.88℃ respectively.

2.3.Air quality in rural houses

In the early 18th century, due to environmental pollution brought about by the development of the industrial revolution, researchers gradually began to research air quality. They found that dirty air posed a health risk and began to initial awareness of environmental protection. Scientists are beginning to focus on indoor air quality while assessing the effects of outdoor air pollution. People gradually realize that indoor pollution is far more harmful than outdoor pollution, so various countries and institutions have developed particular research and development programs for indoor air quality. In 1978, an international conference on indoor air quality was held in Copenhagen, Denmark; in 1986, the U.S. Environmental Protection Agency decided to shift its focus to indoor air pollution research; in 1989, the North Atlantic Treaty Organization launched a study on indoor air quality.

Research into indoor air quality and the development of relevant standards in China is later than in developed countries. The earliest research on indoor air quality can be traced back to the early 1980s, when researcher Jiang Hengguang of the Institute of Environmental Chemistry, Chinese Academy of Sciences, measured indoor air pollutants under different fuel use conditions and found that the concentrations of CO, SO_2, particulate matter, and benzo(a)pyrene in homes using cellular coal were significantly higher than those using LPG (Liquefied Petroleum Gas). CO pollution is higher indoors than outdoors, and SO_2 pollution is higher outdoors than indoors [27].

2.3.1.Air quality standards

Ambient air quality standards are an essential means of controlling environmental pollution. As global environmental pollution. In 1987, WHO issued the Air quality guidelines for Europe, which set air quality concentration limits for organic pollutants, inorganic pollutants, conventional pollutants, and characteristic indoor pollutants [28]. In the revised guidelines in 2005, limit values for respirable particulate matter (PM_{10} and $PM_{2.5}$), NO_2, SO_2, and O_3 concentrations were promulgated. In 2010, WHO published the Indoor Air Quality Guidelines for the first time, which published quantitative standards for indoor air toxins that have an impact on health, providing evidence for countries around the world to develop relevant regulations. The report addresses three issues: the dangers of indoor air pollution, the sources of indoor air pollution, and the main pollutants in indoor air, urging governments to take the necessary action to reduce the adverse health effects of these pollutants [29]. This standard was applied worldwide. Currently, air quality standards are gradually being improved in countries worldwide, and the relevant standards and monitoring items are as follows (Table 2.4).

Table 2.4. National air quality standards and monitoring items

Countries and Organizations	Year	Standard	Main monitoring items
WHO	1987	Air quality guidelines for Europe	SO_2, CO, NO_2, O_3, $PM_{2.5}$, PM_{10}
	2005	Air Quality Guideline (AQG)	
	2010	Guidelines for indoor air quality: selected pollutants	
America	1971	NAAQS	O_3, CO, NO_2, O_3, $PM_{2.5}$, PM_{10}, Pb
	2010	NAAQS Revised	
Europe	1999	Directive on Limit Values for SO_2, NO_2, NOX, PM_{10}, Pb in Ambient Air	SO_2, CO, NO_2, O_3, $PM_{2.5}$, PM_{10}, Pb, Benzene, BaP, As, Cd, Ni
	2000	Directive on Limit Values for Benzene and CO in Ambient Air	
	2002	The Directive on O_3 in Ambient Air	
	2004	Directive on Arsenic, Cadmium, Mercury, Nickel and Polycyclic Aromatic Hydrocarbons in Ambient Air	
	2008	Directive on Air Quality and Cleaner Air in Europe	
Japan	1973	Japanese Environmental Quality Standards	SO_2, CO, NO_2, PM_1, Benzene, Photochemical oxidant, Trichloroethylene, Perchloroethylene, Dichloromethane (Methylene chloride), Dioxin
China	1996	Ambient air quality standards (GB3095－1996)	SO_2, CO, NO_2, O_3, $PM_{2.5}$, PM_{10}, TSP, Pb, BaP, Fluoride
	2010	Ambient air quality standards (GB3095－1996) modification	
	2012	Ambient air quality standards (GB3095－2012)	
	2018	Ambient air quality standards (GB3095－2012) modification	

2.3.2.Studies on factors influencing indoor air quality

With the development of energy-saving and air quality improvement in cities, some scholars have begun to focus on relatively backward rural areas. It was found that rural indoor air quality is mainly related to behaviours such as winter heating and daily cooking activities.

Zhang et al, through field measurements found that indoor air quality in rural houses in northern China was strongly related to gases produced by burning coal and biomass during rural heating and cooking, and that different fuels had different degrees of impact on air quality in farm houses, among others [30-31]. Jyoti et al. tested rural residential air quality parameters in different countries and found that biomass fuels produce large amounts of Inhalable particulate matter and CO_2, etc., during combustion [32-33]. High concentrations of Inhalable particulate matter are more likely to cause serious health problems [34]. Wang et al. measured indoor air quality parameters in rural houses and found that air quality in farmhouses was mainly related to parameters such as CO, CO_2, respirable particulate matter, formaldehyde, and TVOC concentrations [35]. Fabienne et al. found that the most influential factors on indoor air quality in rural areas were $PM_{2.5}$ and CO_2 concentrations and suggested that the burning of biomass fuels should be reduced [36-37]. Deepti et al. concluded that indoor air quality is related to biomass fuel combustion spaces [38].

Table 2.5. Air quality influences factors in rural houses

Authors (Year)	Country	Main influencing factors	Core viewpoints
Xueyan Zhang, et al (2015)	China	CO_2, PM_{10}	Measured smoke emissions and soot composition from biomass combustion during heating and cooking in rural areas, found significant differences in the effects of different fuel combustion efficiencies and energy consumption patterns on indoor air quality in rural houses.
Zhang Yue, et al. (2018)	China	CO, $PM_{2.5}$, TVOC	Different cooking energy sources have different levels of impact on air quality in residential kitchens. used liquefied petroleum gas (LPG) as a cooking energy source, CO pollution is severe, while $PM_{2.5}$ and TVOC concentrations are low. Used straw as the cooking energy source, $PM_{2.5}$ concentrations are severely exceeded and TVOC concentration levels were higher than the former.

Table 2.5. (Continued)

Authors (Year)	**Country**	**Main influencing factors**	**Core viewpoints**
Jyoti (2001)	India	PM_{10}	Tests on a rural house in India found that unprocessed biomass fuels produce 10-100 times more Inhalable particulate matter during combustion than modern fuels.
Wangchu, et al. (2016)	Bhutan	$PM_{2.5}$, CO_2	Study of indoor air quality in Bhutan during cooking and heating with three types of biomass-fuelled stoves (metal chimney stoves, traditional mud stoves and stone tripod stoves), showed that indoor $PM_{2.5}$ and CO_2 levels were 40 and 18 times higher than usual during the operation of the stoves.
Turčina (2021)	America	Fine PM	High concentrations of fine particles are more likely to enter the body, which can lead to serious health problems.
Fang Wang, et al. (2016)	China	Temperature, Relative Humidity, CO, CO_2, $PM_{2.5}$, PM	Monitored Indoor air quality parameters such as temperature, relative humidity, CO and CO_2 concentrations, $PM_{2.5}$ and PM_{10}. the study showed that the way residential heating energy is used has a significant impact on indoor air quality.
Fabienne, et al. (2011)	Australia	$PM_{2.5}$	Air quality monitoring in rural southern Australia has shown that indoor air quality is heavily influenced by smoke from biomass burning, with $PM_{2.5}$ having the most significant impact.
Mitchell (2017)	New Zealand	PM concentration	Surveyed Several rural communities in New Zealand, found wood-burning contribute to up to 95% of ambient winter PM concentrations, with residential solid fuel burning having a more severe impact on air quality.
Deepti and Suresh (2019)	India	Openness and particulate matter	Studied the effect of biomass combustion on indoor air quality in rural house in northern India under three kitchen characteristics: closed, semi-closed and the open type.

2.3.3.Research on improvement of indoor air quality

Cheng used a combination of household testing and questionnaire research and found that indoor ventilation can effectively reduce the concentration of indoor pollutants [39]; Cheng et al. studied the indoor air quality and energy consumption of typical houses under different purification methods to provide a selection basis and data support for selecting appropriate ventilation methods for houses in rural areas [40]. Liv et al. developed a residential indoor air quality model to assess indoor air quality by simulating CO_2 and indoor pollutant ($PM_{2.5}$, UFP, O_3, NO_2, VOC and aldehyde) concentrations [41-42]. Mamdooh et al. investigated the effect of air catcher shape on indoor air velocity and the improvement effect on indoor air quality [43].

Table 2.6. Air quality influences factors in rural houses

Authors (Year)	Country	Improvement methods	Core viewpoints
Rongsai Cheng (2018)	China	Indoor ventilation	Indoor ventilation was found to be effective in reducing indoor pollutant concentrations. Formaldehyde and VOC concentrations are influenced by indoor temperature and absolute humidity.
Xionglei Cheng (2018)	China	Fresh air system, Purifier purification	Compared the indoor air quality and residential energy consumption of a typical house with fresh air system and purifier purification methods. Found that purifiers were more effective than fresh air systems.
Torkan, et al. (2018)	America	Improved model	Developed a residential energy and indoor air quality improvement model. Annual space conditioning energy consumption of the US household stock was predicted by modelling indoor pollutants including $PM_{2.5}$, UFP, O_3, NO_2.
Hari, et al. (2021)	America	Improved model	Developed a building model to predict indoor pollutant (O_3, formaldehyde, particulate matter) concentrations.
Mamdooh, et al. (2020)	Saudi Arabia	New and innovative wind catcher designs	Research new and innovative wind catcher designs to increase indoor air velocity and thus improve indoor comfort and indoor air quality. Studies have shown that curved shapes have the highest wind speed drive pattern.

2.4.Energy-saving design on rural houses

At the beginning of the 20th century, numerous scholars have already conducted research on energy-saving in buildings, including energy-saving in rural houses. Current research on the design of rural residential energy-saving is divided into three main areas: energy-saving design standards for rural houses, building envelope renovation, and sunroom design.; in terms of research methods, there are two main approaches: actual measurements and simulations through building energy simulation software.

China's research on rural residential energy-saving began in the early 1980s. In 1983, Wang Ruihua and others conducted renovation experiments on rural houses in Beijing and other places, and proposed renovation strategies for the architectural form, building orientation, and envelope structure of houses [44]. At present, through the unremitting efforts of many scholars, the work on building energy-saving has achieved specific results.

2.4.1.Relative standards in rural houses

With the development of the industrial revolution, the global ecological and environmental crisis, resource and energy shortages, and abnormal climate changes have become increasingly severe. After the oil crisis in the 1970s, countries around the world realized the importance of building energy-saving, developed countries took the lead in formulating relevant policies and standards to achieve building energy-saving goals. At the same time, the development of energy-saving standards in developing countries has been relatively slow. However, with the development of the economy and the country's emphasis on the environment, China's building energy-saving standards have gradually shown a trend of diversification.

This Study summarizes the trends and experience gained in the development of energy-saving standards in Germany, the United States, Japan, and other developed countries and China,

(1) Germany

Germany's building energy-saving has an early origin, which has been concerned with building energy-saving since 1938 when the standard *DIN 4110 - Insulation of High-Rise Buildings* was promulgated. In 1977, Germany enacted its first building energy-saving regulation, *the Building Insulation Ordinance* (WSVO 1977), which requires new buildings must have energy-saving insulation design. This regulation spawned several building energy efficiencies regulations, such as *the Building Insulation Ordinance* and *the Heating Equipment Ordinance*, it set requirements for reducing carbon emissions. The two regulations mentioned above were combined in 2002 to become the new version of *the Building Energy Efficiency Regulation* (EnEV 2002), which has now been updated for the 2016 edition. To implement the requirements in the EU published *Building Energy Efficiency Directive 2010*, Germany implemented *the Energy Conservation Act (2013ENEG)* in 2013. in 2020, Germany enacted *the Building Energy Act (2020GEG)*, integrating the existing *Building Energy Efficiency Ordinance*, *the Energy Conservation Ac*t and *the Act on the Promotion of Renewable Energy for Heating* into a German implementation of near-zero energy simpler and more transparent legal framework for building standards [45].

Table 2.7. Development of energy efficiency standards for rural housing in Germany

Year	Standard	Core viewpoints
1938	DIN 4110 - Insulation of high-rise buildings	The insulation performance of the envelope was proposed: The thermal resistance value of the external wall shall not be less than 0.47 ($m^2 \cdot K$) W.
1977	Building Insulation Regulations (WSVO 1977)	New buildings must have an energy-saving insulation design and limit their envelope and amount of heat loss.
2002	Building Energy Efficiency Regulations (EnEV 2002)	Take Converting individual building envelope energy-saving insulation targets into actual building energy consumption. Before the new building is started, it should meet the standard of heat loss of the peripheral structure, the standard of the core value of energy consumption of the building, and the standard of energy needed for heating.
2013	Energy Conservation Act (EnEG 2013)	New buildings owned or used by the German government should achieve near-zero energy building levels from January 1, 2019.All new buildings should achieve near-zero energy building levels from January 1, 2021.
2020	Building Energy Act (2020GEG)	The building's energy consumption for heating, cooling, ventilation, and hot water lighting must be less than 75% of the reference building's 50kWh/($m^2 \cdot a$) energy consumption as defined by the Act.

(2) America

In 1975, the U.S. began to focus on building energy-saving and enacted *the Energy Policy and Conservation Act 1975*, which mandated that energy-saving state energy-saving plans should include: mandatory lighting energy-saving standards for non-government buildings; mandatory government energy-saving procurement regulation; and mandatory minimum temperature performance requirements for non-government buildings [46]. In 1992, The *Energy Policy Act of 1992* was enacted

[47]. This legislation established that the department of energy would continue to be responsible for preparing and promoting building energy-saving standards. And provided that the standards prepared by ASHRAE would be the fundamental energy codes for public buildings and mid-rise residential buildings established the American Society of Building Officials standards as the base energy code for low-rise residential buildings. The most widely used codes in the United States are *the IECC Standards*, which are revised every three years, and *the Energy Conservation Code for Buildings Other Than Low-Rise Residential Buildings.* [48]. *The IECC Standard* mainly applies to residential buildings of three floors and less and all public buildings; *the Energy Conservation Code for Buildings Other Than Low-Rise Residential Buildings* is the most influential building energy design standard in the U.S. and global, focusing on the energy design requirements for public buildings and residential buildings with more than three floors [49].

Table 2.8. Development of energy efficiency standards for rural housing in America

Year	Standard	Core viewpoints
1975	Energy Policy and Conservation Act 1975	Begin to focus on building energy-saving by requiring that energy-saving state plans include: mandatory lighting energy-saving standards for non-government buildings, mandatory government energy-saving procurement regulation, mandatory minimum temperature performance requirements for non-government buildings.
1992	Energy Policy Act 1992	This legislation established that the department of energy would continue to be responsible for preparing and promoting building energy-saving standards. and provided that the standards prepared by ASHRAE would be the fundamental energy codes for public buildings and mid-rise residential buildings established the American Society of Building Officials standards as the base energy code for low-rise residential buildings.
2018/ 2021	International Energy Conservation Standards IECC Standards	Originated from the 1977 Basic Code for Energy Conservation in New Buildings prepared by CABO, the name of this standard was adjusted to Basic Energy Conservation Code in 1983, the name was changed to IECC Standard.
2019	Energy Conservation Code for Buildings other than Low-Rise Residential Buildings	Energy Conservation Code for Buildings other than Low-Rise Residential Buildings

(3) Japan

The Japanese government enacted *the Energy Conservation Law* in 1979, after which it served as the foundation law for Japan's energy-saving policy. Under the requirements of *the Energy Conservation Law*, requirements, the Japanese government enacted the Energy Conservation Standard for Residential Buildings in 1980, which provided detailed regulations on three aspects of residential buildings: thermal performance of the external envelope, primary energy consumption, and design methods. Effectively reducing the energy consumption of residential buildings [50] In 2013, *the Energy Conservation Standard for Residential Buildings* and *the Energy Conservation Standard for Public Buildings* were integrated into one standard, *the Building Energy Conservation Standard 2013* [51], this standard reorganized the entire standard system. It adopted design primary energy consumption as the measurement index. In addition, to promote the development of building energy-saving, the Japanese government has launched a series of financial incentives subsidy programs, such as the priority program for CO_2 emission reduction in residential buildings, the energy-saving renovation promotion program, the residential zero energy promotion program, and the long-term excellent residential renovation program, and so on.

Table 2.9. Development of energy efficiency standards for rural housing in Japan

Year	Standard	Core viewpoints
1979	Energy Conservation Act	The laws underlying Japan's energy conservation policy were revised several times in 1983, 1993, 1998, 2002, 2005, and 2008.
1980	Energy Efficiency Standards for Residential Buildings	In 2013, *the Energy Conservation Standard for Residential Buildings* and *the Energy Conservation Standard for Public Buildings* were integrated into one standard, *the Building Energy Conservation Standard 2013*. This standard reorganized the entire standard system and adopted design primary energy consumption as the measurement index. In addition, to promote the development of building energy-saving.
1997	Law on the Rationalization of Energy Use	The previous energy conservation standards have been revised and improved, and the annual air conditioning and heating load standard for residential buildings has been added as a comprehensive evaluation of building energy-saving.
2000	Law on the Promotion of Quality Assurance in Housing	A residential performance indication system has been established to evaluate the current performance of residential buildings in terms of thermal performance, durability and air quality and to maintain and manage and repair and renovate poorly performing buildings.

Table 2.9. (Continued)

Year	Standard	Core viewpoints
2001	Comprehensive performance evaluation system for the built environment	The environmental quality and performance of the building and the external environmental load of the building are evaluated, and a 5-point rating system is used.
2013	Energy Efficiency Standards for Buildings 2013	The energy-saving standards for residential and public buildings were integrated into one standard system, and the primary energy consumption design was adopted as the measurement index.
2014	Building Energy Performance Indication System	Promoted energy-saving

(4) China

The standardization of building energy-saving in China started in the 1980s, it has gone through three main development stages: the initial stage (early 1980s-early 1990s), the development stage (1995-2005), and the comprehensive promotion stage (2005-present) [52].

The JGJ 26-1986 *Energy-saving Design Standards for Civil Buildings -Heating Residential Buildings*, promulgated in 1986, was China's first energy-saving design standard for buildings. This period was the initial stage of China's building energy-saving efforts, with a target energy-saving rate of 30%.

In 1995, *JGJ 26-1995 Energy Conservation Design Standards for Civil Buildings -Heating and Residential Buildings* symbolized the beginning of the development period of China's building energy-saving work, with a target energy-saving rate of 50%. During this period, *JGJ 26-1995 Energy-saving Design Standards for Civil Buildings -Heating Residential Buildings Part-* was re-revised and completed, and three standards were formulated: *JGJ 134-2001 Energy-saving Design Standards for Residential Buildings in Hot Summer and Cold Winter Areas, JGJ 75-2003 Energy-saving Design Standards for Energy Conservation Design Standards for Residential Buildings in Hot Summer and Warm Winter Areas, and GB 50189-2005 Energy Conservation Design Standards for Public Buildings.* At this period, China's building energy-saving efforts were on the right track.

After 2005, the standardization of building energy-saving in China entered a period of comprehensive promotion, building energy-saving standards were gradually revised and improved. In 2010, *JGJ 26-1995 Energy-saving Design Standards for Civil Buildings-Heating Residential Buildings Part*, was renamed *JGJ 26-2010 Energy-saving Design Standards for Residential Buildings in Severe Cold and*

Cold Areas, the energy-saving target was increased to 65%.

In 2013, China promulgated the first energy-saving renovation standard for rural areas: *Energy-saving Design Standards for Rural Residential Buildings*, to improve the indoor comfort of existing rural houses and propose different renovation technical measures for buildings in different areas; it greatly contributed the Coordinated sustainability of the rural environment and improved rural residential comfort.

Table 2.10. Development of energy- saving standards for rural houses in China

Year	Standard	Core viewpoints
1986	GJ 26-1986	The energy-saving rate is targeted at 30 per cent. Of this, buildings are responsible for approximately 20 per cent and heating systems for approximately 10 per cent.
1995	JGJ 26-1995	The target energy-savings rate is 50%.
2010	JGJ 26-2010	Targeted energy-savings rate of 65%.
2013	GBT 50824-2013	The standard requires the heat transfer coefficient K≤0.40W/(m^2·K≤0.50W/(m^2·K) for external walls and K≤2.20 W/(m^2·K) for external windows in harsh cold regions, and the calculated indoor temperature in winter is 14°C.
2019	GJ 26-1986	Energy-saving improved by more than 30%, heat transfer coefficient ≤ 0.50 W/(m^2·K) for external walls, heat transfer coefficient K ≤ 2.80 W/(m^2·K) for external windows
2010	JGJ 26-1995	Energy Conservation Design Standards for Civil Buildings (Heating Residential Buildings) Encouraged and supported scientific research and technological development in civil building energy conservation and promoting new technologies, techniques, materials and equipment for civil building energy conservation. Set up special funds for energy conservation in residential buildings built by farmers.

In order to respond to the energy-saving policies and standards promulgated by China, Shandong Province issued *JD 14-046-2019 Technical Guidelines for Energy-saving Renovation of Rural Existing Residential Building Envelopes in Shandong Province (for Trial Implementation)* and proposed that the renovation of rural existing residential buildings should take into account the level of local economic development, It is desirable to achieve more than 30% improvement in energy-saving after renovation. In 2010, Qingdao City issued the *Qingdao Civil In 2010, Qingdao City issued the Regulations on Energy Conservation in Civil Buildings*, which aimed to encourage and support the energy-saving renovation of civil buildings.

2.4.2.Energy-saving design of the building envelope

(1) Energy-saving design of building walls

The thermal performance of the envelope is an essential factor in the energy consumption of a building [53]. In 2014, Damyar S simulated with eQUEST energy simulation software and found that renovation upgrades to the roof, windows, external walls, balconies, floor edges and ground floor slabs of a prototype building in Toronto resulted in energy-savings of 0.8%, 9.4%, 27%, 2% and 2.2%, respectively [54]. By combing through foreign literature on building energy-saving design, domestic and foreign scholars have mainly focused on three aspects of the energy-saving design of the external envelope: walls, windows and doors, and roofs.

In terms of energy-saving design of the building envelope, Qing Suan et al. studied the building envelope in rural areas and found that external insulation of the building envelope was more helpful in reducing building energy consumption and reducing the magnitude of indoor temperature variation [55]. Wei Ling et al. conducted an energy-saving optimization design of rural houses in severe cold areas by means of actual measurements and software simulations, and found that constructing external walls with straw bricks can substantially save energy and reduce environmental pollution [56-57]. Nicolae et al. have evaluated the common high performance insulation materials available [58-59]. Chen Cellophane Jing et al. studied the performance of common external wall insulation materials: XPS, PU and other insulation panels, and the thickness of the insulation layer for optimal energy efficiency [60]. Mandilaras et al. developed new insulation and energy-saving materials such as vacuum insulation panels or PCM-based composite integrated walls in external walls, reducing the thermal conductivity of walls and heat loss [61-62]. Tan Yufei et al. studied new energy-saving materials for external wall insulation: the GTC solar wall system, 3D-VtGW, etc., which provide a reference for energy-saving insulation in the new era [63-64]. Mohamad et al. found that when renovating old external walls, the use of aerogel plaster with low radiation coating and infrared reflective wall paint can reduce heat loss, building energy consumption and save economic expenses and reduce the damage to valuable historical buildings [65-66].

Table 2.11. Energy-saving design of building walls

Authors (Year)	Country	Research materials	Core viewpoints
Qing shan (2018)	China	Rigid polyurethane insulation board	The results show that rigid polyurethane insulation panels help reduce building energy consumption and reduce the magnitude of indoor temperature variation when they are used for external wall insulation compared to internal insulation.
Wei Ling, et al. (2015)	China	Grass tile eco wall	The annual energy consumption, CO_2 consumption and ecological footprint of eco-buildings are lower than conventional houses, 69.61%, 17.5t and 99.47%, respectively.
Jiang Mu (2019)	China	straw brick	Simulations with energy simulation software show that replacing the envelope of a traditional farmhouse with a new straw brick envelope can result in a 45.5% energy-savings.
Nicolae, et al. (2015)	Romania	EPS, XPS, PUR	EPS is the best insulation, XPS is more durable than PUR, and EPS and XPS polystyrene are more flammable than PUR polyurethane.
Yassine (2017)	Morocco	PCM layer (epcm)	The optimum thickness of the PCM layer (epcm) in the wall envelope is between 0.5 and 2 cm; the optimum melting temperature of the PCM is 20°C.
Chen Dingjing, et al (2017)	China	XPS insulation board	When the thickness of the XPS insulation board is equal to 40mm, the highest energy-saving rate; plastic steel hollow glass windows can significantly improve the overall performance of the window, energy-saving rate of up to 50.78%.
Mandilaras, et al. (2014)	Greece	Vacuum Insulation Board	Incorporating vacuum insulated panels into external walls reduces the thermal conductivity of the walls; the thermal resistance of vacuum insulated panels is higher than that of traditional polystyrene panels, making them more conducive to building insulation.

Table 2.11. (Continued)

Authors (Year)	Country	Research materials	Core viewpoints
Ravi, et al. (2019)	America	PCM and DIMS Integrated Wall	Phase change material PCM and Dynamic Insulation Material System DIMS integrated walls have a higher energy-saving potential than DIMS integrated walls only or PCM integrated walls only. PCM-DIMS integrated walls can reduce annual heat gain by 15-72% and annual heat loss by 7-38%.
Tan Yufei, et al (2016)	China	Solar wall system with glass transmissive collectors	A solar wall system with GTC was proposed for the poor thermal comfort caused by heating in rural areas of Northeast China, and the average indoor temperature increased from 12.12°C to 16.17-18.19°C.
Yawen He, et al. (2020)	China	3D-VtGW Wall	3D-VtGW buildings offer significant potential for energy-savings and improved thermal comfort. 3D-VtGW's integrated greening system significantly reduces external wall temperatures and over-wall heat fluxes through the combined effects of plant shading, evaporation and soil heat storage.
Mohamad, et al. (2018)	French	Aerogel plaster with low radiation coating	When refurbishing old walls, aerogel plaster with a 0.5cm and 1cm low-e coating can reduce energy consumption by 21% and 30% respectively.
Sebastian Malz, et al. (2020)	Germany	Infrared reflective wall paint	Infrared reflective wall paint combined with historic brick masonry can reduce heat loss by 18%.

(2) Energy-saving design of building roofs

Concerning the energy-saving design of building roofs, Yang Panpan, through actual measurements and software simulations for rural houses in cold areas, concluded that the heat consumption of buildings is ranked as follows: external walls > roofs > air leakage > floors and external doors and windows, indicating that the roofs of buildings have a significant influence on building energy consumption [67-68]. Amir et al., through software simulations, found that roofs treated with reflective insulation can save energy and improve the thermal comfort of buildings [69-71]. Kasun et al. developed a new roof insulation system to reduce the peak cold load [72]. Fan et al. developed a new roof energy-saving system, analysed it compared to conventional roofs, and found that it can significantly improve energy-saving [73-75]. Momose et al. found that green roofs can also provide thermal insulation in winter and compared roofs with Comparative Analysis [76].

Table 2.12. Energy-saving design of building roofs

Authors (Year)	Country	Research Material	Core viewpoints
Haie Huo (2017)	China	—	The key components for taking energy-saving measures are the roof and the wall.
Yang Panpan (2019)	China	Rigid polyurethane foam	The energy-saving contribution of roofs is second only to that of walls. Rigid polyurethane foam sloped roofs are the most energy efficient, with energy-savings of up to 27.97 %.
Amir, et al. (2018)	America	High albedo roofs	High albedo roofs save 41% of energy and improve thermal comfort by 23% in residential buildings
Stefano, et al. (2019)	Italy	Reflective Insulated Roof	The reduction of summer heat gain in the interior of roofs treated with reflective insulation ranges from 10% to 53%
Luis (2020)	Argentina	Low IR emissivity insulation	Insulation of the roof by multiple air gaps separated by low IR emissivity insulation, saving up to 53% material compared to solid EPS insulation
Kasun, et al. (2020)	England	New roof insulation system	Investigated a new roof insulation system and computer simulations showed that it could achieve a peak cooling load reduction of about 20% on a sunny tropical day.
Yuling Fan, et al. (2017)	China	Rooftop solar panel systems	Simulated the degradation of rooftop solar panels and studied maintenance options. To achieve energy sustainability and its long-term impact on the renovation program.

Table 2.12. (Continued)

Authors (Year)	**Country**	**Research Material**	**Core viewpoints**
Dongliang Zhao, et al. (2019)	China	Rooftop integrated radiant air cooling system	For single-family homes, an integrated radiant air cooling system on the roof can reduce attic temperatures by a significant 15.5-21.0°C compared to a typical summer flat roof.
Jianying Hu, et al. (2019)	China	TC Roof	Compared to conventional envelopes, the use of TC roofing saves 13% of total energy consumption and reduces CO_2 emissions by 4%. The increase in TC roof thickness increases total energy-savings by 29% and reduces CO_2 emissions by 8%.
Momose (2021)	Japan	Roof vegetation types	Compared the heat fluxes of roofs treated with seven different vegetation types in western Japan under winter conditions, measurements revealed that the most vital performing plant type was Luzula capital, which lost 50% less heat than the worst-performing species.

(3) Energy-saving design of building windows and doors

Regarding the energy-saving design of building windows and doors, Ujin Gaohua et al. analysed the performance indicators of windows, explored the relationship between external windows and building energy efficiency, and selected the optimal window types for each region of China [77]. Papaefthimiou et al. used vacuum technology and chemical methods to manufacture electrochromic vacuum glass and tested its durability performance, and found that electrochromic windows can significantly reduce the energy consumption of buildings [78-79]. Hassouneh et al. find significant savings in building energy consumption with insulated glass windows [80]. Tan, Liangcai et al., studied to obtain the most suitable thickness of glass or air interlayer for different building types by software simulation [81-82]. Kiran et al. found that building energy-saving is related to the colour and reflectance of glass windows through field measurements and software simulations [83]. Gorantla identified the best energy-saving window system by comparing different colour combinations of inflatable double-pane reflective glass windows [84]. Wang et al. found that the new composite coated windows positively impact both the indoor thermal environment and the energy-saving of insulation in buildings [85-86]. Rahman et al. found that SNG-SC window renovation coating, the nano-vo2 coating, can adjust the size of window light transmission, thereby reducing the energy consumption of the building [87-88].

Table 2.13. Energy-saving design of building windows and doors

Authors (Year)	Country	Research materials	Core viewpoints
Wujin Gaohua (2005)	China	—	By analysing the external window heat transfer coefficient, orientation, and airtightness, explored the relationship between external windows and building energy-saving and proposed a method for the energy-saving design of external windows for residential buildings in Baotou, Inner Mongolia
Papaefthimiou, et al. (2006)	Greece	Electrochromic vacuum glass	Electrochromic vacuum glass was manufactured using vacuum technology and chemical methods and tested for durability performance.
Soheil (2021)	Iranian	Electrochromic (EC) windows	Electrochromic (E.C.) windows and other tools have reduced the building's energy consumption by 35.57%.
Hassouneh, et al. (2010)	Jordan	insulating glass window Low-E insulating glass windows	Insulating glass in the south direction saves five times more energy than regular glass, and Low-E insulating glass windows should be preferred in the north direction.
Tan Liangcai (2004)	China	Ordinary insulating glass	In residential buildings, the most energy-saving glazing is 8mm+8 mm plain insulating. The energy-saving potential is more significant in the northwest direction than in the south direction, and energy-saving windows should be better placed mainly in the northwest direction.
Hong Yang (2020)	China	Plastic insulated glass casement window	Replace ordinary single-glass wooden windows with plastic insulating glass casement windows, plus sealing materials, with 12mm air layer in the middle of the glass, which can improve the thermal insulation and airtight performance of external windows and airtight performance of doors and windows.

Table 2.13. (Continued)

Authors (Year)	Country	Research materials	Core viewpoints
Kiran, et al. (2017)	India	Bronze reflective glass window	Mudbrick wall buildings with bronze reflective glass windows lost the least heat; mud-brick wall buildings with bronze, green and bronze reflective glass gained 2.52%, 3.83%, and 6.46% less heat through the walls than those with mud-brick wall buildings with clear glass windows, respectively.
Gorantla, et al. (2020)	India	10mm air gap double glazed ash gold reflective glass combination windows	Double glazed grey reflective glass combination C13 (grey reflective glass - air gap 10mm - gold reflective glass) window system saves the highest annual net cooling and heating costs
Dongming Wang (2019)	China	F+TiO_2 coating	The F+TiO_2 thin-film energy-saving window coating reduced the interior temperature of the hot box by 5.3 ℃ Celsius in the thermal test.
Sen Lin (2019)	China	(AgNWs/PVB) coating	AgNWs/PVB coatings have high visible light transmission (83.0%), high mid-infrared reflectivity (69.8%), low emissivity, and good thermal insulation properties.
Rahman (2019)	Canada	SNG-SC window renovation coating, low-e argon glass unit	The SNG-SC window refurbishment coating provides annual energy savings of 13-16%, while the replacement windows with low-e argon glass units provide energy efficiency of 11-22%.
Marina, et al. (2021)	Australia	Nano-VO_2 Coated Glass	By adjusting the magnitude of light transmittance and coating nano-VO_2 directly onto the glass, developed thermochromic glass with different light transmittance and corresponding solar modulation. Energy efficiency of 7.1 to 46.4% per year can be achieved.

2.4.3.Indoor heating methods and sunroom design

Solar energy is widely used in domestic energy, such as heating and cooling, lighting, power generation, cooking, hot water, etc., especially in indoor heating. Research on sunroom originated in the United States, where Godfrey L. Cabot et al. developed a solar heating program at MIT in 1938, and they built four experimental sunrooms in succession [89]. Yuanzhe Li proposed that passive sunrooms can be divided into four types: direct benefit type, heat collection and storage wall type, roof heat collection and storage type, and additional sunroom type [90]. Ana Sanchez-Ostiz et al. measured in the field that sunrooms improve the indoor thermal environment and significantly reduce energy consumption [91-92]. Haider. et al. tested the energy-saving rate of passive solar rooms in different regions through software simulations [93-95]. Liu et al. tested the energy-saving of different sunrooms through software simulations and found that the attached sunroom had the highest energy-saving [96]. Li et al., through software simulations, calculated the most suitable parameters about the depth of penetration and window-to-wall ratio for the attached sunroom [97-98].

Table 2.14. Indoor heating methods and passive solar design

Authors (Year)	Country	Core viewpoints
Yuanzhe Li (1993)	China	The passive sunroom can be divided into four types: direct benefit type, heat collection and storage wall type, roof heat collection and storage type, and additional sunroom type
Ana Sanchez-Ostiz (2014)	Spain	Used horizontal heat storage device and vertical heat device as the primary heat collection components, proposed two forms of passive sunroom and compared with ordinary local buildings the final results show that these two passive sunrooms play an effect of improving indoor thermal comfort
Monge-Barrio A. (2015)	Spain	Field tests and simulations of six houses have shown that additional sunrooms can make full use of passive solar heat in winter, reduce heating energy consumption and provide a good thermal environment in summer without air conditioning.
Haider Albayyaa (2019)	Australia	Used passive solar and energy-saving design strategies to build standard fibre and brick veneer houses, the total energy required to heat the house in winter was reduced by 37% and 36%, respectively
Anastasiia An (2020)	China	Used a new Swedish development, the Bysjöstrand eco-village, as the object of Study. The Study shows that passive solar design strategies can reduce annual heating energy consumption by nearly 17%.

Table 2.14. (Continued)

Authors (Year)	Country	Core viewpoints
Yujie Tang (2020)	China	The passive house with auxiliary solar heating technology is about 3℃ higher than the natural room temperature without application, with good effect of regulating room temperature, and the natural room temperature can reach the relevant winter heating standard of 14℃.
Xuiayan Liu (2007)	China	Three types of solar rooms were designed in Daqing: direct benefit type, heat collection and storage wall type and additional sunroom type, and the energy-saving rates of the three solar rooms were 0.66, 0.59 and 0.71 respectively by the SLR method for thermal engineering calculations.
En Li (2016)	China	Based on the widely distributed additional sunroom type passive solar room building in Lhasa, established a model and simulated it using THERB software. It is concluded that the passive solar room can effectively reduce the building energy consumption, and it is more suitable at 1.2m depth.
Guangyu Zou (2016)	China	Considering the human scale factor, the additional sunroom depth of 1200mm-1500mm is appropriate; the window-wall ratio of 0.6-0.7 is appropriate.

2.5.Summary

This chapter compares the current status of research on energy-saving and environmental improvement of rural houses in different countries and finds that scholars in various countries have interpreted the theories and methods of building energy-saving and environmental improvement mainly from three perspectives: thermal comfort of rural houses, the air quality of rural houses, and energy-saving design of rural houses. Objective and detailed analysis of the current research results on building energy-saving and environmental improvement in various countries reveals certain limitations in the existing research. Most of the existing studies have been conducted for designated regions with distinct regional characteristics and climate features. Therefore, the results of the studies are not yet generalizable.

In terms of rural residential thermal comfort research, this paper finds that the thermal comfort evaluation index system has been completed by combing thermal comfort evaluation indexes, residential thermal comfort evaluation research, and residential thermal comfort improvement research in the United States, the United Kingdom, Denmark, China and other countries, but there are fewer research results on thermal comfort indexes in China, and innovative research, in theory, is insufficient. However, at the practical level, due to China's geographical location, the research on thermal comfort evaluation and improvement of residential houses in China is more extensive and comprehensive than in other countries. In this paper, we summarize the experiences of different countries through comparative studies and lay the foundation for the next step of environmental improvement of rural houses.

Indoor air quality is an essential factor affecting human health and is an essential indicator for evaluating the indoor environment of buildings. This chapter focuses on three aspects of air quality standards, factors influencing indoor air quality, and improvement studies. Reading the literature, it is found that the studies on indoor air quality in various countries are similar but have various focuses. Currently, countries pay more attention to the effects of respirable particulate matter and CO_2 on air quality. Studies on air quality improvement in rural houses are mainly at the level of traditional ventilation, and further research is needed to be expanded.

In terms of the energy-saving design of rural houses, the existing literature can be divided into three main areas: energy-saving design standards for rural houses, building envelope renovation, and passive solar design. The existing residential energy-saving standards system has been basically completed, but there are still deficiencies in rural areas. Due to the constraints of economic and technical conditions, which limit the energy-saving of rural houses, the energy-saving standards for rural houses need to continue to be improved. The current building renovation mainly focuses on analysing the single factor of the envelope structure, and the comparative analysis of the combination of each part of the envelope structure with each other is insufficient. In addition, research on passive solar energy has made significant progress in various countries, but in the application of energy-saving in rural houses the further exploration is needed.

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Chapter 3. Methodology of in-site surveys, experiments and simulations

3.1.Introduction

To get a clear picture of the current situation of coastal rural houses in Qingdao, develop appropriate strategies for the energy-saving design and environmental improvement of rural houses. Our team used a range of methods to measure, test, and simulate buildings. This chapter will introduce the theory of collecting data sources, experimental simulations, simulation models, and simulation tools. The main topics covered are field survey methods, SHB-HFM experimental methods, and EnergyPlus simulation methods.

3.2.In-site surveys on the present building state in winter

The investigation process is divided into two stages and three levels. The first stage is research hypothesis and pre-investigation. Through the pre-survey in the typical rural areas of Qingdao, Shandong Province, the problems are found, and then the questionnaire setting is adjusted to make the questionnaire scientific and reasonable to make basic preparations for large-scale, in-depth research. The second stage is the field investigation stage. Go deep into coastal rural areas to feel the life of rural residents and the indoor thermal environment and air quality of rural houses, and conduct rural houses surveying and mapping, thermal environment and air quality testing. Conduct detailed investigation on the current situation of rural houses, heating methods of rural houses, and the living conditions of rural residents through interviews and questionnaires to master first-hand data.

The field investigation stage is divided into three levels. The first level is the investigation of the overall situation of the countryside, that is, through interviews with village cadres to understand the climate characteristics, infrastructure, resources, economic level, customs, population composition, residential type, energy consumption characteristics of the village. The second level is the household survey; 15 rural houses are randomly selected in each village for the household survey. We used a face-to-face interview-based questionnaire for the survey method, taking into account the education level of rural residents and the collection of survey information. The survey method used a face-to-face interview-based questionnaire., survey method adopts a face-to-face interview questionnaire survey. The third level is the combination of questionnaire survey and field test, that is, select typical rural houses such as brick concrete and stone for household questionnaire survey, and conduct field test on indoor and outdoor temperature, relative humidity, indoor polluted gas, heat transfer coefficient of envelopes and other parameters of rural houses. The research at the three levels has different pertinence, including the macro characteristics of the village and the individual differences of each rural house and each villager. At the same time, it makes an in-depth test and research on the typical rural house. The survey data between the three levels can confirm and complement each other, increasing the accuracy and reliability of the survey data.

3.2.1.In-site questionnaire

(1) Content and Methods

This paper analyses rural houses in the northern coastal region using interviews, questionnaires, field tests, and surveys. Collect the basic information of rural houses and rural residents through interviews and questionnaires, master the heating mode of rural houses and the living habits of rural residents, and understand the subjective evaluation of rural residents on indoor thermal environment and smell. Appendix A shows that the main contents include gender, age, family composition, family population, number of permanent residents, etc.

(2) Survey Sample Scale

Firstly, the rural houses in 38 villages (760 households) were preliminarily investigated in 2019. Considering national policy requirements, distribution of rural economic status and years of rural housing construction in Qingdao, this study further screened the villages in Chapter 4, Appendix A, and identified five villages for in-depth study. Since the winter of 2020, further research on rural houses in Qingdao has been carried out, 120 questionnaires have been issued, more than 1000 photos have been taken, and 60 typical rural houses have been tested on the spot. Through the research, the first-hand data of rural houses in the severe cold area of Northeast China have been mastered, which has laid a foundation for the in-depth study of the energy-saving design of rural houses.

(3) Questionnaire design

Questionnaire survey is a research method to collect data by asking questions in writing. It is a standard data collection means of a social survey. It has the characteristics of a vast research scope, easy data statistics and quantitative analysis.

Questionnaire design transforms the research purpose and research content into specific problems, making the research problems specific, organised, and operable to form a series of measurable variables or indicators. Each question in the questionnaire should contribute to the information to be collected or serve a specific purpose. The quality of questionnaire design directly affects the quality of collected data. The questionnaires can be divided from different angles, such as question answers, survey methods, questionnaire purposes, etc. According to the way of answering questions, it can be divided into structural, semi-structural and open. The advantage of a structured questionnaire is that the answers are standardised, and the answers are coded, which is easy to analyse; The meaning of the questions is clear, and the respondents are easy to answer, which is conducive to improving the questionnaire recovery rate; Its disadvantage is that it is difficult to detect when the respondent's understanding of the topic is incorrect; Respondents may have "order deviation" or "position deviation". Some studies have shown that respondents choose the first answer or the last answer for declarative answers. The advantage of an open questionnaire is that the respondents can fully express their views on the questions and get unexpected answers; There are two main disadvantages: first, the answers recorded by the investigators are easy to be mixed with personal bias; Second, the answers are not unified, and it is difficult to sort out and analyse the latest data. Therefore, open questions are suitable for exploratory research and are not suitable for large-scale sampling surveys. The semi-structured questionnaire is structured and open. Its advantage is that it uses open answers to answer structured questions, which can effectively supplement the predetermined answers, make up for the missing information in the questionnaire design, and expand the amount of questionnaire information collection; The disadvantage is that the answers are not unified, which increases the difficulty of later data processing.

According to the research purpose, a questionnaire of rural houses on the north coast is designed. The questionnaire was structured and semi-structured, supplemented by an open-ended format (Appendix A), taking into account the education level of rural residents, the depth of the study, and the amount of information in the study. In the setting of questionnaire language, it is easy for rural residents to understand, minimise the application of professional terms, and use more idioms in Qingdao to facilitate rural residents to correctly understand the problems and ensure the validity of questionnaire data.

The subjective sensation of residents is essential to analyse the indoor thermal environment. The questionnaire design is divided into five parts: surveyed family, architectural form, envelope, heating system, thermal environment and air quality feel. The households surveyed included basic demographic information such as the age, gender, clothing and activity level of the villagers. The architectural form includes architectural function, floor, courtyard layout, construction (transformation) age and other information. The envelope includes the form, material, and structural level of external walls, doors, windows, and roof. The heating system includes heating mode and type, quantity and location of heating facilities. The Thermal Environment and Air Quality Perception Poll includes a tally of votes from residents and volunteers on odour, heat and humidity. The Thermal Sensation Vote (TSV) is based on the American Society of Heating, Refrigeration, and Air-Conditioning Engineering (ASHRAE) seven-point scale.

As shown in Table 3.1, the thermal sensation is divided into ASHRAE 7-point scales: cold (-3), cool (-2), slightly cool (-1), neutral (0), slightly warm (1), warm (2) and hot (3), while humidity sensation is also divided into 7-point scales: very humid (-3), humid (-2), slightly humid (-1), neutral (0), slightly dry (1), dry (2), and very dry (3). In addition, indoor smell intensity is surveyed and divided into 4-point scales: neutral (0), slightly odour (1), odour (2), and pungent odour (3). Since residents have become accustomed to the local climate, separate questionnaires were developed for the residents (Appendix A) and volunteers (Appendix B). Moreover, interviews were held to understand the questionnaire content better.

Table 3.1. Scales of questionnaire parameters

Name	Thermal sensation	Humidity sensation	Indoor smell intensity
-3	Cold	Very humid	--
-2	Cool	Humid	--
-1	Slightly cool	Slightly humid	--
0	Neutral	Neutral	Neutral
1	Slightly warm	Slightly dry	Slightly odour
2	Warm	Dry	Odour
3	Hot	Very dry	Strong odour

3.2.2.In-site building survey

(1) Content of survey

Collect the functional layout and envelope structure of rural houses through field tests. Appendix C shows the main contents: village name, rural houses construction time, construction cost, structural form, roof form, orientation, number of floors, floor height, envelope, etc. The thermal performance of rural houses includes wall materials, wall thickness, insulation layer form, ceiling form, door bucket form, door and window materials, door and window air tightness, heating mode, etc. Moreover, detailed mapping of rural houses, drawing the floor plan, rural houses plan and elevation.

(2) Survey instrument

The construction survey needs to carry out systematic surveys with professional instruments and tools on the layout of rural houses and the dimensions of doors and windows. The types, accuracy and contents of the main test instruments and the photographs of the instruments are listed in Table 3.2.

Table 3.2. Field survey instrument information form

Name	Equipment Information		
	Instrument model	LJD10	
	Function	Measuring length	
Tape Measure	Accuracy	0.001m	
	Measuring range	0-3m	
	Resolution	0.001m	

Table 3.2. (Continued)

Name	Equipment Information		
Laser Rangefinder	Instrument model	UT390A+	
	Function	Measuring length	
	Accuracy	±0.002m	
	Measuring range	0-50m	
	Resolution	0.001m	
Laser level	Instrument model	MBS-8969	
	Function	Output laser vertical plane and horizontal point	
	Accuracy	5m±0.001m	
	Line width	0.002m-5m	
	Resolution	0.001m	
Unmanned Aerial Vehicle	Uncrewed model	DJI Mavic 3	
	Function	Aerial photography	
	Pixel	2000w	
	Flight altitude	0-500m	
	Image transmission distance	0-8000m	

3.2.3.Thermal environment and air quality measurements

(1) Testing Subjects and programs

Appendix C can be divided into two parts. The first part is the thermal environment test of rural houses, and the second part is the indoor air quality test of rural houses. The thermal environment test includes indoor and outdoor air temperature, relative humidity, black ball temperature, etc. The indoor concentrations of CO_2, PM1.0, PM2.5 and PM10 were selected for indoor air quality testing, taking into account the local use of solid fuel materials.

(2) Testing plan and instruments

The thermal environment and air quality test is divided into three stages, including the preparation stage, test stage, and data processing stage. The preparation stage includes commissioning the instrument, preparing the level, dovetail clamp and other test auxiliary supplies, and conducting a pre-test. In the test preparation stage, field test aids have played a significant role in ensuring the smooth completion of the test. Now the field test aids and their functions are listed in Table 3.3. The main experimental instruments and their functions are introduced in detail in the section of test instruments. Table 3.4 shows the accuracy and range of the measuring instruments used. These instruments are calibrated before each use, and their accuracy meets the requirements of relevant standards. In order to ensure good measurement accuracy, the measurement time of each parameter lasts for more than 20 minutes, and the measurement is repeated three times to ensure steady-state conditions. The measurement equipment was placed 1.5 m above the ground in the main room of each building.

Table 3.3. Information form of field test supporting supplies

Field test aids	**Purpose**
Medical vaseline	Stick the heat flow meter sensor tightly to the test object
Adhesive tape	Paste external temperature acquisition recorder
Plasticene	Outdoor fixed external temperature acquisition recorder in a cold climate
Sticking hook	Indoor hanging temperature and humidity acquisition recorder
Glass fibre rope	Hanging temperature and humidity acquisition recorder
scissors	Cut the fibreglass rope
data line	Read temperature and humidity acquisition recorder data
batteries	Equipment backup battery
Wire, plug-in	The power supply of each instrument

Table 3.4. Accuracy and measuring range of measurement instruments

Name	Equipment Information		
iBEM	Tested parameter	CO_2	
	Accuracy	±75ppm	
	Measurement Range	300~5000 ppm	
	Resolution	1ppm	
JTR2020-black bulb temperature indicator	Tested parameter	black bulb and air temperature	
	Accuracy	±0.3°C	
	Measurement Range	-40°C ~80°C	
	Resolution	0.1°C	

Table 3.4. (Continued)

Name	Equipment Information		
JTR01	Tested parameter	Surface heat flow	
	Accuracy	5%	
	Measurement Range	0-2000W/m^2	
	Resolution	0.1W/m^2	
JTR05	Tested parameter	Solar radiation	
	Sensitivity	7~14mv/kw·m^{-2}	
	Measurement Range	0~2000W/m^2	
	Spectral range	0.3~3.2μm	
U9-001 Environmental Status Data Logger	Tested parameter	Relative humidity	
	Accuracy	±5%	
	Measurement Range	0%~99.9%	
	Resolution	1%	
Testo 405i	Tested parameter	Air velocity	
	Accuracy	± (0.1 m/s + 5 % of measured value) (0 ~ 2 m/s) ± (0.3 m/s + 5 % of measured value) (2 ~ 15 m/s)	
	Measurement Range	0 ~ 30 m/s	
	Resolution	0.01 m/s	
ERUN-PG71S1-FC	Tested parameter	$PM_{1.0}$, $PM_{2.5}$, PM_{10}	
	Accuracy	≤±2%	
	Measurement Range	0~1000μg/m^3	
	Resolution	1μg/m^3	

(3) Testing Standards

As shown in Table 3.5, China has formulated a series of test standards related to indoor thermal environment and air quality. Field testing according to industry standards can ensure the standardisation of measurement and the accuracy of results.

Table 3.5. Relevant test standards for thermal environment and air quality

Standards	Regulations related to this study
Evaluation standard for indoor thermal and humid environment of civil buildings. (GB/T 50785-2012)	Layout requirements for location and quantity of measuring points for indoor thermal and humid environment tests.
Testing standard for energy efficiency of residential buildings. (JGJ/T 132-2009)	Detection requirements for indoor average temperature of buildings, thermal defects of peripheral protective structures and heat transfer coefficient of main parts of protective structures.
Design standard for energy efficiency of rural residential buildings. (GB/T 50824-2013)	The indoor calculated temperature of rural residence, thermal performance of enclosure structure, etc
Indoor air quality standard (GB/T18883-2002)	It specifies the point selection requirements, sampling time and frequency, sampling methods and instruments, inspection methods, quality assurance measures, test results and evaluation of various parameters in indoor air.
Ambient air quality standard. (GB3095-2012)	It specifies the classification, standard classification, pollutant items, average time and concentration limits, detection methods, the effectiveness of data statistics, implementation and supervision of ambient air functional areas.

3.3.Experiment on the wall insulation performance

3.3.1.Experimental principle

There are many standards for the test method of the thermal transmittance of the envelope structure, such as standard *ISO 8301 Thermal insulation- Determination of steady-state thermal resistance and related properties- Heat flow meter apparatus* [1] and *ISO 8302 Thermal insulation- Determination of steady-state thermal resistance and related properties- Guarded hot plate apparatus internationally* [2], the standard *ASTM C1199-14 Standard Test Method for Measuring the Steady-State Thermal Transmittance of Fenestration Systems Using Hot Box Methods* [3] and *ASTM C518-2017 Standard Test Method for Measuring the Steady-State Thermal Transmittance Properties by Means of the Heat Flow Meter Apparatus in the United States* [4], *JIS A 1412-1 Test method for thermal resistance and related properties of thermal insulations - Part 1: Guarded hot plate apparatus* [5] and *JIS A 1412-2 Test method for thermal resistance and related properties of thermal insulations- Part2: Heat flow meter apparatus in Japan* [6] and *GBT23483-2009 Standard for heat transfer coefficient and heating heat detection method of building envelope in China* [7]. Two main test methods in the above standards are the guard hot box method (GHB) and the heat flow meter method (HFM). In order to test the insulation performance of various materials, this experiment uses the simple hot box heat flow meter method (SHB-HFM). SHB-HFM has higher measurement accuracy than HFM and less difficulty of operating equipment than GHB [8].

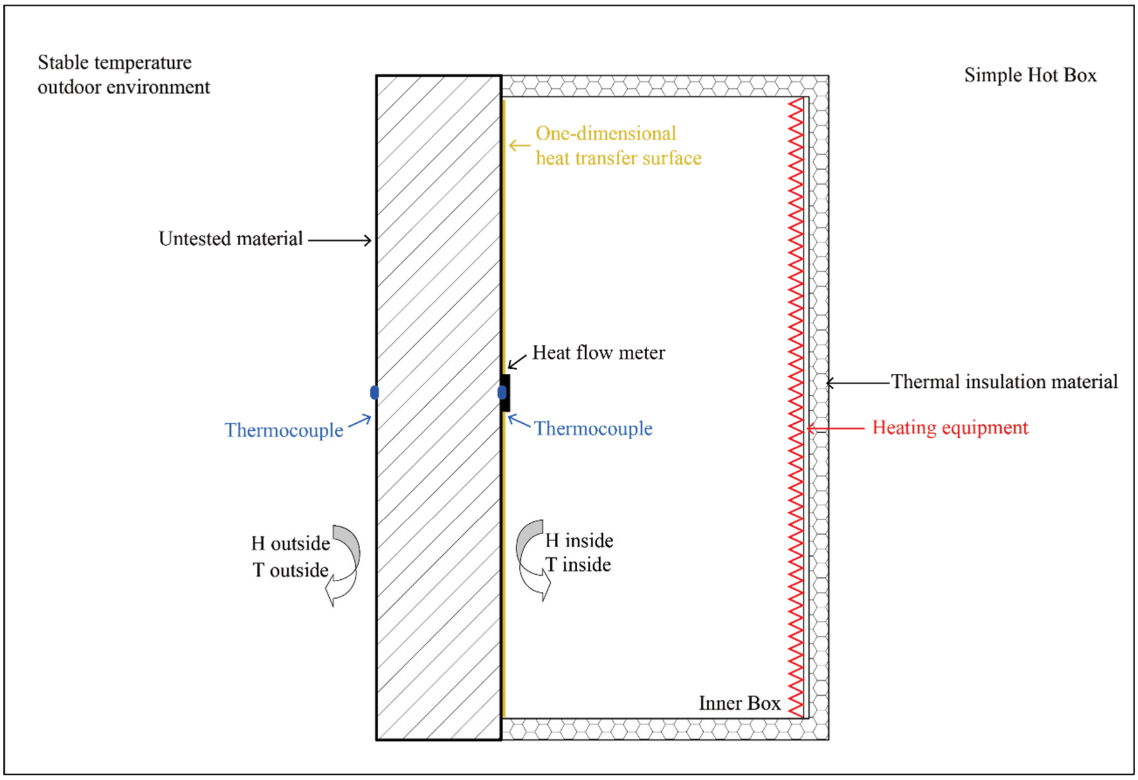

Figure 3.1. Experimental diagram of SHB-HFM method

Figure 3.1 shows the method of SHB-HFM to measure the wall thermal transmittance in summer. The experimental wall will be sealed with heat-insulating materials to form an approximate one-dimensional heat transfer wall. Moreover, a simple heat box is installed on one surface, and the central area corresponds to the experimental one-dimensional heat transfer wall. While the heating box is heated, the relatively stable outdoor temperature maintains the natural temperature. There will be a relatively stable high-temperature difference. A fan will be used for stirring in the heating box to form an even and stable thermal environment. The installed heat flow meter and thermal sensor can measure and calculate the wall heat transfer coefficient.

Unlike HFM, SHB-HFM has no requirement for testing time and does not need to be tested in the coldest months. Regardless of the season, SHB-HFM always creates a temperature difference on both sides of the wall using a heating box, which is always installed on the side with a higher temperature. Nevertheless, it is still necessary to ensure no drastic outdoor temperature change during the test. During the test, the air temperature in the hot box should remain stable, and the fluctuation range of temperature in the heating box should be within ±3 K.

The surface temperature of the low-temperature side should not be higher than the surface temperature of the high-temperature side at any time during the detection process. The surface temperature of the higher side and the surface temperature of the lower side of the envelope structure should meet the requirements of Table 3.6.

Table 3.6. Demands of the temperature difference between both sides

Estimated heat transfer coefficient（K）	**The temperature difference between both sides**
K≥0.8（$W/(m^2 \cdot K)$）	≥12℃
0.4（$W/(m^2 \cdot K)$）≤K＜0.8（$W/(m^2 \cdot K)$）	≥15℃
K＜0.4（$W/(m^2 \cdot K)$）	≥20℃

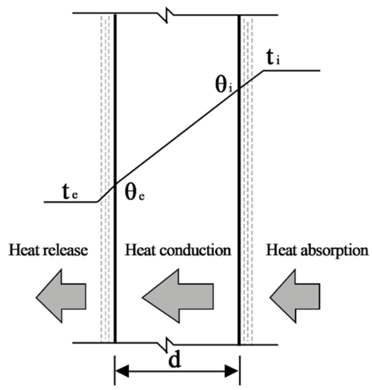

Figure 3.2. Experimental schematic diagram of heat transfer coefficient of insulation materials

The basic principle for measuring the thermal conductivity of materials is the steady-state heat transfer through flat walls. The steady-state heat transfer process of the flat wall is shown in Figure 3.2. The process is divided into three parts: heat absorption from the inner surface of the flat wall, heat conduction from the flat wall material layer and heat dissipation from the outer surface of the flat wall. During the thermal conductivity of the flat-walled material layer. Suppose there is a flat wall of a homogeneous material with a scale of length and width much greater than the thickness d of the wall (or the flat wall is enclosed with insulation), and assume that the indoor air temperature t_i is higher than the outdoor air temperature t_e, $t_i>t_e$. The temperatures on both sides of the wall are θ_i and θ_e, respectively, and $\theta_i>\theta_e$. in-unit area, unit time through the wall of the heat conduction heat, known as heat flow intensity, usually expressed: q, its value is:

$$(1)\quad q = \lambda \frac{(\theta i - \theta e)}{d}$$

As can be seen from the above equation, the value of the thermal conductivity λ reflects the thermal conductivity of the wall material. It is numerically equal to: when the temperature difference of the unit thickness of the material layer is 1K, the heat passes through the surface area of 1 m^2 in unit time. The value of the thermal conductivity λ of a material is directly related to the thermal conductivity of the heat transfer. Different materials or substances have a defined thermal conductivity, an essential thermophysical parameter under certain conditions. Eq. (1) can also be written as:

$$(3)\quad q = \frac{(\theta i - \theta e)}{\frac{d}{\lambda}} = \frac{(\theta i - \theta e)}{R}$$

The above equation R is called the thermal resistance, and its unit is ($m^2 \cdot K/W$). Thermal resistance is the resistance encountered by the heat flow through the wall. It reflects the ability of the biscuit to resist the passage of heat flow. The more excellent the thermal resistance, the same temperature difference, the less heat passes through the biscuit. To increase the thermal resistance, can increase the thickness of the flat wall d or choose a material with a small value of thermal conductivity λ.

Similarly, in the other two processes (heat absorption on the inner surface of the flat wall and heat dissipation on the outer surface of the flat wall), there is also a temperature difference and heat transfer. In summary, when the indoor temperature is higher than the outdoor temperature, the envelope passes through the three stages mentioned above to transfer heat to the outside. As the temperature only varies in the direction of the thickness of the envelope, which is commonly referred to as a one-dimensional temperature field, and as the temperature of all surfaces is in a steady-state that does not vary with

time, the heat transfer from all surfaces must be equal.
Under the same indoor and outdoor temperature difference conditions, the greater the total thermal resistance R, the greater the total thermal resistance R of the flat wall, the less heat will be transferred through the flat wall, the less heat is transferred through the wall. It can also be seen that the total thermal resistance of a flat wall represents the amount of resistance to heat transfer from one side of the flat wall to the other.

The total thermal resistance and the total heat transfer coefficient of a flat wall are interrelated. The physical meaning of the total heat transfer coefficient K of a flat wall is to indicate the total heat transfer capacity of the flat wall, which is numerically the amount of heat transferred through the unit area of the flat wall in a unit of time when the difference between the indoor and outdoor air temperatures is 1°C. Both the total thermal resistance R and the total heat transfer coefficient K are essential indicators of the thermal performance of a flat wall under stable heat transfer conditions [9].

3.3.2.Experimental devices

(1) Requirements of instruments

The heat flow meter should meet the requirements of Table 3.7. Install the heat flow meter directly on the inner surface of the tested envelope structure and make complete contact with the surface. The location of the measuring point should be avoided close to thermal bridges, cracks and parts with air leakage, and should not be directly affected by heating, cooling instruments and fans. The external surface of the test area should be protected from rain, snow and direct sunlight.

Table 3.7. Physical properties of heat flow meter

Project indicators		**Indicators**
Standard coefficient	Scope	from 10W/(m^2·Mv) to 200W/(m^2·mV)
	Stability	≤5%
	Uncertainty	≤5%
Thermal resistance		≤0.008（m^2·K/W）
Operating temperature		from -10℃ to 70℃

The temperature sensor range should be 50℃-100℃, the resolution should be 0.1℃, and the error should not be greater than 0.5℃ and the system time error should not be greater than 20×10^{-5}. Install temperature sensors on both sides of the tested envelope structure. The inner surface temperature sensor should be installed close to the heat flow meter, and the external surface temperature sensor should be installed at a position corresponding to the heat flow meter. The installation location of the temperature sensor should not be directly affected by solar radiation or indoor heat sources. The temperature sensor and its lead should be in close contact with the measured surface, and the lead length should not be less than 0.1m. Use a temperature recorder for continuous testing, the interval between testing data recording should not exceed 60 min, and the duration of testing should not be less than 72 h.

(2) The basic information of instruments used in this experiment

The types, accuracy and contents of the main test instruments and the photographs of the instruments are listed in Table 3.8.

Table 3.8. Accuracy and measuring range of measurement instruments

<table>
<tr><th>Name</th><th colspan="3">Equipment Information</th></tr>
<tr><td rowspan="4">JTR01 temperature sensor</td><td>Tested parameter</td><td>Temperature</td><td rowspan="4"></td></tr>
<tr><td>Accuracy</td><td>0.1°C</td></tr>
<tr><td>Measurement Range</td><td>-40°C-120°C</td></tr>
<tr><td>Resolution</td><td>0.1°C</td></tr>
<tr><td rowspan="4">JTNT-A multi-channel heat flow meter</td><td>Tested parameter</td><td>Heat flow intensity</td><td rowspan="4"></td></tr>
<tr><td>Accuracy</td><td>±0.3 W/m²</td></tr>
<tr><td>Measurement Range</td><td>±100W/m²</td></tr>
<tr><td>Resolution</td><td>0.1 W/m²</td></tr>
</table>

3.3.3.Data processing method

The detection data analysis of the heat transfer coefficient of the envelope structure should be calculated by the average arithmetic method. The dynamic analysis method can be used when the calculation error of the arithmetic average method does not meet the requirements. When using the average arithmetic method for data analysis, the thermal resistance of the envelope structure should be calculated according to formula (3). The difference between the last calculated value R and the first calculated value of R should not be more than 5%;

$$(3)\ R = \frac{\sum_{j=1}^{n}(T_{ij}-T_{oj})}{\sum_{j=1}^{n}q_j}$$

In the formula (3):

R ----Thermal resistance of insulation material;

T_{ij} ---- The j times measurement value of the inner surface temperature of the envelope;

T_{oj} ---- The j times measurement value of the outer surface temperature of the envelope;

q_j ---- The j times measurement value of the heat flow.

The heat transfer coefficient of the envelope structure should be calculated according to formula (2)

$$(4)\ K = \frac{1}{R_i + R + R_e}$$

In the formula (4)：

U ---- Heat transfer coefficient of insulation material;

R_i---- Heat transfer resistance of the inner surface of the insulation material;

R_e ---- Heat transfer resistance of the outer surface of the insulation material.

In addition to this, the thermal inertia D of the material reflects the ability of the maintenance structure to resist temperature fluctuations under the influence of periodic heat waves. The greater the thermal inertia, the lower the internal temperature at a distance from the surface. An indicator of the thermal inertia of the envelope is the sum of the thermal inertia indicators of the layered materials as

$$(5)\ D = D_1 + D_2 + \cdots + D_N = R_1 S_1 + R_2 S_2 + \cdots R_N S_N$$

In the formula (5)：

R_1, R_2…R_N---- Heat transfer resistance of the different layers of the insulation material；

S_1, S_2…S_N---- Thermal storage coefficient of different layers.

3.4.Simulation on Thermal environment improvement

3.4.1.EnergyPlus introduction

Building energy simulation software is a powerful tool for calculating and analysing building performance, assisting in the design and operation of building systems and guiding the development of building energy efficiency standards, and has been increasingly widely used. According to statistics, there are currently more than a hundred building energy simulation software programs worldwide, such as BLAST, DOE-2, EnergyPlus in the USA, ESP-r in the UK, DeST in China, etc. [10].

In this paper, Energyplus is chosen as the simulation software. EnergyPlus building energy simulation software was officially released in April 2001. It was developed by Lawrence Berkeley National Laboratory, the University of Illinois, the US Army Building Engineering Laboratory, Oklahoma State University and others, with the support of the US Department of Energy, and is a completely new software that not only incorporates the advantages of the older generation of building energy analysis software DOE-2 and BLAST but also has many new features [11-12].

3.4.2.Numerical model

(1) EnergyPlus calculation principle

The calculation method used by the EnergyPlus program is the room heat balance method. The basic principle is to assume that the air temperature in the room and the surface temperature of the envelope are uniforms and to divide the room heat balance into two parts: the envelope surface heat balance and the air heat balance [13-14].

1) Air thermal balance

EnergyPlus uses the zonal air heat capacity method when dealing with air heat balance, which uses the previous time step to predict the system response and change the zone temperature for the current event step. In previous sequential simulation programs, a one-hour step was often used to facilitate data logging while maintaining a reasonable calculation time. However, the dynamic process of regional air state change is accomplished over a much smaller period than one hour, and the expression for the time constant τ for regional air is given by:

$$(6)\ \tau \approx \frac{\rho V c_p}{|Q_{load}+Q_{sys}|}$$

The numerator represents the regional air heat capacity, and the denominator represents the absolute value of the heat entering the region.

There is no doubt that the value of τ is also variable since the zone load and the heat output of the system are variable during the simulation. Therefore, it is necessary to use suitable variable periods shorter than one hour as step sizes for updating the system parameters. To achieve stability in the simulation, a zone temperature equation with an unstable zone heat capacity term needs to be established, and a method for determining the zone parameters and the response of the system at successive time steps needs to be defined. The basis of this set of equations is the regional heat balance equation.

$$(7)\ C_z\frac{dT_z}{dt}=\sum_{i=1}^{N_{sl}}Q_i+\sum_{i=1}^{N_{surfaces}}h_iA_i(T_{si}-T_z)+\sum_{i=1}^{N_{zones}}m_iC_p(T_{zi}-T_z)+m_{inf}C_p(T_\infty-T_z)+Q_{sys}$$

Where $\sum_{i=1}^{N_{sl}}Q_I$ is the total internal convective load, $\sum_{i=1}^{N_{surfaces}}h_iA_i(T_{si}-T_z)$ is regional hot surface convection heat transfer, $\sum_{i=1}^{N_{zones}}m_iC_p(T_{zi}-T_z)$ is heat exchange due to mixing of air between zones, $m_{inf}C_p(T_\infty-T_z)$ is heat exchange due to external air infiltration, Q_{sys} is system heat output, $C_z\frac{dT_z}{dt}$ is total internal convective load.

If the air heat capacity is neglected, the system heat output of the steady-state system is:

$$(8)\ -Q_{sys}=\sum_{i=1}^{N_{sl}}Q_i+\sum_{i=1}^{N_{surfaces}}h_iA_i(T_{si}-T_z)+\sum_{i=1}^{N_{zones}}m_iC_p(T_{zi}-T_z)+m_{inf}C_p(T_\infty-T_z)$$

The air system provides hot/cooled air to meet the heat/cooling load requirements of the zone. The energy output of the system to the zone Q_{sys} can be accurately described by the difference between the enthalpy of the air entering the zone air zone and the enthalpy of the air exiting the zone.

$$(9)\ Q_{sys}=m_{sys}C_p\left(T_{sup}-T_z\right)$$

This equation assumes that the mass flow rate of air entering the region is precisely equal to the mass flow rate of air exiting the region. The temperature of these two when inside the region is the average regional air temperature. Substituting equation (9) into equation (7) yields the equation:

$$(10)\ C_z\frac{dT_z}{dt}=\sum_{i=1}^{N_{sl}}Q_i+\sum_{i=1}^{N_{surfaces}}h_iA_i(T_{si}-T_z)+\sum_{i=1}^{N_{zones}}m_iC_p(T_{zi}-T_z)+m_{inf}C_p(T_\infty-T_z)+m_{sys}C_p\left(T_{sup}-T_z\right)$$

This equation expresses the meaning that the sum of the regional load and the energy output of the system is equal to the energy stored in the regional air. Typically, only the heat capacity of the zone air is represented. Nevertheless, the heat balance between the heat flow and the zone air should be included in this term. In order to calculate the derivative term, a finite difference approximation needs to be introduced, as follows:

$$(11)\ \frac{dT}{dt} = (\delta t)^{-1}\left(T_z^t - T_z^{t-\delta t}\right) + O(\delta t)$$

Long simulations with numerical integration may result in increasing truncation errors after multi-step calculations. This problem is exacerbated by the lower order finite differences in the present simulation. However, the day-based cycle nature of the building energy simulation will allow the truncation error to disappear after one day's cycle is completed so that no absolute error will be generated even if the simulation is carried out over multiple days. Substituting Euler's equation (11) into equation (10) and moving the term containing the average regional air temperature to the left of the equation gives equation (12), the regional air temperature solution equation.

$$(12)\ C_z \frac{T_z^t - T_z^{t-\delta t}}{dt} + T_z^t\left(\sum_{i=1}^{N_{surfaces}} h_i A_i + \sum_{i=1}^{N_{zones}} m_i C_p + m_{inf} C_p + m_{sys} C_p\right) = \sum_{i=1}^{N_{sl}} Q_i^t + m_{sys} + C_p T_{supply}^t + \left(\sum_{i=1}^{N_{surfaces}} h_i A_i T_{si} + \sum_{i=1}^{N_{zones}} m_i C_p T_{zi} + m_{inf} C_p T_\infty\right)^{t-\delta t}$$

The rectification shift term moves the differential approximation containing the hysteresis temperature to the right-hand side to give an energy balance equation containing the regional heat capacity.

$$(13)\ T_z^t = \frac{\sum_{i=1}^{N_{sl}} Q_i^t + m_{sys} C_p T_{supply}^t + \left(C_z \frac{C_z}{\delta t} + \sum_{i=1}^{N_{surface}} h_i A_i T_{si} + \sum_{i=1}^{N_{zones}} m_i C_p T_{zi} + m_{inf} C_p T_\infty\right)^{t-\delta t}}{\frac{C_z}{\delta t} + \left(\sum_{i=1}^{N_{surface}} h_i A_i + \sum_{i=1}^{N_{zones}} m_i C_p + m_{inf} C_p + m_{sys} C_p\right)}$$

Equation (8) can estimate the regional air temperature, but under certain conditions, the equation has very stringent requirements on the time step. Higher-order expressions for higher-order truncation errors need to be found to eliminate this drawback. This makes it possible to use the first-order Euler equation in simulations without introducing instability problems. Taylor [15] believes that the best results are obtained from the approximate solution of the finite difference of the third order.

$$(14)\ \left.\frac{\mathrm{d}T_z}{\mathrm{d}t}\right|_t \approx (\delta t)^{-1}\left(\frac{11}{6}\,T_z^t - 3\,T_z^{t-\delta t} + \frac{3}{2}\,T_z^{t-2\delta t} - \frac{1}{3}\,T_z^{t-3\delta t}\right) + O(\delta t^3)$$

Substituting the differential decomposition of equation (14) into equation (12) yields:

$$(15)\ C_z(\delta t)^{-1}\left(\frac{11}{6}\,T_z^t - 3\,T_z^{t-\delta t} + \frac{3}{2}\,T_z^{t-2\delta t} - \frac{1}{3}\,T_z^{t-3\delta t}\right) = \sum_{i=1}^{N_{sl}} Q_i + \sum_{i=1}^{N_{surfaces}} h_i\,A_i(T_{si} - T_z) + \sum_{i=1}^{N_{zones}} m_i\,C_p(T_{zi} - T_z) + m_{inf}C_p(T_\infty - T_z) + m_{sys}C_p\left(T_{sup} - T_z\right)$$

Then the equation for solving for a regional temperature becomes:

$$(16)\ T_z^t = \frac{\sum_{i=1}^{N_{sl}} Q_i + \sum_{i=1}^{N_{surfaces}} h_i A_i T_{si} + \sum_{i=1}^{N_{zones}} m_i C_p T_{zi} m_{inf} C_p T_\infty + m_{sys} C_p T_{sup} - \left(\frac{C_z}{\delta t}\right)\left(-3T_z^{t-\delta t} + \frac{3}{2}T_z^{t-2\delta t - \frac{1}{3}T_z^{t-3}\delta t}\right)}{\left(\frac{11}{6}\right)\frac{C_z}{\delta t} + \sum_{i=1}^{N_{surface}} h_i A + \sum_{i=1}^{N_{zones}} m_i C_p + m_{inf} C_p + m_{sys} C}$$

It is this equation that EnergyPlus uses. The load simulation is the starting point for the entire simulation process and will provide the demand parameters to the air conditioning system. The system simulation provides the actual supply capacity and then makes the necessary adjustments to the zone air temperature based on the balance between supply and demand, thus completing the entire building energy simulation process.

2) Thermal balance of the envelope surface

In solving heat transfer problems for opaque enclosures, EnergyPlus generally uses the CTF (Conduction Transfer Function) or finite difference method, which is essentially a reaction coefficient method based on the internal surface temperature of the wall. In contrast, the finite difference method can handle, for example, phase change materials or materials with variable thermal conductivity. In recent years, the adequate moisture penetration depth (EMPD) model has been invented to solve the surface heat transfer problem of the envelope in humid thermal environments. However, the current EMPD model in EnergyPlus is a single penetration depth model, which is less accurate for long-term moisture fluctuations.

① Conduction Transfer Function (CTF)

The basic form of the solution of the transfer function of conduction is represented by the following two equations. Equation (17) is the internal heat flow and equation (18) is the external heat flow:

$$(17)\ q_{ki}''(t) = -Z_o T_{i,t} - \sum_{j=1}^{nz} Z_j\,T_{i,t-j\delta} + Y_o T_{o,t} + \sum_{j=1}^{nz} Y_j\,T_{i,t-jz} + \sum_{j=1}^{\mathrm{nq}} \Phi_j\,q_{ki,t-j\delta}''$$

$$(18)\ q''_{ko}(t) = -Y_o T_{i,t} - \sum_{j=1}^{nz} Y_j\, T_{i,t-j\delta} + X_o T_{o,t} + \sum_{j=1}^{\mathrm{nz}} X_j\, T_{o,t-jz} + \sum_{j=1}^{\mathrm{nq}} \Phi_j\, q''_{ko,t-j\delta}$$

②Combined Heat and Moisture Transfer (HAMT)

The combined heat and moisture transfer (HAMT) is one of the finite difference method models. The HAMT model can simulate moisture storage and the transport of heat and moisture within the building envelope. The following equation is a theoretical model for heat and moisture transfer in the building envelope.

$$(19)\ \frac{\partial H}{\partial T}\frac{\partial T}{\partial t} = \nabla(\lambda \nabla T) + h_v \nabla\left(\delta_p \nabla(\varphi p_{sat})\right)$$

$$(20)\ \frac{\partial w}{\partial \varphi}\frac{\partial \varphi}{\partial t} = \nabla\left(D_\varphi \nabla \varphi + \delta_p \nabla(\varphi p_{sat})\right)$$

③ Effective Moisture Penetration Depth (EMPD)

The EMPD model is a simplified, lumped approach to modelling the adsorption and desorption of surface moisture. It assumes that a thin layer close to the wall dynamically exchanges moisture with air. The model solves the following equation.

$$(21)\ \rho_{\mathrm{matl}} A d_{EMPD}\frac{d\mu}{dt} = h_m(\omega_{zone} - \omega)$$

The time derivative water content of the EMPD model conversion is carried into the following equation:

$$(22)\ \rho_{matt} A d_{EMPD}\left(\frac{\partial \mu}{\partial \omega}\right)\frac{d\omega}{dt} = h_m(\omega_{zone} - \omega) + \rho_{mat} A d_{EMPD}\left(\frac{\partial \mu}{\partial T}\right)\frac{dT}{dt}$$

Substituting the above equation yields:

$$(23)\ \rho_{matl} A d_{EMPD}\left(\frac{\partial \mu}{\partial \omega}\right)\frac{d\omega}{dt} = h_m(\omega_{zone} - \omega) + \rho_{matl} A d_{EMPD}\left(\frac{\partial \mu}{\partial T}\right)\frac{dT}{dt}$$

(2) EnergyPlus operation process

As shown in figure 3.3, the process of calling a program in EnergyPlus is divided into three main phases: pre-processing, function module calling and output processing. When performing simulations, EnergyPlus requires various input files describing the building and surroundings to be simulated, and it, while outputting files, likewise requires other commands for further processing of data to visualise the simulation results [16].

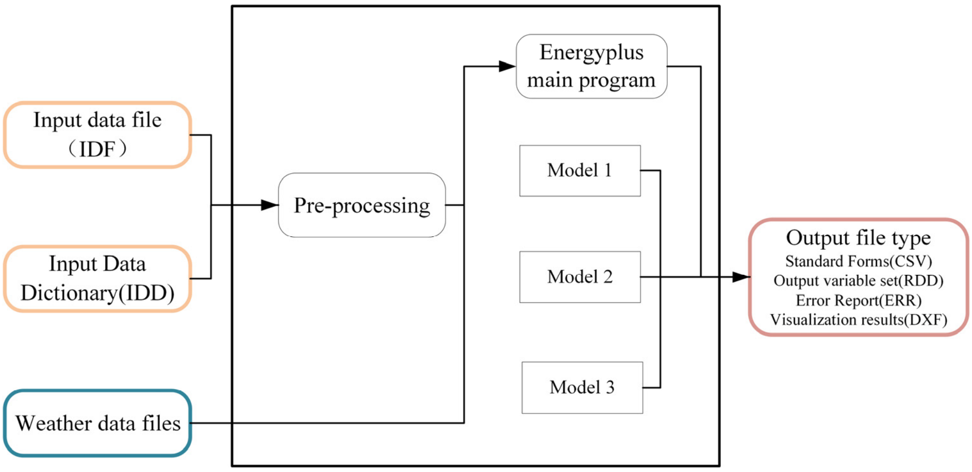

Figure 3.3. EnergyPlus working principle diagram

3.4.3.Evaluation Parameters: PMV and ePMV

PMV is known as Predicted Mean Vote. PMV is calculated using the comfort equation for human heat exchange, and the PMV calculation includes four physical parameters (air temperature, airflow rate, air humidity, mean radiant temperature) and two personal parameters (metabolic rate and clothing insulation thermal resistance).

$$(24)\ PMV = f\left(\dot{M}, \dot{W}, f_{cl}, p_a, T_{db}, T_{cl}, h_c\right)$$

Where M refers to mechanical power (or adequate mechanical power), T_{cl} refers to the average temperature of the surface of the garment, f_{cl} refers to the ratio of the surface area of the garment worn to the exposed surface area, and the detailed expression for PMV is:

$$(25)PMV = \left[0.303 \cdot e^{(-0.036 \cdot \dot{M})} + 0.028\right] \cdot \{(\dot{M} - \dot{W}) - 3.05 \cdot 10^{-3} \cdot \left[5733 - 6.99 \cdot (\dot{M} - \dot{W}) - p_a\right] \cdot 0.42\left[\dot{M} - \dot{W} - 58.15\right] - 1.7 \cdot 10^{-5} \cdot \dot{M} \cdot (5867 - p_a) - 0.0014 \cdot \dot{M} \cdot (34 - T_{db}) - 3.96 \cdot 10^{-8} \cdot f_{cl} \cdot [(T_{cl} + 273)^4 - (T_{MR} + 273)^4] - f_{cl} \cdot h_c \cdot (T_{cl} - T_{db})\}$$

Terms that appear in this expression include:

The surface temperature of the garment, T_{cl}, can be obtained by iteratively solving the implicit equation:

$$(26)\ T_{cl} - 35.7 + 0.28 \cdot (\dot{M} - \dot{W}) + I_{cl} \cdot \{3.96 \cdot 10^{8} \cdot f_{cl} \cdot [(T_{cl} + 273)^{4} - (T_{MR} + 273)^{4}] + f_{cl} \cdot h_{c} \cdot (T_{cl} - T_{db})\} = 0$$

The convective heat transfer coefficient can be solved iteratively by:

$$(27)\ h_c = \begin{Bmatrix} 2.38 \cdot |T_{cl} - T_{db}|\ for\, 2.38 \cdot |T_{cl} - T_{db}|^{0.25} > 12.1 \cdot \sqrt{v_{ar}} \\ 12.1 \cdot \sqrt{v_{ar}}\ for\, 2.38 \cdot |T_{cl} - T_{db}|^{0.25} > 12.1 \cdot \sqrt{v_{ar}} \end{Bmatrix}$$

The ratio of the dressed surface area to the bare surface area, f_{cl}, is solved by:

$$(28)\ f_{cl} = \begin{Bmatrix} 1.00 + 1.290 \cdot I_{cl}\ for\, I_{cl} \leq 0.078\ m^2 \cdot K \cdot W^{-1} \\ 1.05 + 0.645 \cdot I_{cl}\ for\, I_{cl} \leq 0.078\ m^2 \cdot K \cdot W^{-1} \end{Bmatrix}$$

The ePMV model was first proposed by Fanger and Tofum [8]. It includes a correction factor called the expectation factor ep, which is multiplied by mv to obtain the corrected value of PMV:

$$(29)\ ePMV = e_p \cdot PMV$$

A tiny change in the ep value can significantly change the final result of PMV, and therefore, if e_p is defined in the wrong way, the results obtained can be very different [18]. The expectation factor e_p depends on the annual duration of warm weather in unconditioned buildings [17], and the air conditioning penetration in the area can likewise define the magnitude of the e_p value [18], as detailed in Table 3.9.

Table 3.9. Table of values of ep coefficients in ePMV

Expectation	Duration of hot weather throughout the year	Expectation factor e_p	Prevalence of air-conditioned buildings
High	Areas with short hot summers	0.9-1.0	When air-conditioned buildings are more prevalent in this category, e takes a high value; conversely, e takes a low value
Middle	Areas that are hot throughout the summer, but not in other seasons	0.7-0.9	
Low	Hot areas all year round	0.5-0.7	

3.5.Summary

This chapter describes the methodology of field survey testing, thermal performance experiment of the envelope and numerical simulation of building a thermal environment of rural houses in Qingdao. The main conclusions are as follows:

(1) The field survey methods include interviews, questionnaires and field tests. Firstly, the questionnaire is designed through the pre-survey of typical rural areas in Qingdao, Shandong Province. The questionnaire is mainly structured and semi-structured, supplemented by open-ended. As local residents have been accustomed to the local climate, we have developed a separate questionnaire for local residents (Appendix A) and volunteers (Appendix B). The survey method adopts a face-to-face interview questionnaire. Secondly, the field test and questionnaire survey are combined to test the indoor and outdoor temperature, relative humidity, indoor polluted gas, envelope size and other parameters.

(2) There are many ways to measure thermal conductivity, but they all have the same basic principles (flat-wall steady-state heat transfer method) and the same data processing process. SHB-HFM method combines the advantages of the most common methods, the guard hot box method (GHB) and the heat flow meter method (HFM), with lower requirements for experiments and accurate data results. In the experiment, using this method to test the thermal conductivity of different materials saves costs and obtains accurate data, which has good results.

(3) The calculation method used by the EnergyPlus program is the room heat balance method, and the room heat balance is divided into two parts: the surface heat balance of the envelope and the air heat balance. In this paper, EnergyPlus uses the regional air heat capacity method for the air heat balance, while EnergyPlus uses the CTF (Conduction Transfer Function) method for solving the opaque enclosure heat transfer. Meanwhile, the parameters used in this paper for the evaluation of simulation experiments include temperature, ePMV.

Appendix A. Questionnaire for villagers

Questionnaire on the basic situation of rural housing (Interviewed villagers)

一、Basic information Time：_____________

1. Name_______2. Gender_____3. Age _______ 4. Transformation time______

5. Construction time of farmhouse? □1950-1960 □1970-1980 □1990 □After 2000

6. What is the heating mode of your home in winter?

□Hot Kang □Stove □Radiator □Air conditioner □Electric Kang □Solar room □other______

7. What is the type of heating energy in your home?

□Coal □Electric energy □Natural gas □Solar energy □Other______

8. Are you inclined to change the heating mode? □YES □NO

9. Where is the heating stove? □ side room □Interview room □Adjacent to the interview room □Other

10. How do you feel about indoor air quality during heating?

□Strongly pungent □More pungent □Slightly pungent □No feeling

11. Overall indoor working intensity in winter: □Sit quietly □Cooking □Do housework

12. Please give the heating feeling of your whole body at the moment (Please tick √ in the corresponding case)

hot	warm	slightly warm	neutral	Slightly cool	cool	cold
-3	-2	-1	0	+1	+2	+3

13. What do you think caused the room temperature to be too low?

□The wall is too thin □Poor sealing of doors and windows □Insufficient heating intensity □other___

14. How do you want to increase the indoor temperature?

□Increase wall thickness (Add insulation layer) □Improve the air tightness of doors and windows □Increase heating equipment □other_____

15. You feel the humidity of indoor air at this time (Please tick √ in the corresponding case)

Very dry	dry	Slightly dry	moderate	Slightly damp	damp	Very damp
-3	-2	-1	0	+1	+2	+3

16. You feel the indoor air velocity at this time (Please tick √ in the corresponding case)

No wind feeling	Breeze feeling	Windy	Strong wind feeling
0	+1	+2	+3

17. Clothing: (can be combined)

□shirt □vest □sweater £loose coat

Appendix B. Questionnaire for Volunteer

Questionnaire on the basic situation of rural housing (Volunteer)

Time：__________

1. Structural level of the exterior wall of the rural house? (Draw drawings according to the interviewee's dictation)
2. Roof structure hierarchy? (Draw drawings according to the interviewee's dictation)
3. Form of doors and windows (Dimensions, materials, etc. / draw drawings according to the interviewee's dictation)
4. Please give the heat feeling of your whole body at the moment (Please tick √ in the corresponding case)

hot	warm	slightly warm	neutral	Slightly cool	cool	cold
-3	-2	-1	0	+1	+2	+3

5. What do you think caused the room temperature to be too low?

□The wall is too thin □Poor sealing of doors and windows □Insufficient heating intensity □other___

6. How do you want to increase the indoor temperature?

□Increase wall thickness (Add insulation layer) □Improve the air tightness of doors and windows □Increase heating equipment □other_____

7. You feel the humidity of indoor air at this time (Please tick √ in the corresponding case)

Very dry	dry	Slightly dry	moderate	Slightly damp	damp	Very damp
-3	-2	-1	0	+1	+2	+3

8. You feel the indoor air velocity at this time (Please tick √ in the corresponding case)

No wind feeling	Breeze feeling	Windy	Strong wind feeling
0	+1	+2	+3

9. Clothing: (can be combined) □shirt □vest □sweater □loose coat
10. What do you think caused the room temperature to be too low?

□The wall is too thin □Poor sealing of doors and windows □Insufficient heating intensity □other

Appendix C. Building survey record form

Survey Record Form

Date：________ No.____

Measurement records ：

<table>
<tr><td>Address</td><td colspan="4"></td></tr>
<tr><td rowspan="2">Courtyard</td><td>Forms</td><td colspan="3"></td></tr>
<tr><td>Schematic</td><td colspan="3"></td></tr>
<tr><td rowspan="5">Wall</td><td>Materials</td><td></td><td rowspan="5">Formal and structural levels</td><td rowspan="5"></td></tr>
<tr><td>Thickness</td><td></td></tr>
<tr><td>Insulation layer material and thickness</td><td></td></tr>
<tr><td>Eave height</td><td></td></tr>
<tr><td>Ridge height</td><td></td></tr>
<tr><td rowspan="4">Roof</td><td>Materials</td><td></td><td rowspan="4">Formal and structural levels</td><td rowspan="4"></td></tr>
<tr><td>Thickness</td><td></td></tr>
<tr><td>Insulation layer material and thickness</td><td></td></tr>
<tr><td>Ceiling materials</td><td></td></tr>
<tr><td rowspan="2">Door</td><td>Materials</td><td></td><td rowspan="2">Dimensions (glass thickness, door frame thickness) and structural form</td><td rowspan="2"></td></tr>
<tr><td>Form</td><td></td></tr>
<tr><td rowspan="2">South side Windows</td><td>Materials</td><td></td><td rowspan="2" colspan="2">Dimensions (glass thickness, window frame thickness) and structural form</td></tr>
<tr><td>Form</td><td></td></tr>
<tr><td rowspan="2">North side windows</td><td>Materials</td><td></td><td rowspan="2" colspan="2">Dimensions (glass thickness, window frame thickness) and structural form</td></tr>
<tr><td>Form</td><td></td></tr>
<tr><td>Ground</td><td>Materials and form</td><td colspan="3"></td></tr>
</table>

Appendix D. Thermal environment and air quality record form

Thermal environment and air quality record form

Date：________ No.____

Measurement records ：

<table>
<tr><td rowspan="2">Temperature</td><td>Indoor air temperature</td><td></td><td>Radiator surface temperature (with or without heating)</td><td></td><td rowspan="2">Pollutant concentration</td><td>CO_2 concentration</td><td></td></tr>
<tr><td>Indoor wall temperature</td><td></td><td>Fire kang surface temperature</td><td></td><td>PM2.5 concentration</td><td></td></tr>
<tr><td>Humidity</td><td>Indoor air relative humidity</td><td colspan="6"></td></tr>
<tr><td>Air velocity</td><td>Indoor air velocity</td><td></td><td>Window and door permeability (around windows)</td><td></td><td>Wind intrusion air velocity (open the door instantly)</td><td colspan="2"></td></tr>
<tr><td>Heating equipment</td><td colspan="7"></td></tr>
<tr><td rowspan="2">Photos</td><td>Courtyard layout</td><td></td><td>Walls, roofs, floors</td><td colspan="2"></td><td>Doors & Windows</td><td></td></tr>
<tr><td>Heating equipment</td><td></td><td>Interviewers fill out questionnaires</td><td colspan="2"></td><td>Measurement process</td><td></td></tr>
</table>

Note：

Reference:

[1] ISO 8301:1991. Hermal insulation — Determination of steady-state thermal resistance and related properties — Heat flow meter apparatus.

[2] ISO 8302:1991(en). Thermal insulation — Determination of steady-state thermal resistance and related properties — Guarded hot plate apparatus.

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Chapter 4. Status of coastal rural houses and indoor environment in Qingdao

4.1. Introduction

Approximately 39.4% of the population currently lives in rural areas in China [1]. There has been increasing attention on the quality of the living environment of the rural population in China, and in particular on the indoor thermal environment and air quality [2]. The thermal comfort in rural areas is lower than in urban areas [3], and rural residents usually have strong adaptability to the thermal environment [4-9]. In cold and severe cold regions of China, indoor heating is essential due to the outdoor poor thermal environment. However, these regions' lack of formal central heating systems has forced residents to adopt various adaptive heating methods and behaviors. Rural areas were restricted by many factors in northern China, such as remote geographical location, underdeveloped economy and uneven distribution of energy resources [10]. Therefore, most rural building envelopes have no thermal insulation structure and poor thermal performance [11]. Therefore, further research on the indoor thermal environment of rural buildings in cold areas is of great significance to people living in rural areas.

Rural buildings in the cold regions of China require heating for several months each year, leading to the consumption of a large quantity of solid fuel, which further results in poor air quality and a range of health problems [12-16]. The inefficient combustion of coal produces high emissions of various air pollutants, such as CO_2, $PM_{2.5}$ and PM_{10}, causing serious pollution in indoor air [17]. The studies [18-25] further strengthened the link between indoor air pollution resulting from use of coal stoves in rural areas and poor respiratory health, thereby emphasizing the importance of reducing coal stove pollution. There was increasing evidence showing that the combustion of solid fuels has a serious impact on air pollution in rural China [26]. In addition, a portion of the pollutants produced by residential stoves diffuses into the indoor living environment, resulting in poor indoor air quality. Therefore, it was of great significance to further study the indoor air quality of rural housing in cold areas for people living in rural areas.

Based on the above review, more attention is paid to the inland area, but there are many of people in the coastal areas [27]. Furthermore, the outdoor thermal environment in the coastal areas is poorer than that in the inland areas due to the ocean climate in winter, so the indoor environment in typical coastal villages has a higher research value and application significance. The present study conducted a field measurement and a questionnaire survey to characterize the indoor living quality of coastal villages during winter in China. The questionnaire was used to identify the indoor heating and humidity experiences of residents, while the field measurements of thermal performance of envelope, indoor thermal environment and air quality were conducted. It is hoped that this study can provide a reference for improving the living environment of coastal rural populations in China.

4.2. Investigated region and basic information

4.2.1. Investigated region

Qingdao has a vast territory, with a total area of 11282 km^2. Affected by the natural environment and customs, there are also differences in rural houses in various districts. To obtain more accurate research data, the preliminary research site did not include the three main urban areas with a high degree of urbanization, but took seven urban areas such as Chengyang District, Jimo District, Laoshan District, Huangdao District, Jiaozhou District, Laixi City and Pingdu City as the research object, and selected 1-2 villages and towns in each urban area as the research object. Each research object selected 2-3 villages for the field survey and investigated the rural houses of 38 villages (760 households) in 2019, including 67 households in Chengyang District, 100 households in Jimo District, 121 households in Laoshan District, 121 households in Huangdao District, 119 households in Jiaozhou District, 106 households in Laixi City and 126 households in Pingdu City. Specific investigation villages showed in Appendix A. Considering the national policy requirements, economic conditions in rural areas of Qingdao and the distribution of rural housing construction years, the villages in Appendix A were further screened, and five villages for in-depth study are determined.

The further study surveyed five typical villages in the Laoshan District of Qingdao within the southern part of Shandong Peninsula, China. It covers 395.8 km^2, a sea area of 3700 km^2 and a coastline of 103.7 km [28]. The five villages surveyed were located in Laoshan District (120 degrees east longitude and 36 degrees north latitude), namely Lanjia village, Bijia village, Beizhaike village, Dongwuyixiang village, and Zhougezhuang village. The East and South of these villages are adjacent to the Yellow Sea, about 12.3-17.5 km from the nearest coastline. Due to the direct regulation of the marine environment, affected by the southeast monsoon, ocean currents, and water masses from the ocean surface, the air is humid, and the rainfall is abundant, which has significant marine climate characteristics. The five villages vary in size, with the most miniature village about 125 households, and the largest about 502 households. Most of the houses in the village are single-storey courtyard houses, consisting of the main house and the side house. Figure 4.1 shows a map of the region as well as building photos in the investigated villages.

4.2.2. Basic information

(1) Outdoor environment

Qingdao was classified as a cold area according to the code for thermal design of buildings GB-50176. Daily outdoor temperature and relative humidity in Qingdao throughout the year were shown in Figures 4.2 and 4.3. It is warm, muggy, humid, partly cloudy in summer, and cold, dry, windy and mostly sunny in winter. In a year, the temperature usually varies between - 3 ° C and 28 ° C, rarely below - 8 ° C or above 32 ° C.

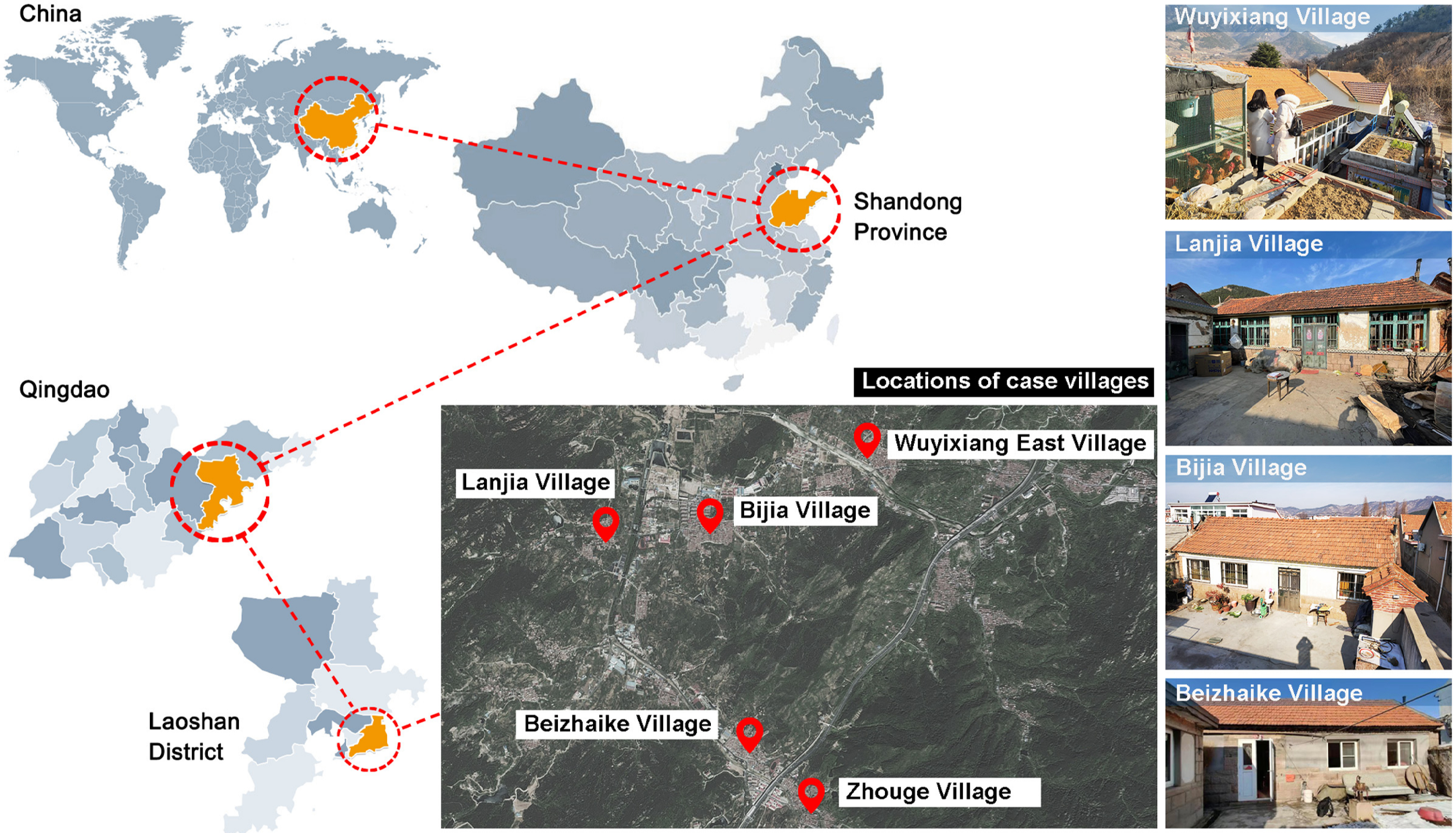

Figure 4.1. Map of the Laoshan District of Qingdao within the southern part of Shandong Peninsula, China and building photos investigated villages

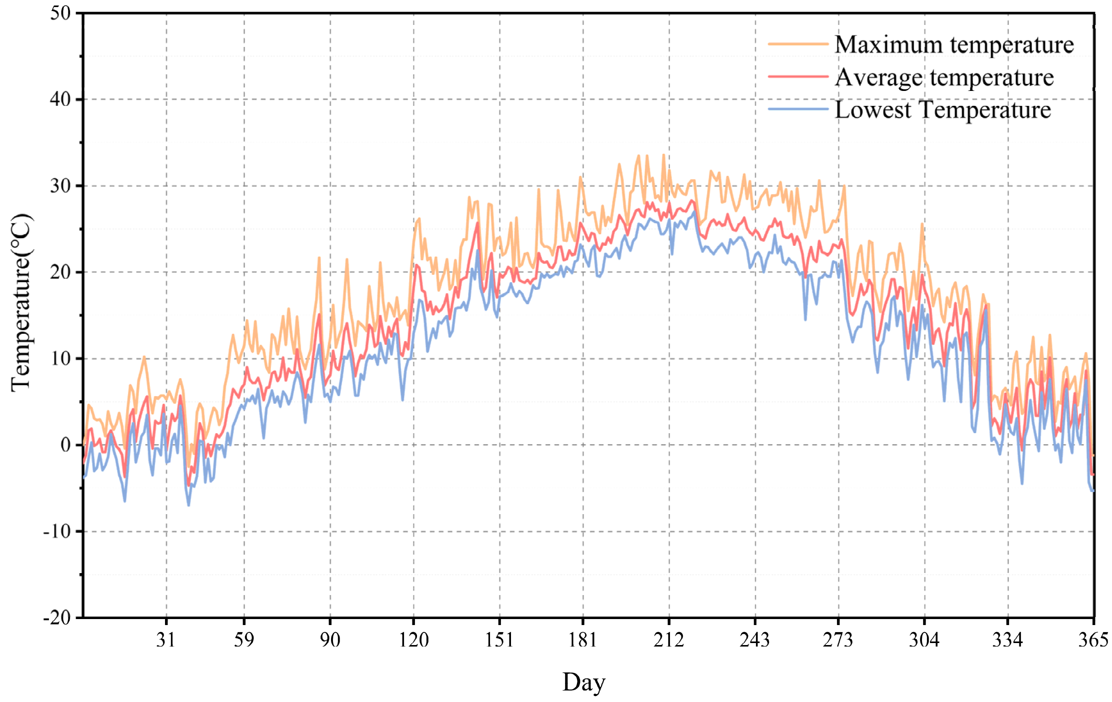

Figure 4.2. Annual daily outdoor temperature in Qingdao in 2020

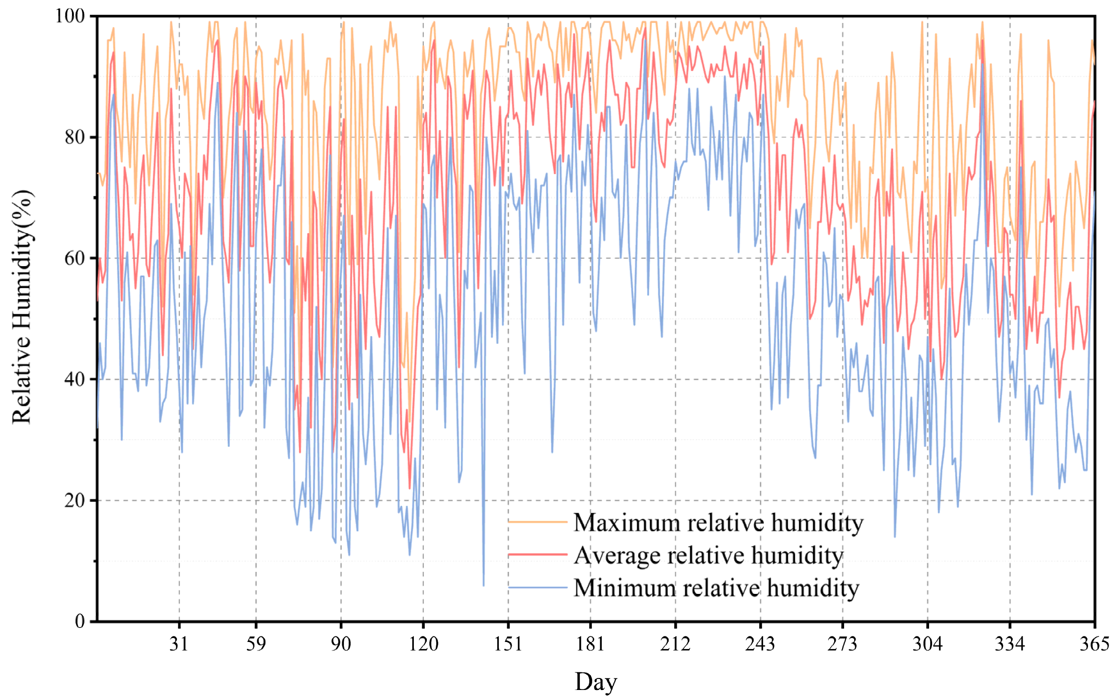

Figure 4.3. Annual daily outdoor relative humidity in Qingdao in 2020

The investigation period was from Jan. 1 to Jan. 4, 2021, and the questionnaire survey was conducted from 9:00 to 10:00. The outdoor thermal environment was relatively stable and similar during the measurement period. During the questionnaire survey period, the average outside air temperature and relative humidity were -1.7℃ and 67.3%, while the concentrations of CO_2 and $PM_{2.5}$ were 491 ppm and 30 ug/m^3, respectively.

(2) Respondents' families

In this survey, the 60 rural buildings from five villages were surveyed, and Table 4.1 lists the essential characteristics of the investigated objects, covering the gender and age of the interviewees, the house construction or renovation time.

Table 4.1. The essential characteristics of the studied objects

Predictor variables		Study population	
		Number	Percentage
Gender			
	Male	27	45.00%
	Female	33	55.00%
Age groups			
	20-40 years old	11	18.33%
	40-60 years old	31	51.67%
	> 60 years old	18	30.00%
Construction (or renovation) time			
	Before 1970	11	18.33%
	1970~1989	24	40.00%
	1990~2010	19	31.67%
	After 2010	6	10.00%

Due to the significant difference in thermal comfort between genders [29], we consciously reduce the gender gap in our choice of interviewees to reduce the margin of error. The proportion of men in the study group was 45%, and that of women was 55%. Within the interviews, women exceeded men by 10%. The survey time is during the day. Most of the young people and children in the village go to work or go to school, while most of the interviewed residents were middle-aged (40-60 years old), accounting for 51.67% of all interviewed residents. The survey covered all building eras, most of which were built after the 1970s, with 18.33 % of houses built before 1970,40 % from 1970 to 1989, and 31.67 % from 1990 to 2010, after 2010 the proportion of houses was 10%.

4.3.Thermal performance of houses in typical coastal villages

4.3.1.Typical architectural layout

(1) Building test

Figure 4.4 displays the location and photos of the monitored buildings. The apartment structure of households with only one floor is mostly two bedrooms, one dining room, one kitchen and one bathroom, and most households with two floors are three bedrooms, one living room, one dining room, one kitchen and one bathroom.

Figure 4.4. The location and photos of monitored buildings

The homestead size is 9-18m in the north-south direction and 10-15m in the east-west direction. More than half of the bases are 12m by 12m (144m^{2}). The house type and envelope information of rural houses were collected through field tests. The layout plan and the structural hierarchy of the envelope were drawn in detail to calculate the thermal performance of the envelope. Figure 4.5. shows the field photos of the building survey process.

(2) House type

The four buildings were selected from different ages and were also typical representatives of different house type courtyards. Figure 4.6 shows the house type of monitored buildings. House type and

Figure 4.5. Field photos of the building survey process

courtyards will affect the indoor temperature and humidity, lighting, and ventilation of the building. House 1 is a typical stone house. It is the only house where the main house was separated from the side house. Residents cook, eat and sleep in the main room, and the side room was used as a storage room and toilet. The residents of House 2 choose to share a homestead equally with others. The reduction of the building area means that the building narrows to the south. Therefore, it has become the only two-story house among the four houses. In addition, residents choose to close their only front yard to resist the harsh weather in winter in cold coastal areas. The courtyard of House 3 is not closed; only a semi-open corridor with a ceiling was added to the south of the main room. House 4 has a large homestead and is the only rural house with two courtyards. The backyard in the north is closed, and the front yard in the south remains open.

The bedrooms of the four rural houses are mostly facing south (at least 2). Indoor bedding was equipped with Kang, and heating facilities were set below the Kang. Most of the Kang’s bottom was

Figure 4.6. House type of monitored buildings

connected with the stove for heating and electric heating was used in some cases. Some residents will finish their winter meals on the Kang. The living room faces South. In addition, it has the function of the dining room. With a few places of worship, most families do not have a separate dining room (shared with the living room and other spaces). The kitchen was often located in rooms on both sides, while some old houses set up a stove in the living room on having a traditional kitchen. The toilet was generally set in the southwest or southeast corner of the yard.

4.3.2. Heating system

(1) Type and number of heating facilities

China's heating methods have distinct regional characteristics. In the southern region (hot summer and cold winter area in the Yangtze River Basin), stoves, electric blankets, electric heating and air conditioning were used. In the north, heating usually uses Kang, coal-fired stove, radiator and air conditioner [30]. A typical Chinese Kang consists of a stove, a Kang body (similar to a bed), and a chimney. It is a comprehensive system that integrates at least four household functions (cooking, bed, household heating and ventilation). According to the survey, although the new heating method based on clean energy can meet the needs of residents in terms of energy-saving, environmental protection, and thermal comfort, it has not been widely used due to its high initial investment, misunderstanding of the main functions and difficulty in perception and application. Kang is still widely used in nearly 85% of rural households in northern China [31].

Figure 4.7. shows the statistical chart of typical heating facilities. Among the five heating methods investigated, except for air-conditioning heating, the heat sources of the remaining four heating methods are coal-fired stoves. The Kang and radiator are connected to the coal-fired furnace and begin to dissipate heat. A small number of radiators use small pumps to circulate hot water. Coal-fired stoves can be used for heating and cooking. Therefore, the locations of coal-fired stoves in the investigated houses are generally kitchens, living rooms or bedrooms.

As shown in table 4.2, air conditioning accounted for indoor heating in only 8.33% of the surveyed buildings, whereas buildings using stoves for heating accounted for over 91%. Most residents choose to use stoves in combination with other radiators for heating, which is more flexible. When installing a radiator and Kang in the house, residents can choose a radiator or Kang according to their own needs or use both. Among the stove-heated buildings, the coal was burned for indoor heating through the stove, the radiator, or the Kang. Outdoor CO_2 and $PM_{2.5}$ concentrations reached up to 491 ppm and 30 ug/m^3 around buildings, which were heated through coal burning.

(2) Location of heating facilities

Heating facilities and their location are essential factors in this study. Figure 4.8. shows the heater location of four monitored buildings. House-1 was heated by a coal-fired stove, which was located in the main room. The other three houses were heated by Kang or radiator driven by the coal-fired stove in the side room. The coal-fired stove of house 2 is located in the secondary room connected with the main room and drives Kang for heating. In house 3 and house 4 the coal-fired stoves are located in separate secondary rooms. House 3 uses a coal-fired stove to drive the radiator for heating. House 4 has two coal-fired stoves which drive Kang and radiator for heating at the same time.

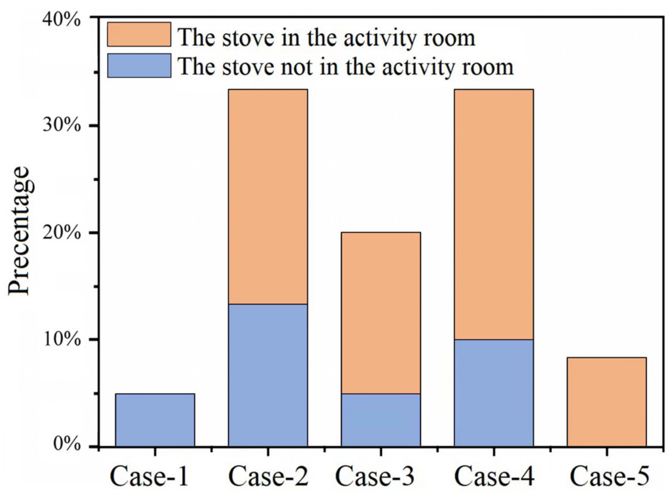

Figure 4.7. Distribution of heating facilities when the stove is in and not in the activity room

Table 4.2. The proportion of typical heating facilities

Typical heating facilities	Number	Percentage (%)
Stove (Case-1)	3	5.00%
Radiator driven by a stove (Case-2)	20	33.33%
Kang driven by a stove (Case-3)	12	20.00%
Radiator and Kang driven by a stove (Case-4)	20	33.33%
Air-conditioning (Case-5)	5	8.33%

4.3.3. Thermal performance of building envelope

The thermal performance of rural house envelopes will have a substantial impact on the indoor thermal environment. The structural information of the roof, exterior wall, and window of four typical houses were investigated. The roof form of the four houses is a red tile double slope roof, and only the roof of house 4 has a thermal insulation structure. The windows of houses 1 and 3 are aluminum alloy window frame single-layer glass, and the windows of houses 2 and 4 are plastic steel window frame single-layer glass. As shown in Figure 4.9, the exterior wall structure level of house 1 is shown. The

Figure 4.8. Heater location of four monitored buildings

lower part is a stone wall, and the upper part is the brick wall. In Figures 4.10 and 4.11, the exterior walls of houses 2 and 3 are brick and stone walls. Figure 4.10 shows that the materials of the upper and lower parts of the wall of House 4 are also different. The upper part is a rammed wall, and the lower part is a stone wall.

Table 4.3 lists the heat transfer coefficients, thermal conductivity, thermal resistance, and thermal inertia of the exterior walls, windows, and roofs of four typical rural houses. In Table 4.3, the thermal inertia value of the upper half (brick wall) of House 1 is 0.5cal/(cm^2·℃·s), which is almost three times that of the lower half (stone wall). The thermal inertia value of the upper part (rammed wall) of House 4 is 0.86cal/(cm^2·℃·s), which is more than four times that of the lower part (stone wall). Thermal inertia refers to the index characterizing the attenuation of the enclosure to the temperature wave, and its value is equal to the product of the thermal resistance of the material layer and the heat storage coefficient. The greater the thermal inertia of the envelope, the better its thermal stability. Thermal inertia is related to building envelope materials, setting sequence of building envelope materials, building envelope thickness and other factors.

As shown in Figure 4.9-4.12, in terms of wall materials, rural houses in Qingdao mostly use stone, brick, rammed and other materials; In terms of roofing materials, straw, ceramic tile, colour steel and other roofing materials were mostly used; In terms of window materials, wooden windows and plastic steel windows were mostly used. The heat storage coefficients of these materials are significantly different. The heat transfer coefficient of the lower half (stone wall) of House 1 is almost twice that of the upper half (brick wall). Wall of house 3 has the highest heat transfer coefficient with 3.33W/(m^2·K). The heat transfer coefficient of the lower half (stone wall) of house 4 is almost three times that of the upper half (wall). Only house 2 has the lowest external wall (brick wall) heat transfer coefficient with 0.36W/(m^2·K), which is less than the limit value. However, the external wall heat transfer coefficients of the other three houses do not meet the relevant standards.

Although the roof of house 4 has a thermal insulation structure, it still cannot achieve a good thermal insulation effect. The lower heat transfer coefficient of the enclosure can enhance its thermal insulation performance. Therefore, in the design and actual construction of rural houses, envelope materials with small heat transfer coefficients should be used more, and thermal insulation measures such as thermal insulation layer should be reasonably applied to reduce their heat transfer coefficient further, to improve the indoor thermal environment in winter.

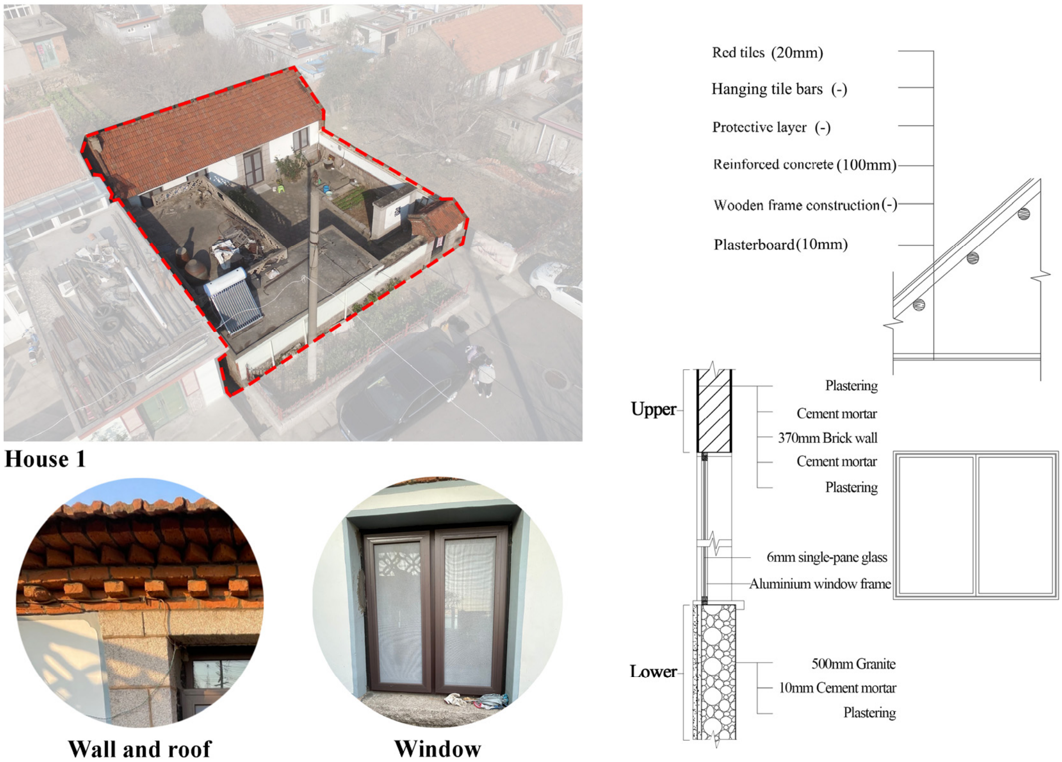

Figure 4.9. The roof, exterior wall, doors and windows of house 1

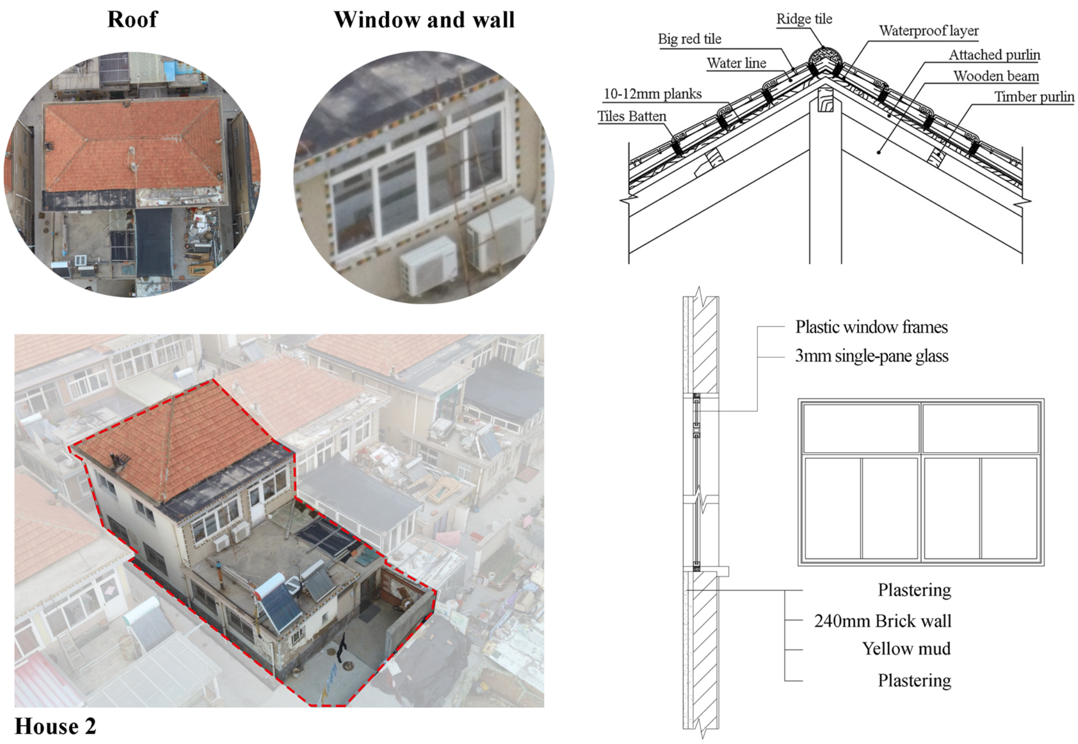

Figure 4.10. The roof, exterior wall, doors and windows of house 2

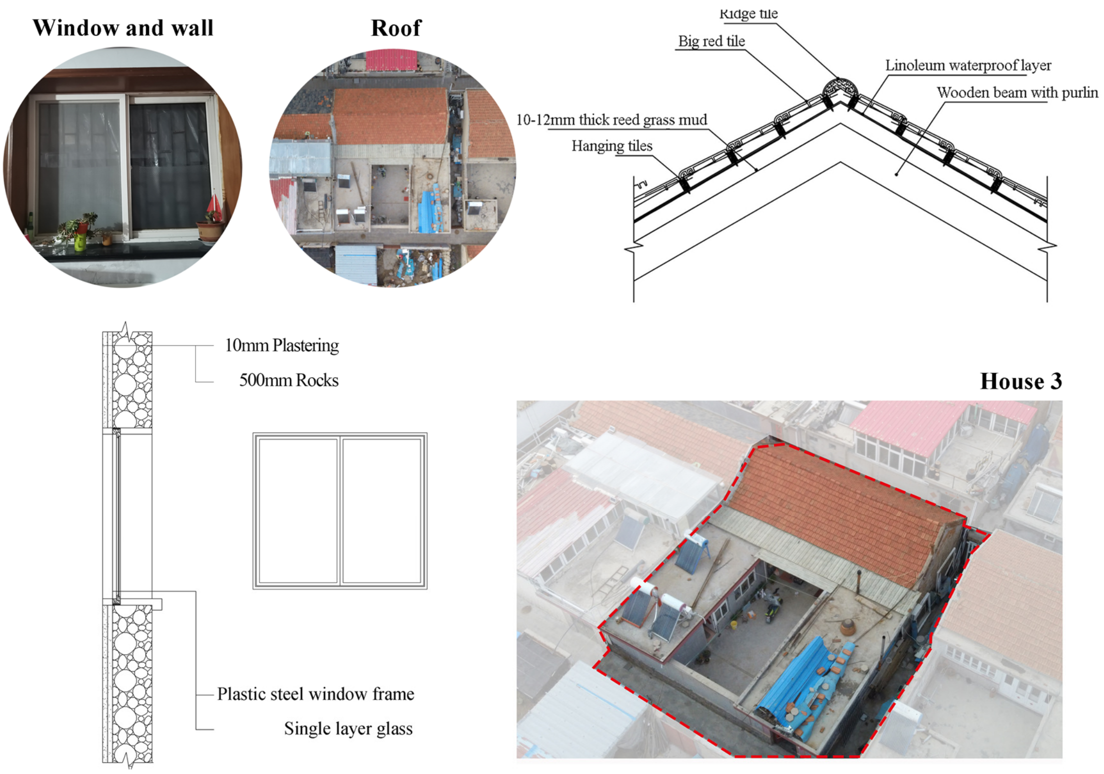

Figure 4.11. The roof, exterior wall, doors and windows of house 3

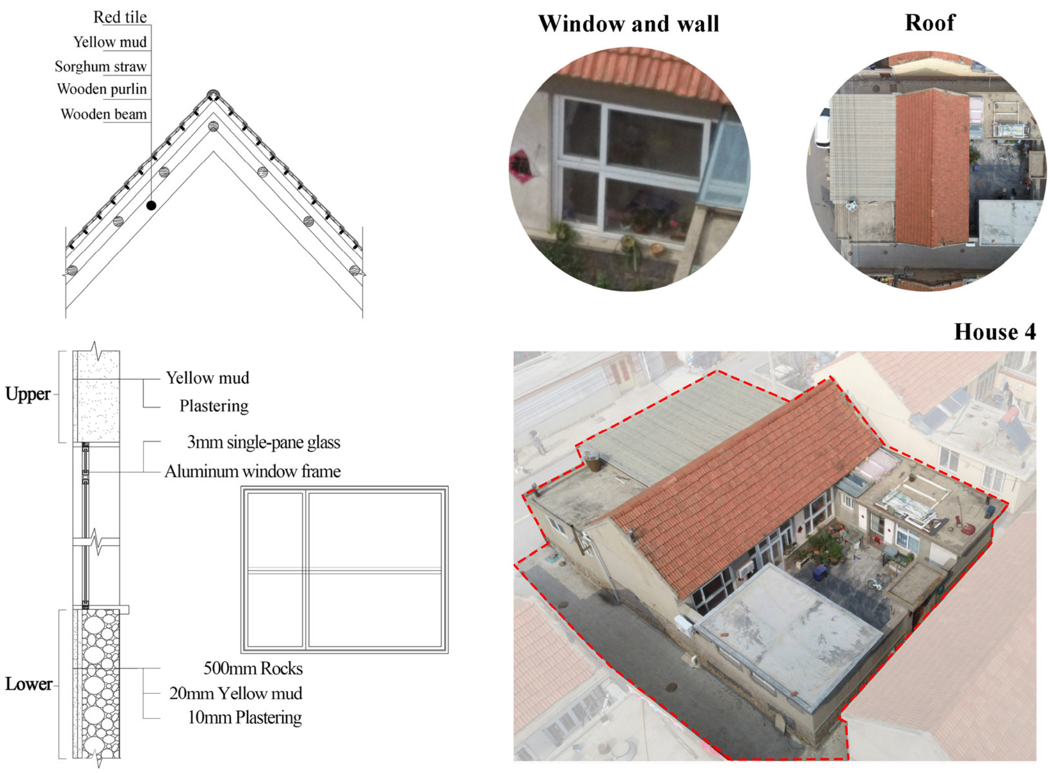

Figure 4.12. The roof, exterior wall, doors and windows of house 4

Table 4.3. Envelope thermal performance test results of typical rural houses

	Thermal performance	Exterior wall	Window	Roof
House 1	Heat transfer coefficient(W/(m^2·K))	1.54 (Upper)	5.70	3.04
		3.13 (Lower)		
	Thermal conductivity(W/(m·K))	0.82 (Upper)	0.2	0.93
		3.06 (Lower)		
	Thermal inertia ((m^2·k)/W)	5.35 (Upper)	1.56	3.98
		3.90 (Lower)		
	Thermal resistance(cal/(cm^2·°C·s))	0.50 (Upper)	0.03	0.15
		0.17 (Lower)		
House 2	Heat transfer coefficient(W/(m^2·K))	0.36	5.00	2.70
	Thermal conductivity (W/(m·K))	0.78	0.06	0.41
	Thermal inertia ((m^2·k)/W)	6.01	0.53	1.34
	Thermal resistance(cal/(cm^2·°C·s))	0.36	0.05	0.22
House 3	Heat transfer coefficient(W/(m^2·K))	3.33	5.80	3.13
	Thermal conductivity(W/(m·K))	3.40	0.15	0.47
	Thermal inertia ((m^2·k)/W)	3.78	0.21	1.21
	Thermal resistance(cal/(cm^2·°C·s))	0.15	0.02	0.17
House 4	Heat transfer coefficient(W/(m^2·K))	0.99 (Upper)	4.9	0.76
		2.86 (Lower)		
	Thermal conductivity(W/(m·K))	0.48 (Upper)	0.12	0.10
		2.65 (Lower)		
	Thermal inertia ((m^2·k)/W)	5.54 (Upper)	0.53	1.81
		4.05 (Lower)		
	Thermal resistance(cal/(cm^2·°C·s))	0.86 (Upper)	0.05	1.17
		0.20 (Lower)		
Standard limit	Heat transfer coefficient(W/(m^2·K))	0.65	2.80	0.50

4.4. Indoor thermal environment

4.4.1.Field measurement and questionnaire survey

During the investigation, the investigators were divided into five groups (four members in each group) and selected 12 houses in five villages to conduct field measurements. The indoor environmental parameters measured include air temperature, relative humidity, CO_2 and PM concentration, black bulb temperature. On the day of the survey, the average outdoor daytime temperature was -0.7℃; the relative humidity was 62%. The investigation time is from 10 am to 6 pm. The sample of the survey included 60 rural houses, and 128 questionnaires were collected (a total of residents and volunteers) . The effective rate of the questionnaire was 94%. Figure 4.13 shows some photographs of the questionnaire survey being conducted.

Figure 4.13. Field photos of the questionnaire survey

In order to ensure residents' understanding of the meaning of the questionnaire, we chose to complete it in the form of an interview. Volunteers explain the questions, talk and ask questions with the villagers, and record the villagers' answers. Secondly, considering that residents have been indoors for a long time, and their adaptation to the local indoor and outdoor environment leads to a deviation in their feelings, we adopt the form of a double questionnaire. In addition to the questionnaire statistics of residents' feedback, volunteers will fill in the questionnaire according to their own feelings according to the situation of each household. Details of the questionnaire are listed in Appendix of Chapter 3.

The indoor temperature and humidity of typical houses were measured to obtain the real indoor thermal environment conditions in winter and facilitate the later software simulation verification. The climate environment of the measuring period has the typical winter characteristic of Qingdao. The measuring point is located in the center of the bedroom, and indoor heating for the Kang. A wireless temperature and humidity recorder HOBO MX1101 is used in the test instrument, which is measured 24 hours a day without interruption. The temperature and humidity information is recorded every 10 minutes.

4.4.2.Results on the indoor thermal environment

(1) Temperature under different heating methods

To show the distribution of indoor air temperature and black bulb temperature clearly, the standard deviations (SD) were gained as follows:

$$(1)\ SD = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2}$$

Where N is the number of surveyed samples; μ is the average value; x_i indicates the i_{th} surveyed sample;

Figure 4.14 shows the distribution of indoor air temperature and black bulb temperature under the different heating methods. As shown, the different heating methods had a specific influence on indoor temperature. Employing radiators achieved the highest indoor temperature and black bulb temperature. Moreover, using a stove in the main room was found to improve indoor temperature due to the high radiant heat emitted from the stove surface. Therefore, the indoor air temperatures and black bulb temperatures of up to 1.75°C and 3.81°C, respectively, were achieved by using a stove in the main room.

Compared between Figure 4.14 and 4.15, the temperature of the black ball was about 4 °C higher than that of the air under the heating system of the stove, and this difference can be attributed to indoor heating by stove heating systems mainly relying on the thermal radiation. In contrast, the air-conditioning systems mainly rely on natural convection. Under the same heating method, whether there is a coal-burning stove in the room has a more significant impact on the temperature of the indoor black bulb. Local houses use coal-fired stoves combined with radiators to achieve better heating effects. In addition, according to the data shown in Figure 4.14 and 4.15, the average indoor air temperature and black bulb temperature of the rural buildings investigated were only 14.1℃ and 16.3℃, which are lower than the typical values of the indoor air temperatures during the heating period, so the present thermal environment in rural villages was lower than that with the central heating. This phenomenon was mainly due to the present heating methods and building thermal performance could not meet the temperature requirement of the central heating and local residents worn more cloths to increase the body insulation performance.

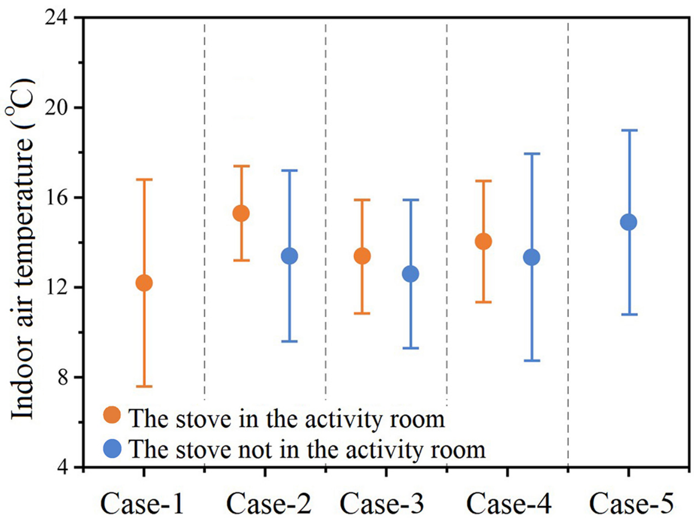

Figure 4.14. Indoor air temperature under different heating methods in rural buildings

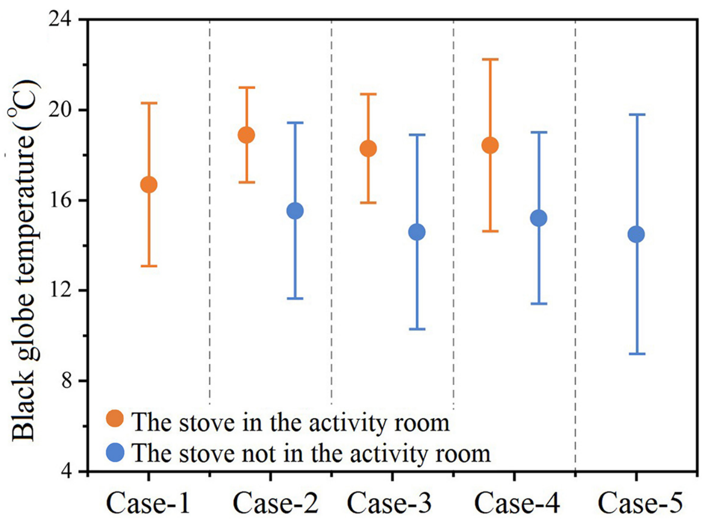

Figure 4.15. Black globe under different heating methods in rural buildings

(2)Thermal and humidity sensation vote

Indoor thermal environment refers to the environmental factors that affect the human body's cold and warm feelings, mainly indoor air temperature, air humidity, airflow velocity, and radiation heat exchange between the human body and the surrounding environment. This research mainly conducts in-depth analysis by establishing the relationship between the subjective evaluation of thermal sensation and humidity sensation and the objective indoor air temperature and indoor relative humidity parameter.

Many field studies conducted worldwide have found that indoor temperature determines thermal sensation [32]. Therefore, this study established a direct relationship between the occupant's thermal sensation and indoor air temperature and black bulb temperature, rather than the relationship between comfort/neutral temperature and outdoor temperature. Although the above analysis showed the present thermal environment in the rural buildings, it was still necessary for residents to evaluate the satisfaction of the indoor thermal environment. Figure 4.16 gives the thermal sensation voting statistic from local residents and volunteers. As shown, over 70% of residents expressed feeling between slightly cool (-1) or slightly warm (1), whereas a more significant proportion of volunteers expressed feeling slightly cool. The average votes of residents and volunteers were 0.25 and -0.56, respectively.

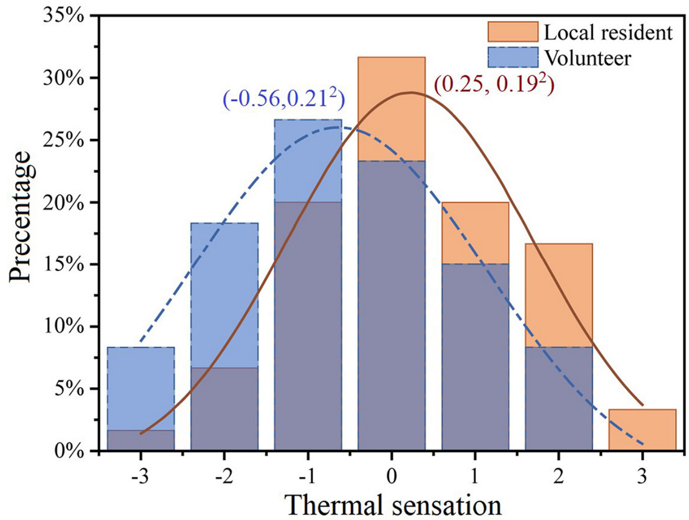

Figure 4.16. Statistical chart of thermal sensation vote

Figure 4.17 shows the thermal sensation vote of residents and volunteers at indoor air temperature. As shown, local residents indicated the neutral temperature to be 13℃, which was 2.18℃ lower than that of volunteers, indicating that local residents had adapted to a lower indoor temperature than volunteers. The results showed that the thermal sensations of villagers and volunteers in the same indoor environment were inconsistent. This may be because the villagers' self-regulation of the indoor environment led to their strong adaptability to low temperatures. Although this study does not consider occupants' behaviour adjustment, we infer that the villagers' thermal sensation of voting in the cold side area is less sensitive, which may also be compensated for occupants' behaviour adjustment, especially clothing adjustment.

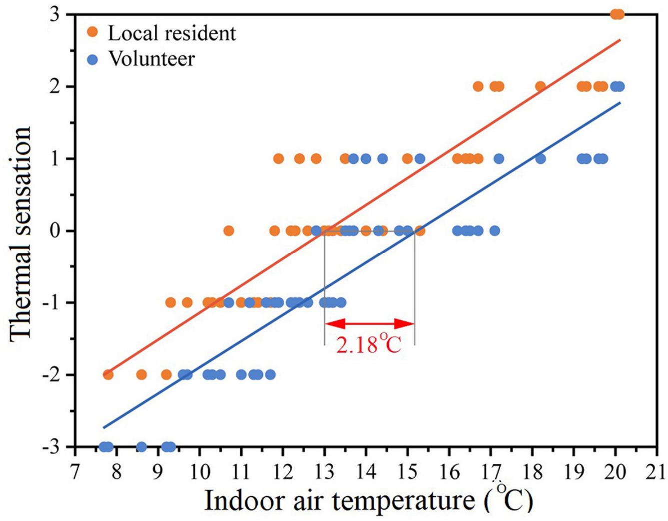

Figure 4.17. Thermal sensation vote with indoor air temperature

Figure 4.18 shows the humidity sensation voting statistic from residents and volunteers. As shown, a higher proportion of residents indicated satisfaction with their indoor humidity experience, and over 61% of residents indicated the conditions to feel between slightly humid (-1) and slightly dry (1). In contrast, a higher proportion of volunteers indicated their humidity experience to be dry. The average humidity sensation votes of residents and volunteers were 0.30 and 1.32, respectively, indicating that residents showed higher tolerance to dry conditions.

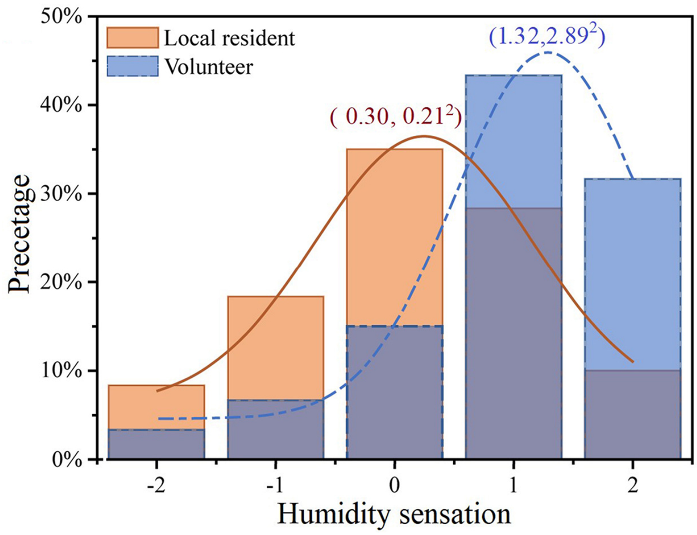

Figure 4.18. Statistical chart of humidity sensation vote

Figure 4.19 presents the humidity sensation vote of residents and volunteers with indoor relative humidity. As shown, residents indicated neutral relative humidity to be 40%, which was 6.30% lower than that of volunteers, indicating that residents had adapted to a drier indoor environment during winter.

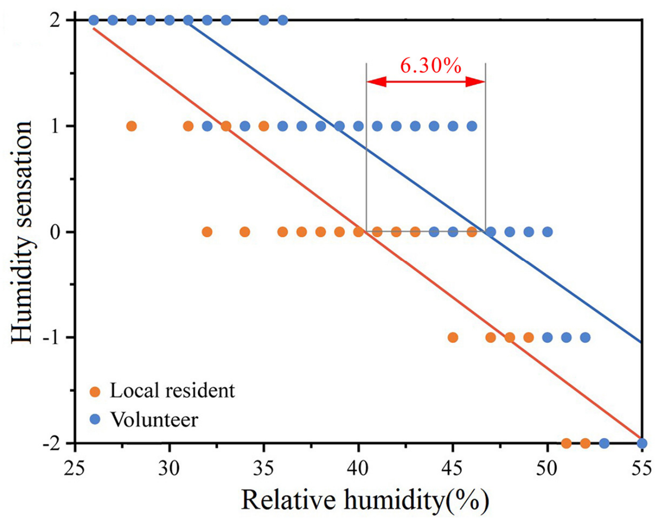

Figure 4.19. Humidity sensation vote with indoor relative humidity

(3)Analysis of indoor air quality

Indoor air quality is vital for residents, so indoor smell intensity, CO_2 and $PM_{2.5}$ concentration were investigated. Figures 4.20 and 4.21 showed the indoor smell intensity voting statistics from residents and volunteers. Volunteers indicated a worse indoor odour experience, compared to local residents with using a coal-fired stove in the main room. This result indicated that residents had adapted to the indoor heating environment. There was a lower difference in indoor odour experience between volunteers and residents without using a coal-fired stove in the main room. The average votes of indoor smell intensity were 1.1 and 0.68 with and without the stove in the activity room, respectively, which showed the coal-fired stove is the primary source of indoor smell owing to the coal combustion.

Figure 4.22 and 4.23 shows CO_2 and $PM_{2.5}$ concentration with the investigated samples. As shown, the maximum and average values of CO_2 concentration are 976.74ppm and 690.78ppm without the stove in the activity room, while those can be up to 1400.00ppm and 1015.47ppm with the stove in the activity room. According to the ASHRAE 180-2018 standards, CO_2 concentrations of 700 ppm will result in discomfort, and CO_2 concentrations of 1,000 ppm will lead to a feeling of drowsiness. Long-term exposure to high CO_2 concentrations can result in poor respiratory health [33]. The indoor

CO_2 concentrations measured in the present study exceeded the ASHRAE 180-2018 standards, particularly in buildings containing a stove in the main. Therefore, residents face a higher risk of poor respiratory health under this condition.

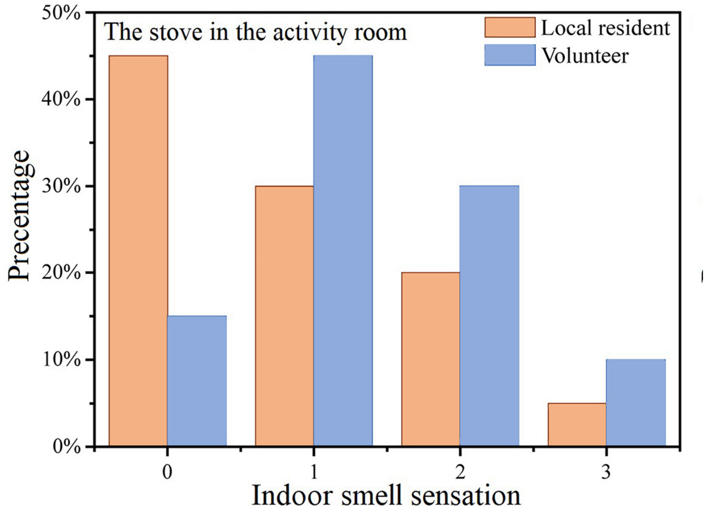

Figure 4.20. Statistical chart of indoor smell intensity vote with the stove in the activity room

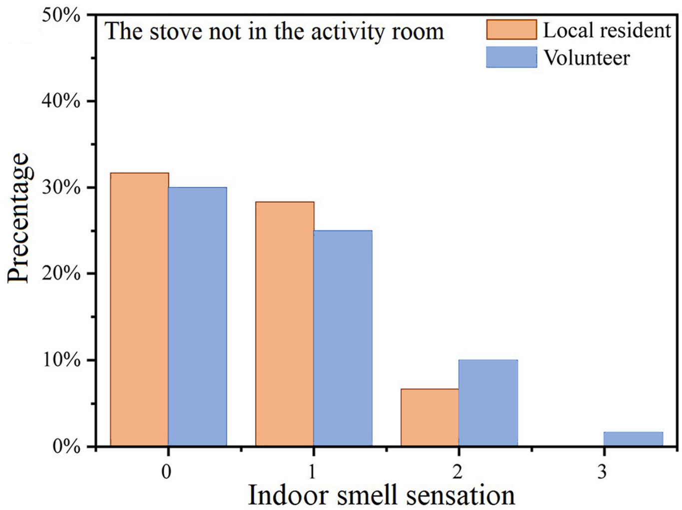

Figure 4.21. Statistical chart of indoor smell intensity vote without the stove in the activity room

In addition, the $PM_{2.5}$ concentration, as an essential indicator of air quality, has been measured in Figure 4.23, and the indoor air quality index limit of $PM_{2.5}$ is 75ug/m^3 [34]. However, the maximum and average values of $PM_{2.5}$ concentration were 316.57ug/m^3 and 62.90ug/m^3 without the stove in the activity room, while those could be up to 565.18ug/m^3 and 199.61ug/m^3 with the stove in the activity room. This result shows that the $PM_{2.5}$ concentrations in most of the surveyed rural buildings exceeded the $PM_{2.5}$ standard of 75 ug/m^3, particularly when using a stove in the main room. Therefore, since $PM_{2.5}$ particles could enter the blood through the bronchi and alveoli, residents faced a higher risk of poor health and premature death [34].

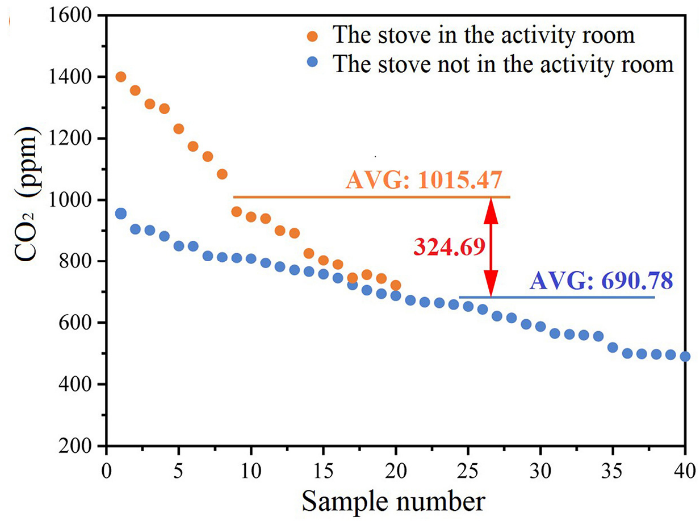

Figure 4.22. Indoor air quality of rural buildings CO_2 concentrations within the investigated samples

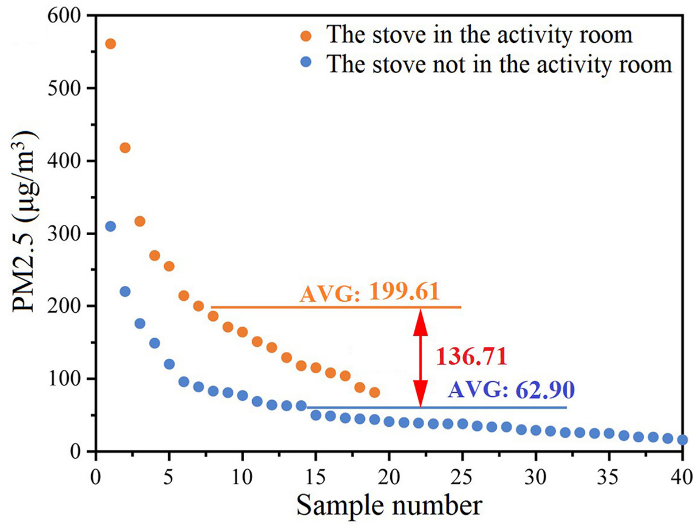

Figure 4.23. Indoor air quality of rural buildings $PM_{2.5}$ concentrations within the investigated samples

4.5. Indoor air quality

4.5.1. Field measurement

The indoor air quality of four rural buildings was studied by field measurement in the winter heating period. Air pollution concentrations (CO_2, $PM_{1.0}$, $PM_{2.5}$ and PM_{10}) were recorded. Chapter 3 shows the accuracy and range of the measuring instruments used. Meanwhile, to ensure the measurement accuracy of the instruments before field measurement, all the instruments were calibrated and debugged. The measurement equipment was placed 1.5m above the ground in the main room of each building, and all data was recorded every 10 minutes. The experimental period was eight consecutive days from Dec. 21 to Dec. 28 in 2020. Figure 4.24 shows the Photographs showing examples of field measurement of indoor air quality

Figure 4.24. Photographs showing examples of field measurement of indoor air quality

4.5.2. Results on indoor air quality

(1)Indoor CO_2 concentration

Indoor CO_2 concentration is a critical evaluation index of air quality, and it can affect the reaction and decision-making ability [20]. Figure 4.25 shows the variation of indoor CO_2 concentration with time in four monitored buildings, and if CO_2 concentration is higher than 1000ppm, the occupancy health has been threatened [21]. As shown in Figure 4.19, indoor CO_2 concentration was higher than 1000 ppm in House 1 and 2 in most experimental time, where the coal-fired stove was located in the main room and the carbon burning releases a lot of CO_2 concentration. When the coal-fired stove was located in the secondary room in House 3 and 4, CO_2 concentration was reduced sharply, compared with House 1 and 2. Moreover, it was easily found that there was a sudden increment phenomenon of CO_2 concentration, especially in House 1 and 2, where the coal-fired stove was located in the main room. Furthermore, this phenomenon usually occurred when the coal was added to the coal-fired stove. It showed that the early combustion of coal releases CO_2 quickly, and this sudden increment of CO_2 concentration has a huge threat to occupancy health.

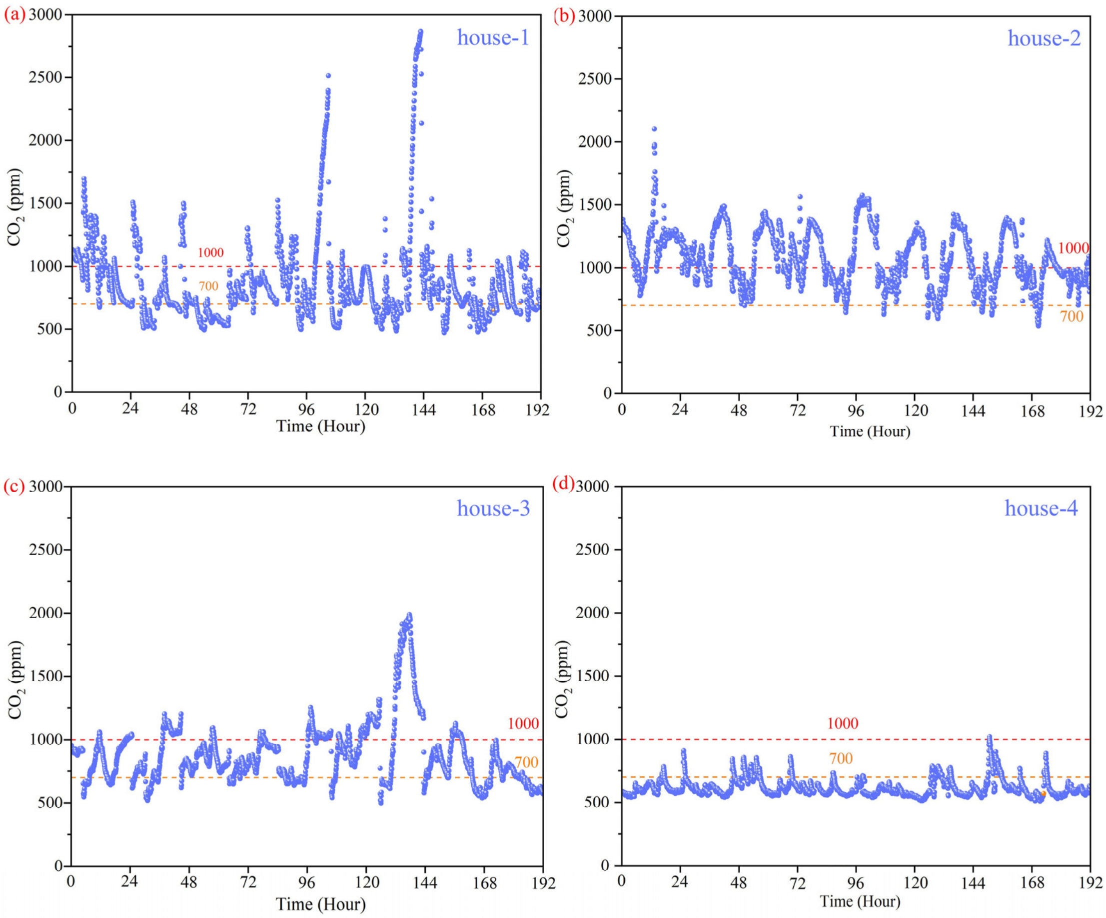

Figure 4.25. Variation of indoor CO_2 concentration with time in four monitored buildings

Table 4.4 shows indoor CO_2 concentrations in four typical houses during measurement. As shown in Table 4.4, the peak CO_2 concentration only in House 4 was close to 1000 ppm, while it was up to 2000-2800 PPM in Houses 1-3. The CO_2 concentration of more than 2000 ppm can lead to hating to work and reducing the elaborative faculty significantly. Moreover, the average CO_2 concentrations in Houses 1-3 were also close to 1000 ppm, which was the upper limit of indoor CO_2 concentration. It shows that indoor CO_2 concentration was too high to be healthy in these buildings. In addition, although the coal-fired stove was located in the secondary room in House 3, the secondary room was connected with the main room with the better cross-ventilation in House 3. The maximum and average concentrations of indoor CO_2 in House 3 were similar to those in House 1 and House 2. Therefore, the coal-fired stove should be located in an independent space as far as possible, independent of the main function rooms of the building.

Table 4.4. Indoor CO_2 concentrations in four typical houses during measurement

Buildings	Maximum (ppm)	Minimum (ppm)	Average (ppm)
House 1	2869	471	872
House 2	2101	536	1085
House 3	1989	498	876
House 4	1021	501	564

(2)Distribution of $PM_{1.0}$ concentrations

The primary particulate matter of coal combustion will affect the concentration of particulate matter (PM) in indoor air. The harmful effects of particulate matter (PM) on health are related to quality and particle size and chemical composition [22-24]. Indoor concentrations of $PM_{1.0}$, $PM_{2.5}$ and PM_{10} in four buildings were measured and recorded in this study.

Finer particles（PM with a diameter of ≤1.0μm）can penetrate respiratory tract problems and enter blood vessels. It usually has a larger specific surface area, which can absorb more toxic pollutants and significantly impact health. Figure 4.20 shows the variation of indoor $PM_{1.0}$ concentration with time in four monitored buildings. Once the indoor $PM_{1.0}$ concentration exceeds the WHO (World Health Organization) standard limit of 25μg/m^3[25], people will face the related health risk. As shown in Figure 4.26, indoor PM1.0 concentration was higher than 25μg/m^3 in most experimental time in Houses 1 and 2, where the coal-fired stove was located in the main room. When the coal-fired stove was located in the secondary room in Houses 3 and 4, $PM_{1.0}$ concentration was reduced sharply. In addition, indoor $PM_{1.0}$ in House 4 exceeded 25μg/m^3 for most of the experimental time, compared to House 3, possibly because it had two coal-fired stoves located in a side room.

Table 4.5 lists the indoor $PM_{1.0}$ concentrations of four typical houses during the measurement period. As shown in Table 4.5, the peak $PM_{1.0}$ concentration in House 1-2 was up to 430-480μg/m^3, while it was close to 150μg/m^3 in Houses 3-4. The $PM_{1.0}$ concentration of more than 400μg/m^3 was significantly associated with the risk of preterm birth [35]. Moreover, the average $PM_{1.0}$ concentrations in Houses 1,2 and 4 were up to 50-90μg/m^3, which was the upper limit of indoor $PM_{1.0}$ concentration.

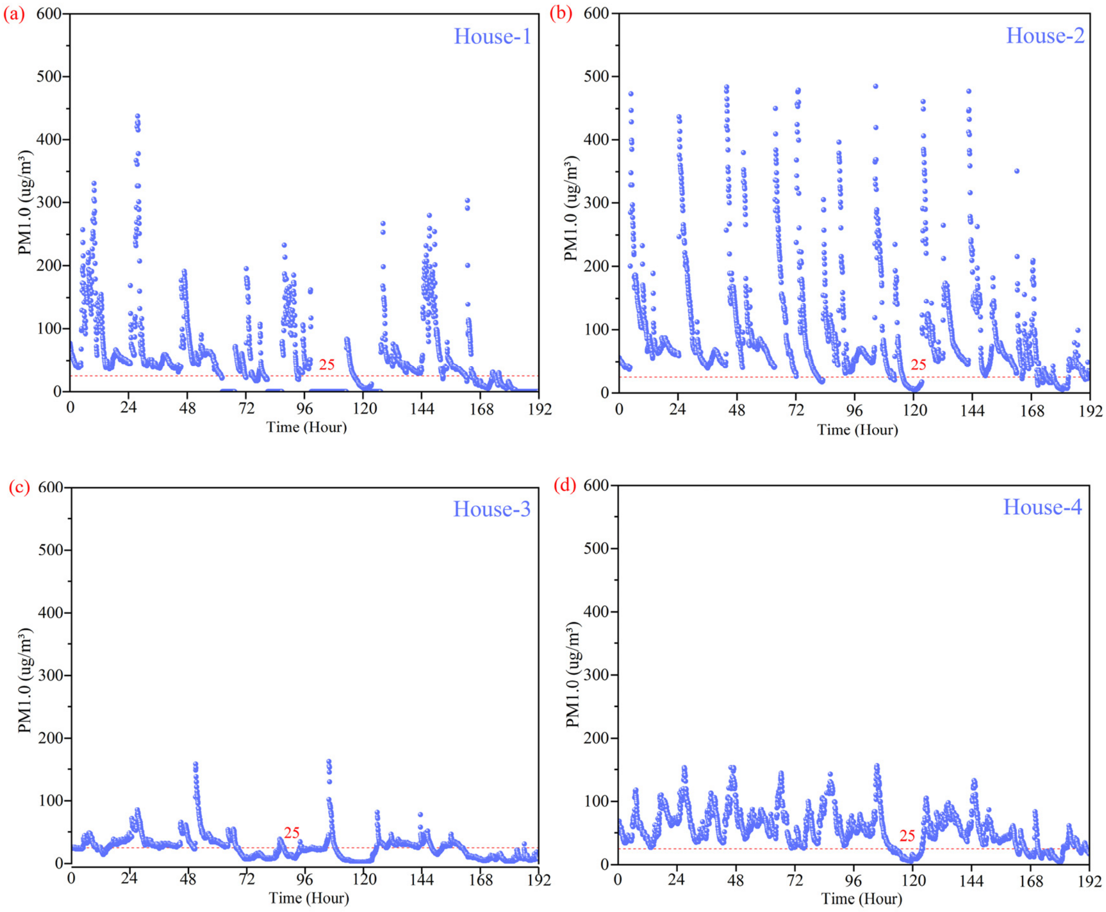

Figure 4.26. Variation of indoor $PM_{1.0}$ concentration with time in four monitored buildings

It showed that indoor $PM_{1.0}$ concentration is too high in these buildings. Although the coal-fired stove was located in the secondary room in House 4, the smoking behaviour of residents increased indoor $PM_{1.0}$ concentrations [36]. As a result, the average daily concentration of $PM_{1.0}$ in House 4 was higher than in House 3.

Table 4.5. Indoor $PM_{1.0}$ concentrations in four typical houses during measurement

Buildings	Maximum (μg/m^3)	Minimum (μg/m^3)	Average (μg/m^3)
House 1	437	5	48
House 2	485	6	89
House 3	162	1	25
House 4	156	4	52

(3)Distribution of $PM_{2.5}$ concentrations

Figure 4.27 shows the variation of indoor $PM_{2.5}$ concentration with time in four monitored buildings, and the indoor air quality index limit of $PM_{2.5}$ is 75ug/m^3[37]. When Indoor $PM_{2.5}$ concentrations exceed 75 ug/m^3, it can cause asthma, bronchitis and cardiovascular diseases. As shown in Figure 4.5, the Indoor $PM_{2.5}$ concentration in House 1 and House 2 was well above 75ug/m^3 for most of the testing period, while the indoor $PM_{2.5}$ concentration in House 3 and House 4 was relatively low. Moreover, the $PM_{2.5}$ peak appears when residents prepare dinner and breakfast. However, the effect of cooking activities lasted for a relatively short time, usually reached the peak in cooking time, lasting about half an hour, and did not significantly increase the daily average concentration of relative pollution days. In contrast, due to the regular fuel supply, heating emissions created a series of peaks. In this case, the impact on $PM_{2.5}$ daily average concentration was significant.

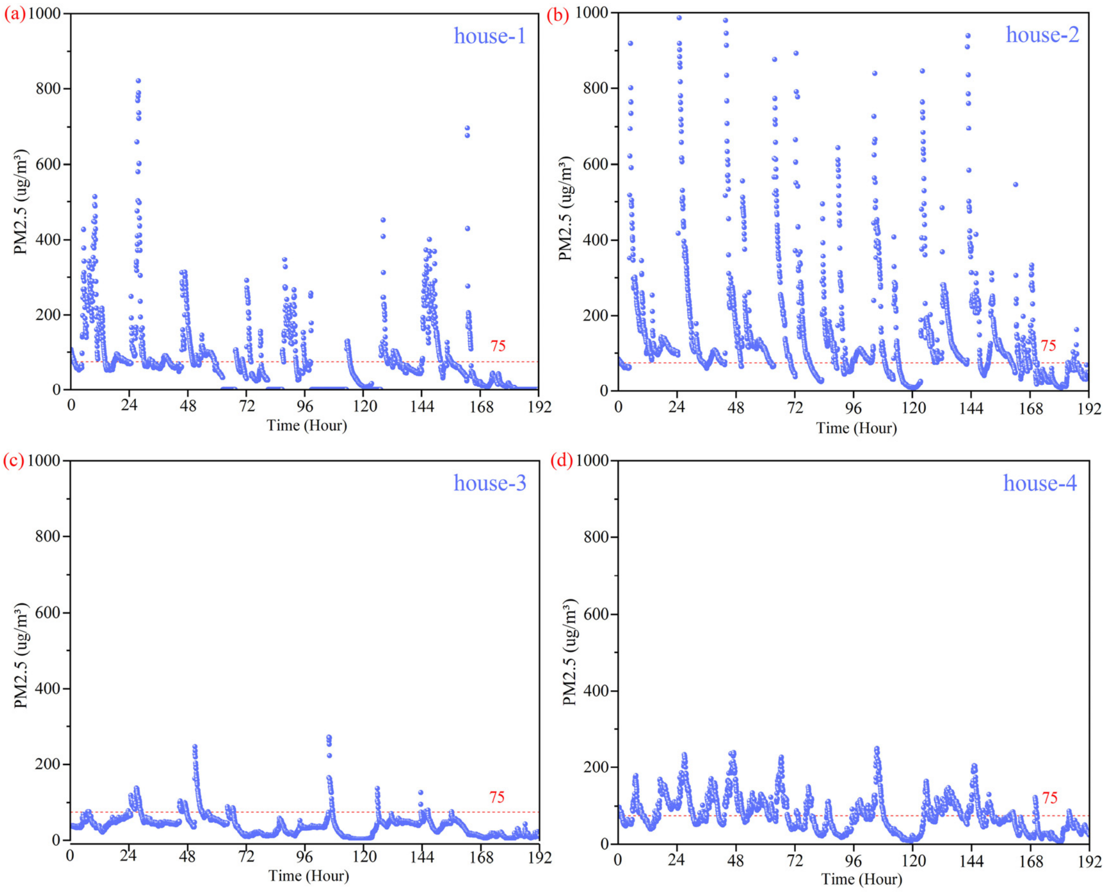

Figure 4.27. Variation of indoor $PM_{2.5}$ concentration with time in four monitored buildings

Table 4.6 lists the indoor $PM_{2.5}$ concentrations of four typical houses during the measurement period. It can be seen from Table 4.9 that the average $PM_{2.5}$ concentrations in Houses 1,3 and 4 were close to 40-70μg/m^3, which was the lower than indoor $PM_{2.5}$ limit. However, the peak $PM_{2.5}$ concentration in these houses was up to 200-800ug/m^3, while it was up to 2000 ug/m^3 in Houses 2. This result showed that the $PM_{2.5}$ concentrations in the case of using a stove in the main room exceeded the $PM_{2.5}$ standard of 75μg/m^3. Therefore, residents faced a higher risk of poor health and premature death. This may be due to the small indoor space, the inadequate ventilation brought by the closed courtyard, and the number of indoor coal-fired stoves was one more than other houses.

Table 4.6. Indoor $PM_{2.5}$ concentrations in four typical houses during measurement

Buildings	Maximum (μg/m^3)	Minimum (μg/m^3)	Average (μg/m^3)
House 1	821	9	73
House 2	1995	7	150
House 3	271	2	39
House 4	250	6	75

(4) Distribution of PM_{10} concentrations

Figure 4.28 shows the variation of indoor PM_{10} concentration with time in four monitored buildings. According to the IAQ standard, the daily average concentration of PM_{10} is 150μg/m^3[16]. When the indoor PM_{10} concentration exceeds the standard, it can easily lead to pathological changes of human organs, especially in older people and children. It can be seen from Figure 4.22 that when the coal-fired stove was located in the main room in houses 1 and 2, PM_{10} concentration was higher than 150μg/m^3, especially in houses 2. This may be due to the immense depth of house 2 and the poor ventilation caused by the closed courtyard. Secondly, the number of residents is large, and the concentration of PM_{10} would increase due to the influence of personnel activities. Indoor PM_{10} concentration is higher than 150μg/m^3 in houses 3 and 4 relatively less experimental time, where the coal-fired stove was located in the secondary room.

Table 4.7 shows the indoor PM_{10} concentrations in four typical houses during measurement. As shown in Table 4.7, the average indoor concentration of PM_{10} only in house 2 was higher than 150μg/m^3. While the peak PM_{10} concentration was up to 3894μg/m^3.The average PM_{10} concentration in Houses 1,3 and 4 was close to 50-90μg/m^3, lower than the standard. The peak PM_{10} concentration in houses 1, 3, and 4 was as high as 300-1000μg/m^3. Therefore, residents face a higher risk of poor respiratory health under this condition.

Table 4.7. Indoor PM_{10} concentrations in four typical houses during measurement

Buildings	Maximum (μg/m^3)	Minimum (μg/m^3)	Average (μg/m^3)
House 1	1036	7	87
House 2	3894	8	182
House 3	368	2	49
House 4	304	7	90

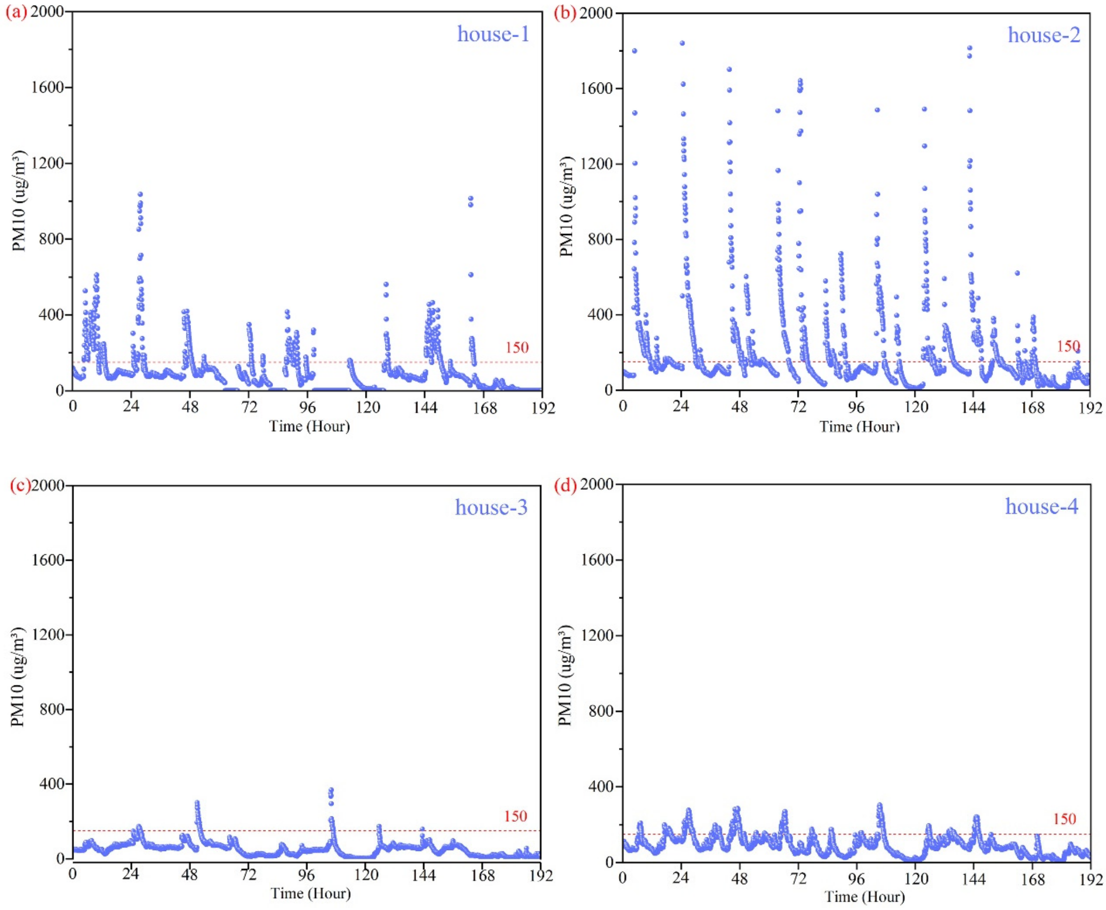

Figure 4.28. Variation of indoor PM_{10} concentration with time in four monitored buildings

4.6. Summary

The living environment of rural residents could seriously affect their quality of life. This present study surveyed the thermal performance of building envelope, indoor thermal environment and air quality in the typical coastal villages of Qingdao during the heating period. The main findings of the present study are listed below:

(1) Over 90% of the buildings employed the coal-fired stove in the main room, the primary indoor heating source. In terms of wall materials, rural houses in Qingdao mostly used stone, brick and rammed; In terms of roofing materials, red ceramic tile are mostly used; In terms of window materials, wooden windows and plastic steel windows are mostly used. The thermal performance of the building envelope does not meet the relevant standards.

(2) Residents showed greater adaptability to indoor temperature and humidity conditions compared to volunteers. The neutral temperature and humidity of local residents were about 13°C and 40%, respectively, which were 2.18°C and 6.3% lower than that of volunteers. The average indoor air temperature and black bulb temperature of the rural buildings investigated were only 14.1℃ and 16.3℃, which are lower than the typical values of the indoor air temperatures during the heating period, so the present thermal environment in rural villages was lower than that with the central heating.

(3) The average indoor odour experience scores were 1.1 (more than "slight odour") and 0.68 (between "Neutral" and "Slight odour") with and without the use of a stove in the main room, respectively, which indicated that employing a coal-fired stove for indoor heating is the primary source of indoor odour due to the combustion of coal. All the collected data show that the indoor CO_2, $PM_{1.0}$, $PM_{2.5}$ and PM_{10} of some coastal villages have very high results compared with the allowable concentration of IAQ standards. They indicate that the indoor air quality of the surveyed buildings during the winter heating period presents a severe threat to human health. Therefore, the coal-fired stove should be located in an independent space as far as possible.

Appendix A. Summary table of investigated villages

Summary table of investigated villages in Qingdao

District	Townships	Villages	Village Type	Industry Condition	Number of samples
Chengyang	Shangma	Wanglinzhuang	Plain	Plantation	29
		Qiujia	Plain	Plantation	21
		Guojiazhuang	Plain	Plantation	17
Jimo	Duanbolan	Duanbolan	Plain	Breeding	22
		Lilin	Plain	Plantation	23
	Jinkou	Guqian 1	Mountain	Folk Tourism	19
		Zhoujiatun	Mountain	Plantation	16
		Yujiatun	Mountain	Plantation	20
Laoshan	Beizhai	Bijia	Mountain	Plantation	25
		Lanjiazhuang	Mountain	Folk Tourism	14
		Xiwuyixiang	Mountain	Breeding	19
	Shazikou	Xidengying	Mountain	Breeding	17
		Lingxi	Mountain	Breeding	24
		Houdengying	Mountain	Plantation	22
Huangdao	Baoshan	Wangjiaxiaozhuang	Plain	Plantation	16
		Hujia	Plain	Plantation	20
		Shangzhuang	Plain	Breeding	18
	Zhangjialou	Yuanzhuang	Plain	Plantation	19
		Dapan	Plain	Fishing	25
		Chengjiazhuang	Plain	Plantation	23

Appendix A. (Continued)

District	Townships	Villages	Village Type	Industry Condition	Number of samples
Jiaozhou	Jiaolai	Zhangyuetun	Plain	Plantation	24
		Guanlu	Plain	Plantation	22
		Jinjiatong	Plain	Breeding	20
	Yanghe	Zhang	Plain	Breeding	14
		Zhongjiaxinzhuang	Plain	Plantation	21
		Peijia	Mountain	Breeding	18
Laixi	Guhe	Guojiazhuang	Plain	Plantation	17
		Sunjiapo	Plain	Plantation	21
		Wanglianzhuang	Plain	Plantation	17
	Xiagezhuang	Gejiazhuang	Plain	Plantation	17
		Cuijiazhuang	Plain	Plantation	15
		Wenjiaponan	Plain	Plantation	19
Pingdu	Liaolan	Wanliuzhou	Plain	Plantation	17
		Zuanxiqiu	Plain	Plantation	19
		Nansunjia	Plain	Plantation	21
	Yunshan	Hedongdabai	Plain	Plantation	23
		Hujiagou	Mountain	Plantation	26
		Maxiang	Plain	Breeding	20

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Chapter 5. Thermal performance enhancement of building envelopes by using crop straw

5.1.Introduction

Based on the current standards in China, the thermal performance of the envelope in rural areas can not satisfy the regulations [1]. A meaningful way to improve the thermal performance of the envelope structure is to add insulation layers. There are many popular insulation materials, such as hollow sintered bricks combined with thermal insulation material (TIM) or Phase-Change Material (PCM) [2-5]. These insulation materials have advantages and disadvantages, so improving the thermal performance of envelope structure is essential.

China is a predominantly agricultural country, producing billions of agricultural tons every year. The total amount of straw produced each year is enormous, but the utilization rate of straw is meagre [6-8]. Straw is burned or left unused in farmland, which causes environmental pollution and a significant waste of resources [9]. On the contrary, as a renewable, high-quality natural material, straw has good building properties such as heat preservation, sound insulation, lightweight, and fire resistance [10]. Therefore, it can be used to develop a heat preservation material for the energy-saving improvement of rural houses.

5.2.Description of straw hollow brick

5.2.1.Straw insulation materials

With the continuous improvement of living standards and indoor comfort, building energy consumption is increasing rapidly, leading to a very urgent task to improve building energy efficiency [11]. In order to promote building energy conservation, China has successively promulgated architecture design standards according to different climate zones to improve the thermal performance of the building's maintenance structure. From the implementation of *Energy-saving Design Standards for Civil Buildings -Heating Residential Buildings (JGJ26-1986)* in 1986, heating energy consumption was reduced by 30%, to *Energy-saving Design Standards for Residential Buildings in Severe Cold and Cold Areas (JGJ 26-2010)*, the energy-saving target was increased to 65% in 2010. Furthermore, Beijing, Shandong, Hebei, Tianjin provinces in China have gradually formulated and implemented 75% efficiency design standards for residential buildings [12]. 75% efficiency design standards for residential buildings are a significant challenge for traditional building materials, such as hollow brick walls, and the insulation material is facing the problem of being too thick under the design standard of 75% energy saving [13].

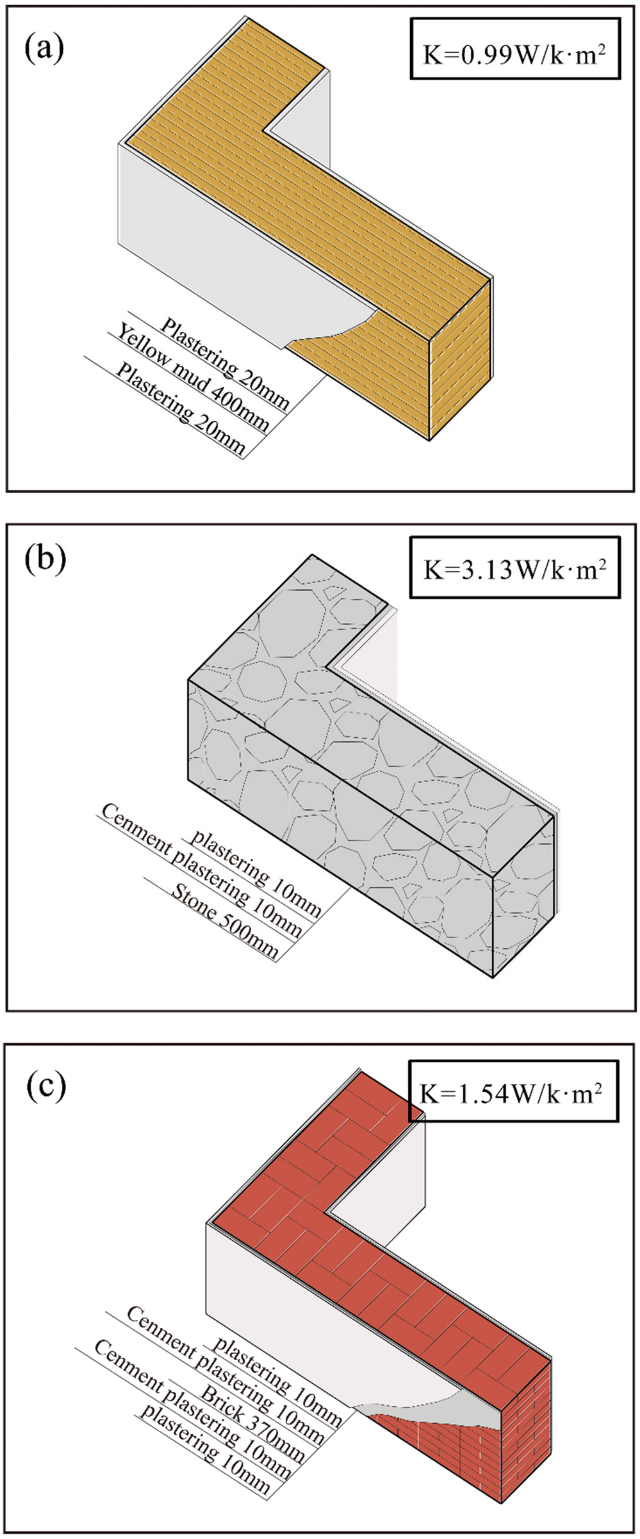


Figure 5.1. Traditional wall structures of rural house

Figure 5.1 shows the three most common maintenance structure forms of existing rural houses after the investigation, which are mud structure (a), stone structure (b), and brick structure (c). Moreover, their heat transfer coefficients are 0.99 W/k·m^2，3.13 W/k·m^2 and 1.54 W/k·m^2, respectively, higher than the energy-saving standard used in China. There are problems in the current heat insulation system, such as the short life of heat insulation material, unsafety, inconvenient treatment of detailed parts, and polluting the environment [14]. So, we need to use a new insulation material to make energy-saving transformations on these structures.

Figure 5.2. Straw and the samples of straw hollow bricks

China is a large agricultural country. Its total output of crop straw is about 1.04 billion tons, and about 900 million tons of crop straws can be collected [6]. Crop straw is a vast number of renewable resources, which has the advantages of diverse varieties, widely distributed, and low prices [7]. Some crop straw materials have hundreds of varieties [8]. Rice and wheat are the most important food crops in China. Rice straw, as the largest crop in China, has wealthy resources. Rice output has maintained at 210 million tons in recent years. Rice in China is mainly grown in the Pearl River Basin, the Yangtze River Basin, and the Northeast area [15]. Wheat in China has the second amount yield to that of rice. The total output of wheat is 131.43 million tons. Shandong province has the most considerable planting amount of wheat. The total annual output of wheat straw in Shandong is 25810kt, which has great potential for utilization [16]. Besides food crops, reeds grow all over the world, and they mostly grow near water sources such as irrigation ditches, riverbanks, and swamps, and they are one of the primary plants that grow in the wetland environment. In China, a wetland with reeds covers an area of 1.367 million hectares, and the area where reeds grow is about 459,000 hectares, which has great application potential [17]. The total amount of straw produced each year is enormous, but the straw utilization rate is shallow. Straw is burned on-site as waste or left unused in farmland, bringing environmental pollution, fire hazards, threats to transportation safety, and a tremendous waste of resources [9]. However, as a kind of renewable, high-quality natural material, straw has the building properties of good thermal insulation, sound insulation, lightweight, and good fire resistance [10].

5.2.2.Description of straw hollow brick

The thermal insulation material studied in this paper is composed of hollow bricks and straw fillings. The hollow bricks take on the structural role, which size is 235mm×235mm×110mm (length × width × height) double-row square hole brick, and each hole size is 63mm×35mm (length × width). In contrast, the straw filling assumes the role of heat preservation. In order to study the thermal insulation performance of different straw materials, this paper produced a total of five different straw filling materials, as shown in Figure 5.2. Moreover, qualities of straws filling into one brick with the pressure of 70N, which is approximately equal to the maximum pressure made by hand, are as follows: the reed leaves are 108.6g; the reed stem is 375.6g; the rice shell is 301.8g; the rice straw is 129.0g, and the wheat stem is 156.0g. By comparing with non-fillings hollow bricks, it is studied how much straw filling materials can improve the thermal performance of the original hollow bricks. Combine the advantages of the two materials of brick and straw to adapt to the construction of new rural areas in China.

5.3.Experimental method

5.3.1. Experimental principle

This experiment uses the simple hot box heat flow meter method (SHB-HFM), which has the characteristics of small experimental error, simple operation, and no seasonal restrictions [18].

Figure 5.3 shows the measuring principle of SHB-HFM to the wall heat transmittance in summer. A simple heat box is installed on one surface, and the central area of the one-dimensional heat transfer wall corresponds to the central area of the simple heat box. While the heat box is heated, the relatively stable outdoor temperature maintains the natural temperature; there will be a relatively stable high-temperature difference. The fan is used for stirring in the heat box to form an even and stable thermal environment. The installed heat flow meter and thermometer can measure the wall heat transfer coefficient.

This experiment was carried out on August 17, 2021, and selected uninterrupted measurements for 15 days during the mildest climate in Qingdao. The data recording interval was every 20 minutes. The weather conditions during the measurement period were sunny or cloudy.

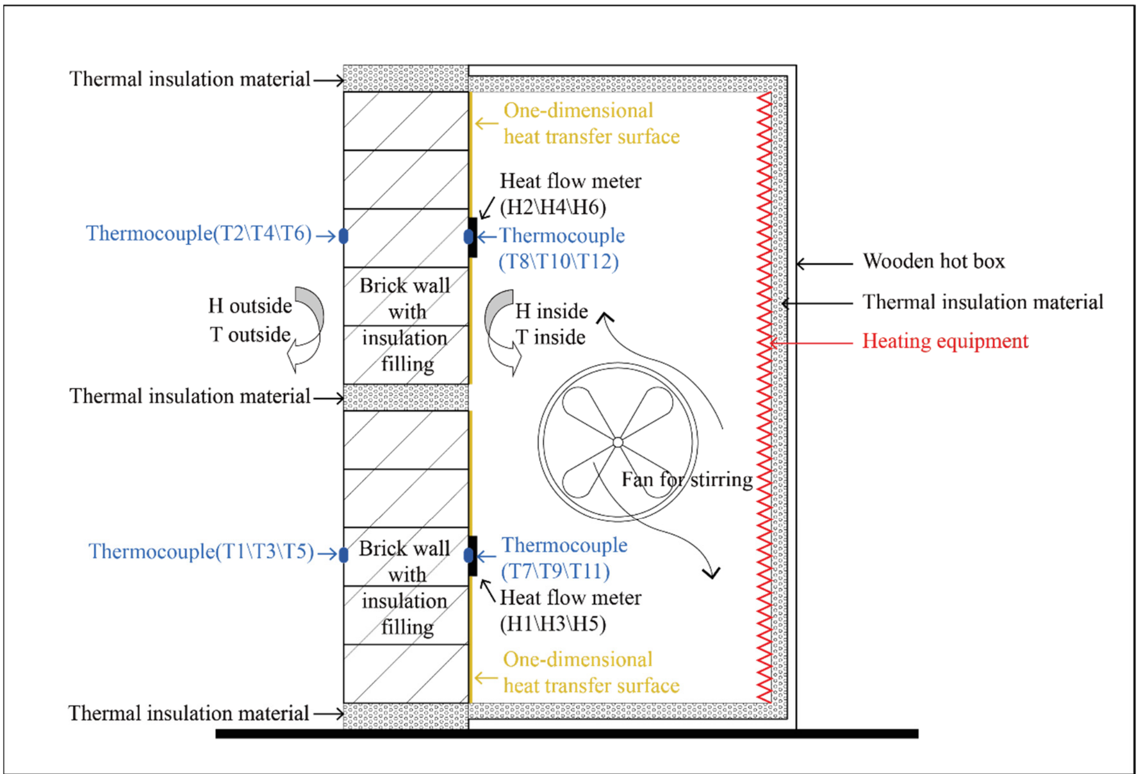
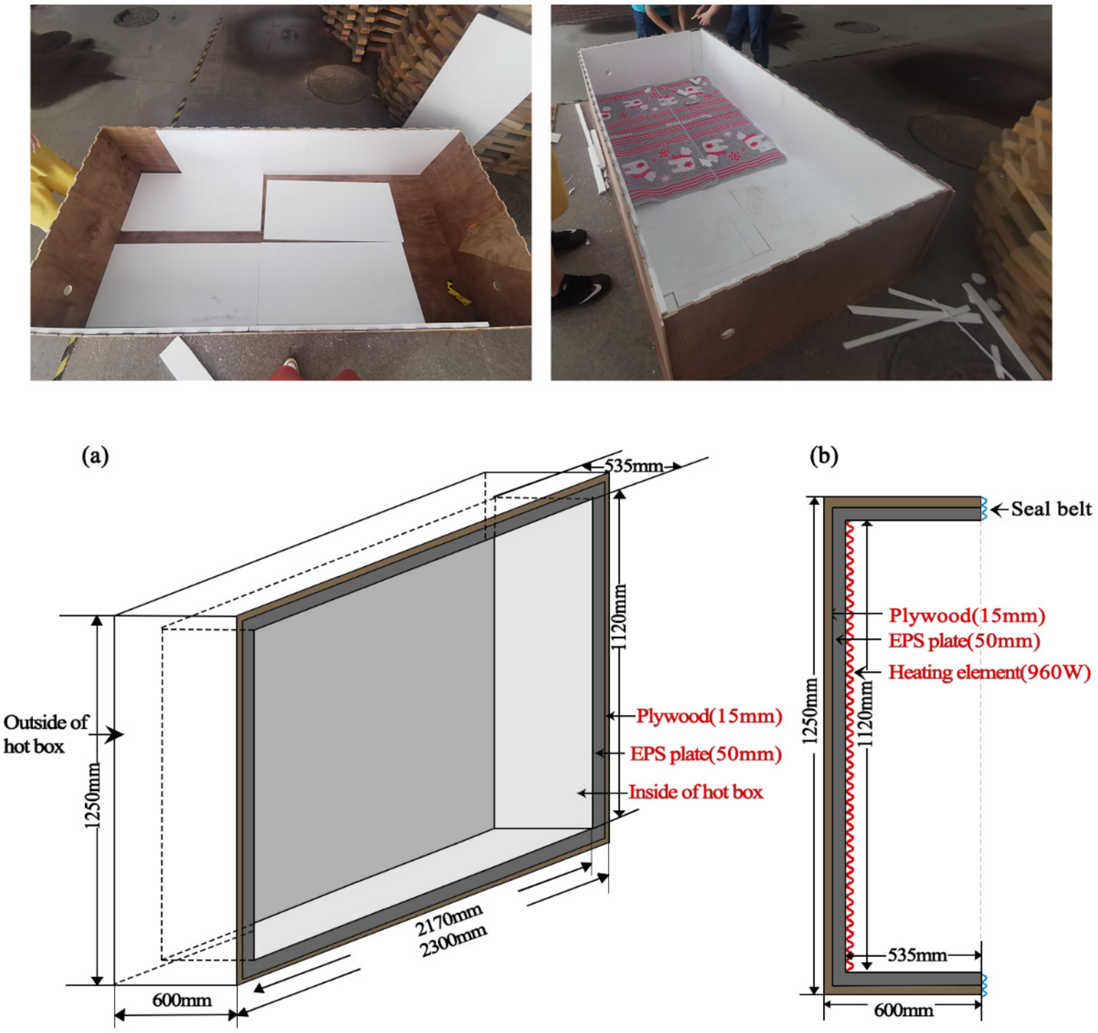


Figure 5.3. The diagram of heat transfer coefficient of straw hollow bricks

The simple hot box structure used in this experiment is shown in Figure 5.4. The hot box comprises a 15mm wood composite board and 50mm EPS thermal insulation board from the outside to the inside. The thermal conductivity of the EPS thermal insulation board is 0.034 W/(m·K), which has good thermal insulation performance. The external dimensions of the box are 2300mm × 600mm × 1250mm (length × width × height), while the internal dimensions of the box are 2170mm × 535mm × 1120mm (length × width × height). Eight electric heating blankets are evenly laid on the front of the heat box facing the tested wall; their total power is 960W. The contact gap between the heat box and the measuring wall is sealed with sealant to reduce the air volume and improve the temperature stability of the air in the box.



(a)The appearance and (b)the section of the simple hot box.

Figure 5.4. The simple hot box structure

Figure 5.5. On-site masonry photo of straw hollow bricks wall

5.3.2.Experimental object

In order to explore the effect of filling straw materials on the thermal performance of hollow bricks, in this experiment, five groups of hollow bricks with different filling materials were constructed in a relatively stable semi-outdoor environment as the experimental groups. Moreover, a group of hollow bricks without filling materials served as a control group. Then, these six self-insulating bricks are grouped with 1:3 cement mortar, and a 5cm thick EPS insulation board is used. The purpose of installing the EPS insulation board between the wall is to isolate the disturbance of the heat flow and reduce the experimental measurement error [18]. Finally, the six groups of walls are taken as a whole, and 5cm thick EPS insulation panels are used to isolate the surrounding environment, forming a wall that can only conduct one-dimensional heat transfer (as shown in Figure 5.5). The filling materials of the six groups of walls are (I) unfilled control group, (II) reed leaves, (III) reed stem, (IV) wheat stem, (V) rice straw, (VI) rice shell (as shown in Figure 5.6).

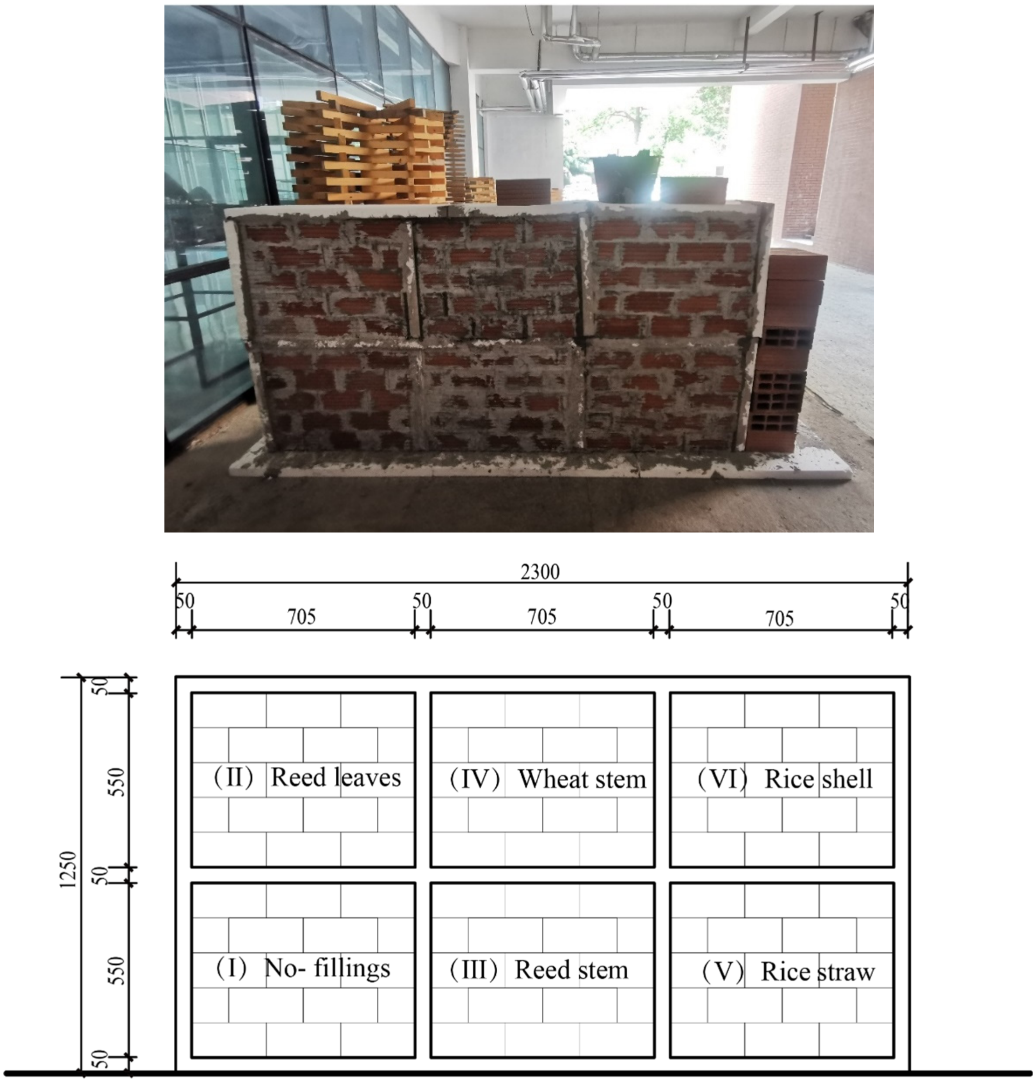


Figure 5.6. Six types of hollow brick wall distribution diagram

5.3.3. The layout of measurement locations

The test points of this experiment are shown in Figure 5.7. The six temperature test points T1-T6 are respectively arranged at the centre of the non-heated surface of the six groups of bricks without cement mortar to measure the value of $T_{n,out}$. At the centre of the heated surface of the six groups of bricks without cement mortar, the six temperature test points T7-T12 are respectively arranged to measure the value of $T_{n,in}$ and six heat flow test points H1-H6 are arranged to measure the value of $q_{n,in}$ besides each heated surface thermometer.

The materials filled in hollow bricks of T1-T6 (T7-T12 or H1-H6) respectively represent the no-fillings, reed leaves, reed stem, wheat stem, rice straw, rice shell. Inside the hot box, six temperature test points ($T_{inside1}$-$T_{inside6}$) are corresponding to the heated surface thermometers to measure the temperature. In addition, there is a thermometer $T_{outside}$ to measure changes in outdoor ambient temperature.

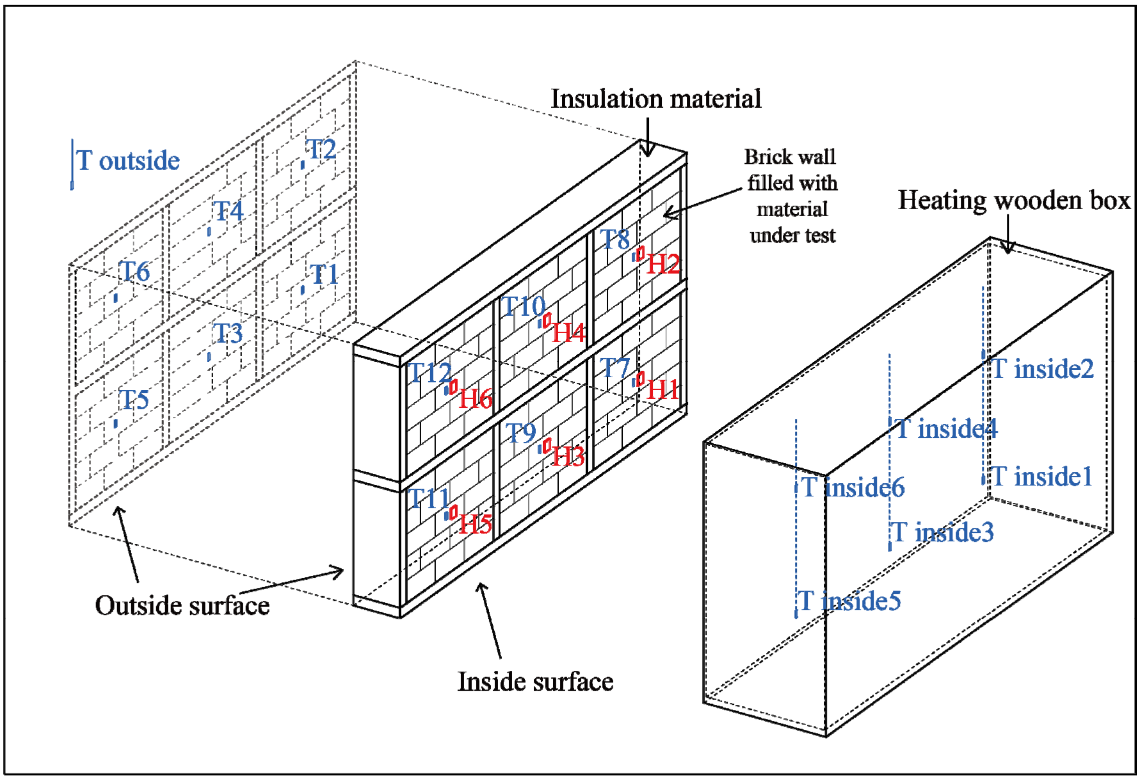


Figure 5.7. The experimental test point of the straw hollow brick wall

5.4. Experimental results on straw hollow bricks

5.4.1. Variation of air temperatures

Figure 5.8 shows the changes in the air temperature inside and outside the hot box measured during the 15 days. From the heating moment, the temperature inside the hot box reaches a stable level about 30°C higher than the outdoor temperature after one day. It then fluctuates with the change of the outdoor temperature. The maximum temperature deviation from $T_{Inside1}$ to $T_{Inside6}$ does not exceed 0.5℃, which keeps the temperature inside the hot box uniform and stable. When calculating the air temperature inside the hot box, take the average of these six temperatures and do not count the data during the heating process on Day 0 to Day 4. Besides that, from Day 9 to Day 10, there was a significant drop in temperature. In order to ensure the accuracy of the test results, we also do not count the data from Day 9 to Day 15. Finally, we only count the test data from Day 4 to Day 8 for a total of 4 days. The statistical results of these four days are shown in Figure 5.8. After the average value, the average inside air temperature is 53.3°C, and the average outside air temperature is 26.1°C.

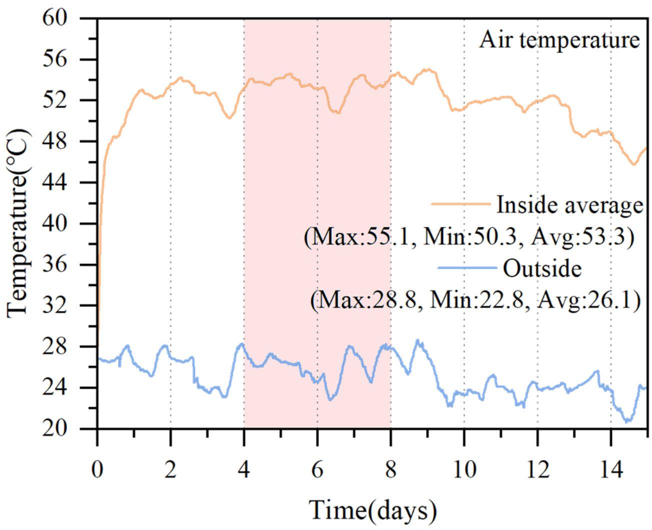


Figure 5.8. The temperature change of the air on both sides of the wall

5.4.2. Variation of wall surface temperatures

The temperature of the non-heated surface of the wall is directly proportional to the thermal insulation performance. The higher the temperature of the non-heated surface of the wall, the worse the thermal insulation performance; conversely, the lower the surface temperature of the non-heated surface of the wall, the better the thermal insulation performance of the wall. Figure 5.9 is an infrared thermal imaging diagram of the surface temperature of the non-heated surface of the wall filled with different materials. It can be seen from the figure that the temperature of the wall without filling material is significantly higher than that of other walls with filling material. However, the temperature difference of other walls with filling material is not very obvious.

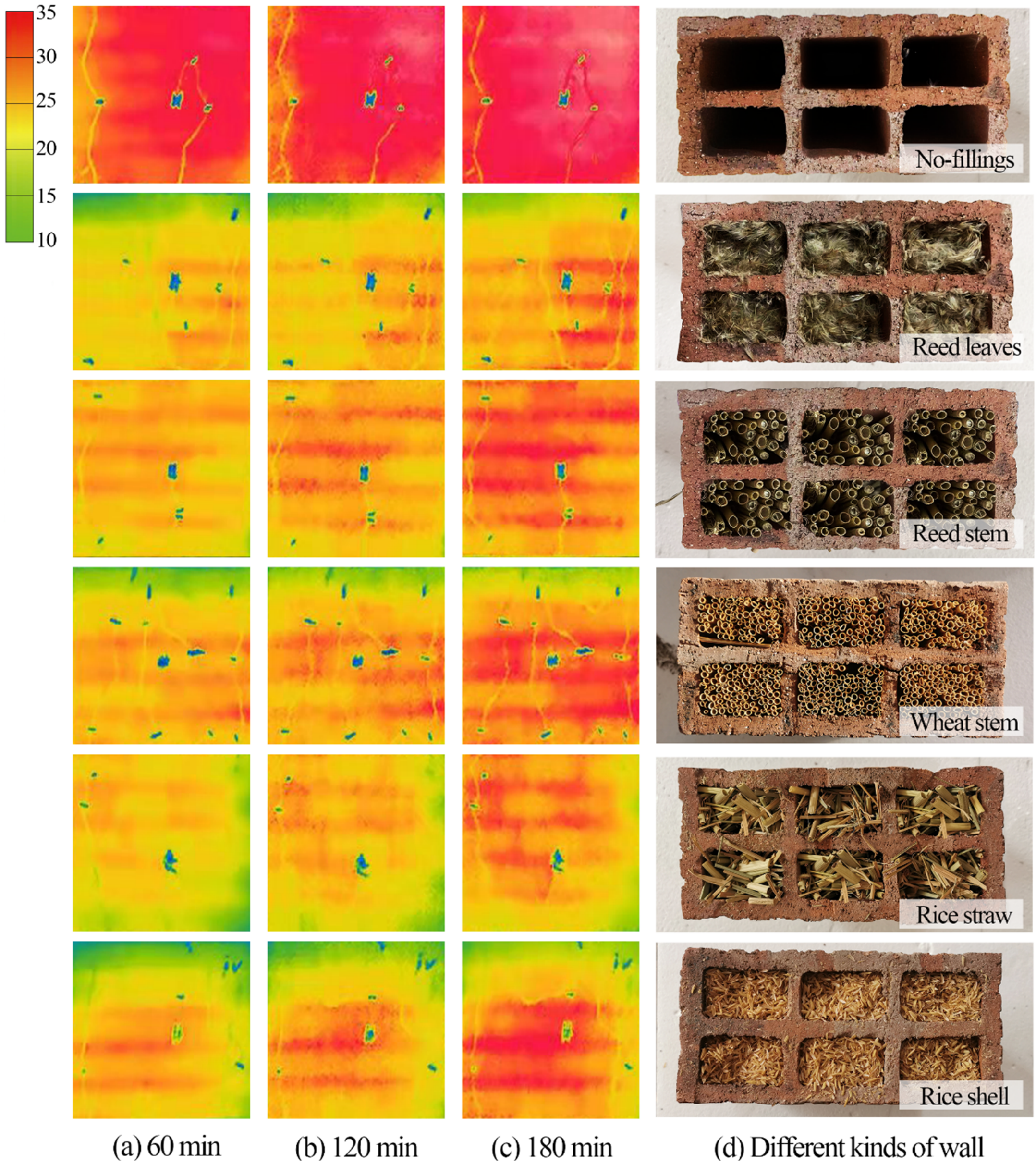


Figure 5.9. Thermal image of the non-heated surface of the hollow brick wall

Similar conclusions can also be drawn from the graphs in Figure 5.10 showing the changes in the surface temperature of the non-heated surface of different hollow brick walls over time. The average temperature of the wall without fillings (The control group) is 30.4°C, which is higher than the temperature of the five experimental groups. The temperature difference between the five experimental groups is tiny, and the average temperature is between 29.3°C and 29.8°C. Taken together, the temperatures of these six groups of walls are all 3.3°C higher than the outdoor temperature and fluctuate with the fluctuation of the outdoor temperature.

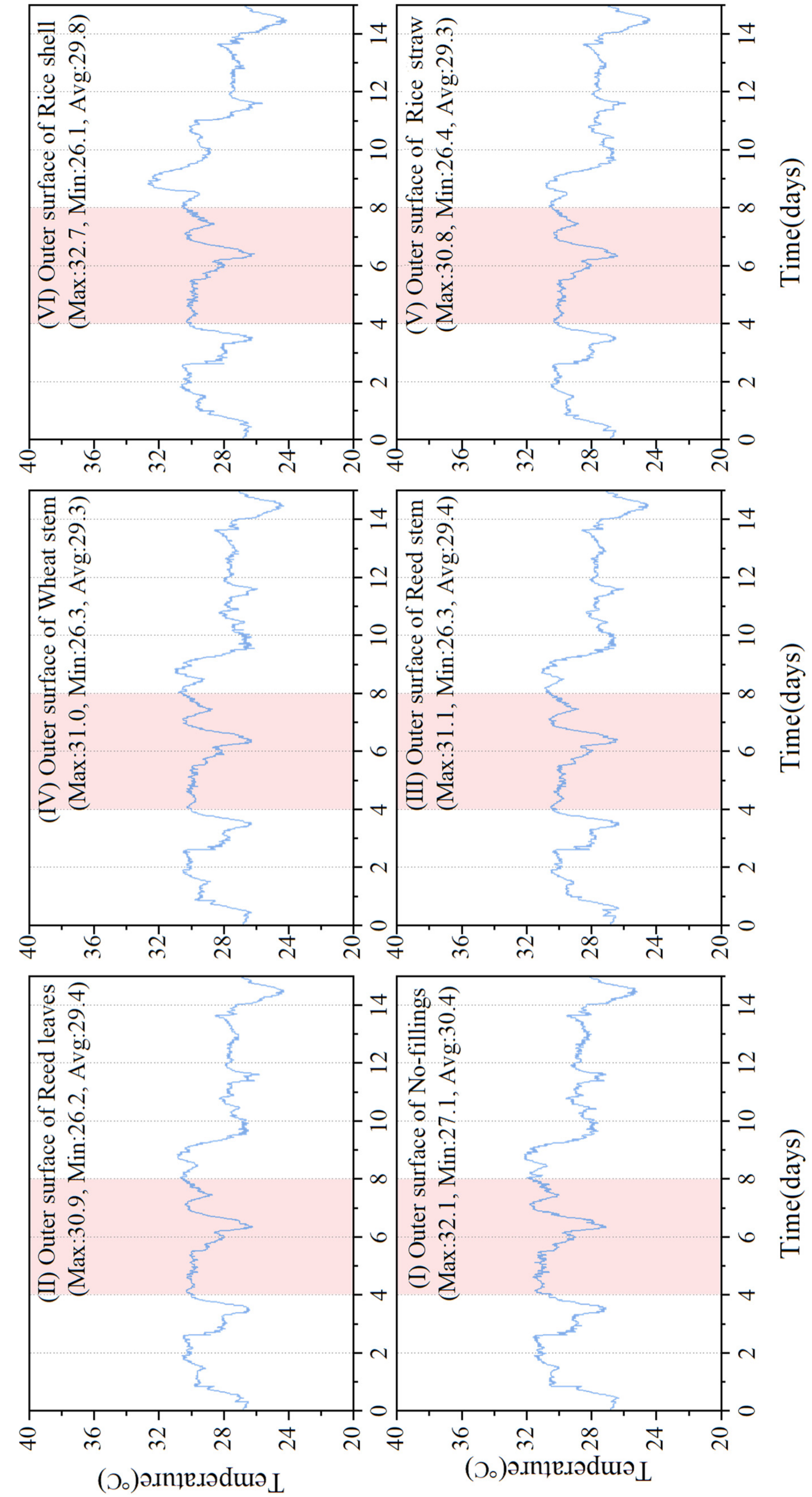


Figure 5.10. The temperature changes of the non-heated surface of the hollow brick walls

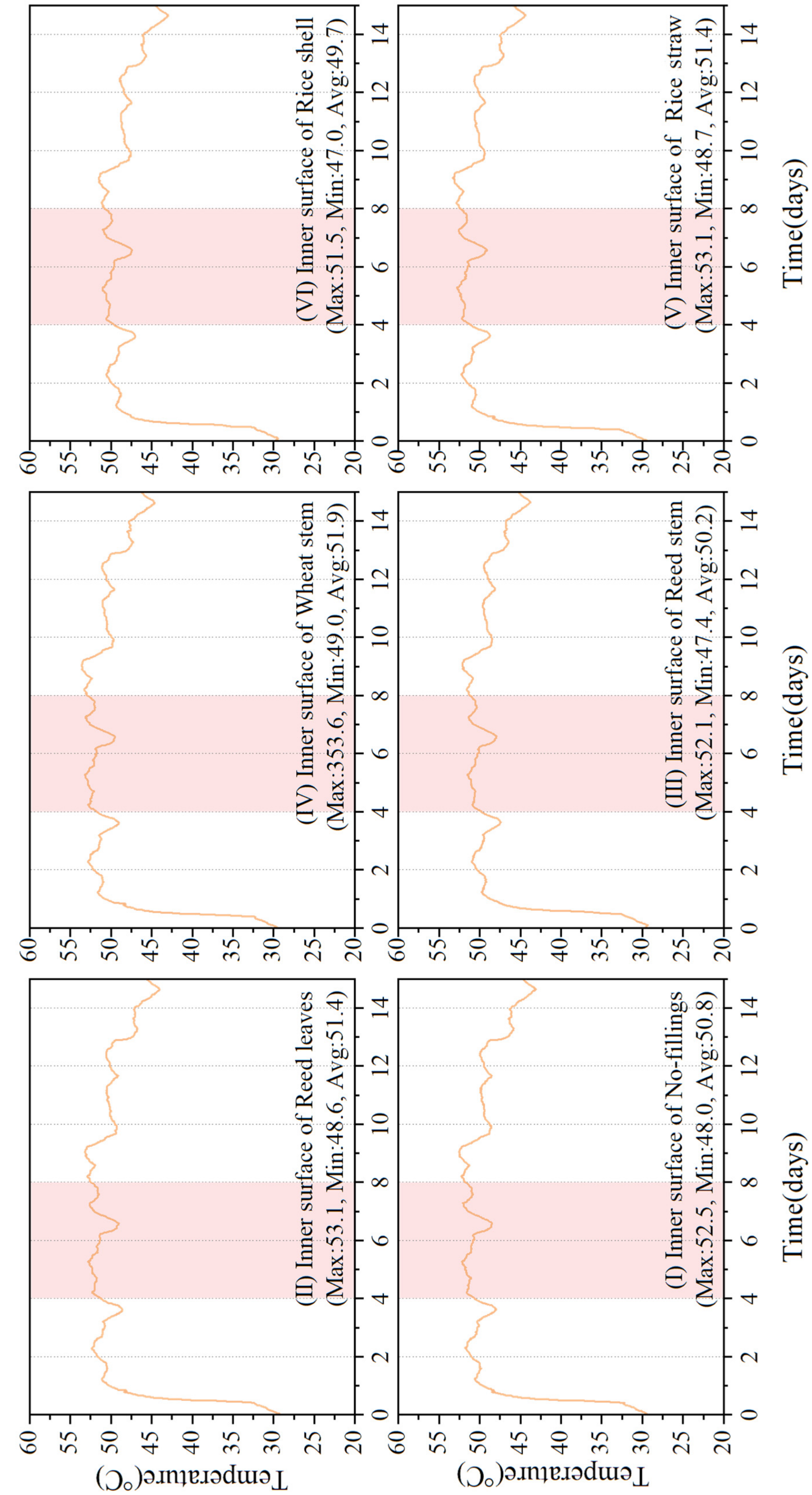


Figure 5.11. The temperature changes of the heated surface of the hollow brick walls

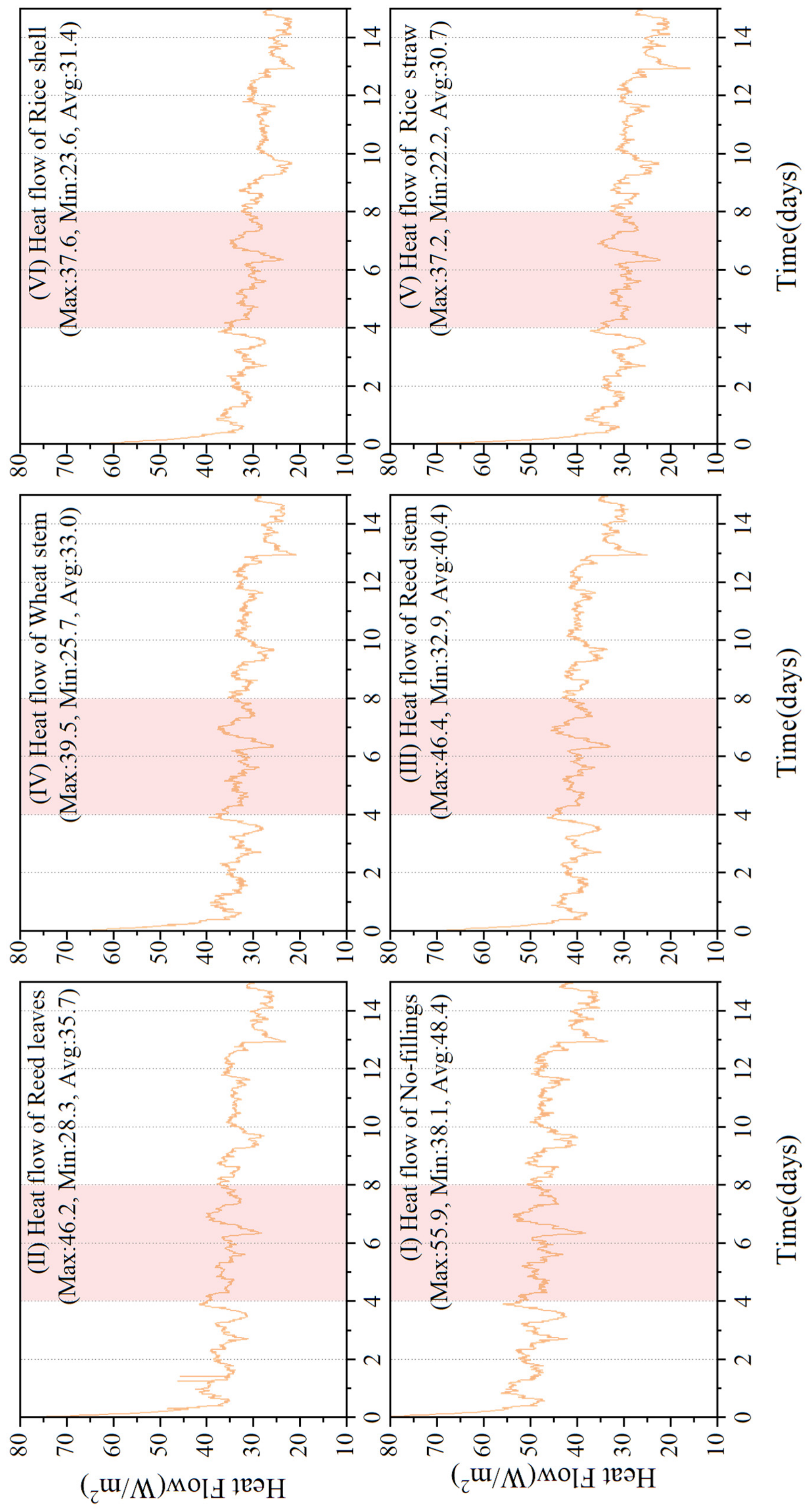


Figure 5.12. The heat flow changes of the heated surface of the hollow brick walls

It can be seen from Figure 5.11 that the surface temperature of the heated surface of different hollow brick walls changes with time. There was no significant difference between the experimental group and the control group. In the experimental group, the highest average temperature was 51.9°C (wheat stem), and the lowest was 49.7°C (rich shell), with a difference of 2.2°C. As for the control group, the average temperature of the hollow brick wall without filling materials was 50.8°C, which was between the experimental group's highest temperature and the lowest temperature. Taken together, the temperature change of the heating surface is the same as the temperature change of the non-heated surface, which fluctuates with the fluctuation of the outdoor temperature, but the amplitude is much smaller.

5.4.3.Variation of wall surface heat flow

It can be seen from the graph of the change of heat flow on the heating surface of different self-insulating hollow brick walls with time in Figure 5.12. There are obvious gaps between various materials. As the control group, the heat flow of hollow brick walls without filling materials was the largest, with an average of 48.4 W/m^2. The minor heat flow in the experimental group is rice straw, having an average heat flow of 30.7 W/m^2; rice shell followed by an average heat flow of 31.2 W/m^2. The largest is the reed stem, with an average heat flow of 40.4 W/m^2. It can be seen that after filling the hollow bricks, the tighter the loose material, the smaller the heat flow through the unit area, the better the heat preservation effect. Reed stems, a material with low apparent density, thick poles, and more voids, have a large heat flow per unit area and poor thermal insulation effect.

5.4.4.Thermal performance evaluation of hollow bricks filled with crop straws

Finally, the data processing method of SHB-HFM is the same as the traditional heat flow meter method. The following formula can obtain the wall heat transfer coefficient:

$$(1)\ \ K = \left(\frac{1}{h_{out}} + \frac{\sum_{n=1}^{N}(T_{n,in} - T_{n,out})}{\sum_{n=1}^{N} q_{in,n}} + \frac{1}{h_{in}}\right)^{-1}$$

In the formula, $T_{n,in}$ is the measured temperature of the heated side of the wall (°C); $T_{n,out}$ is the measured temperature of the unheated side of the wall (°C); $q_{n,in}$ is the measured value of the heat flow meter (W/m^2); h_{out} and h_{in} are the heat exchange law (W/m^2) on the unheated side and the heated side between the air and the wall, and h_{out} is 23 W/m^2, h_{in} is 8.7 W/m^2.

Moreover, the conductivity of different materials can be obtained by the following formula:

$$(2)\ \ U = \frac{\lambda}{R_n}$$

In the formula, R_n (K·m^2/W) is the thermal heat resistance of material，which can be obtained by $T_{n,in}$, $T_{n,out}$ and $q_{n,in}$. Moreover, λ is the thickness of the material, in this experiment is 0.235 m.

The calculation results are shown in Table 5.1 The heat transfer coefficient of the hollow brick without filling materials is 1.59 W/(K·m^2), higher than that of the other experimental groups. The heat transfer coefficient of the insulating hollow bricks with rice straw is the lowest 1.07 W/(K·m^2), the heat-insulating hollow bricks filled with wheat stems is secondly 1.12 W/(K·m^2), and the heat-insulating hollow bricks filled with reed stems has a heat transfer coefficient of 1.39 W/(K·m^2). The heat transfer coefficient of hollow bricks filled with rice straw is reduced by 42% compared with hollow bricks without fillings. We choose heat-insulating hollow bricks filled with rice straw as the material for the following rural wall reconstruction.

Table 5.1. Heat transfer coefficient of six kinds of hollow brick

Material	**No-filling**	**Reed leaves**	**Reed stem**	**Wheat stem**	**Rice straw**	**Rice shell**
K (W/K·m^2)	1.59	1.20	1.39	1.12	1.07	1.17
U (W/K·m)	0.83	0.38	0.46	0.35	0.32	0.36

5.5.Performance measurements of the rice straw board

5.5.1.Experimental method

Since these organic straw thermal insulation materials are loose and difficult to handle, based on the above research results on the wall, we conducted a separate study on the rice straw because of its best thermal insulation effect. We use wood boards with a thickness of 6mm and a thermal conductivity of 0.38 W/(m·K) to make a small box. Furthermore, the external dimensions of the box are 1000mm × 47mm × 1000mm (length × width × height), while the internal dimensions of the box are 988mm × 35mm × 988mm (length × width × height). After that, we fill the rice straw into the small box, and the gap between the different surfaces is sealed with sealant to form a one-dimensional heat transfer plane.

Figure 5.13. On-site masonry photo of rice straw board

The simple hot box structure used in this experiment is shown in Figure 5.13. The hot box comprises a 15mm wood composite board and 50mm EPS thermal insulation board from the outside to the inside. The thermal conductivity of the EPS thermal insulation board is 0.034 W/(m·K), which has good thermal insulation performance. The external dimensions of the box are 1000mm × 600mm × 1000mm (length × width × height), while the internal dimensions of the box are 870mm × 535mm × 870mm (length × width × height). Eight electric heating blankets are evenly laid on the front of the heat box facing the tested wall; their total power is 960W. The contact gap between the heat box and the measuring wall is sealed with sealant to reduce the air volume and improve the temperature stability of the air in the box.

The test points of this experiment are shown in Figure 5.14. One thermocouple test point (T2') was arranged at the centre of the non-heated surface of the rice straw board to measure the value of $T_{n,out}$. Moreover, two other thermocouples (T1' and T3') are laid at an equal distance of 15 cm to measure the outer surface temperature. Three thermocouples (T4', T5' and T6') are laid at the inner surface corresponding to T1', T2' and T3' to measure the inner surface temperature of $T_{n,in}$. Three heat flow meters (H1', H2', and H3') are symmetrically arranged beside each inner surface thermocouples to measure the inner surface heat flow of q_{in}. Multiple points of the same data are tested to ensure the accuracy of the data after averaging. In addition, one thermocouple ($T_{inside'}$) was hung corresponding to the heated surface thermometers to measure the temperature inside the hot box. Besides, there is a thermometer $T_{outside'}$ to measure changes in outdoor temperature.

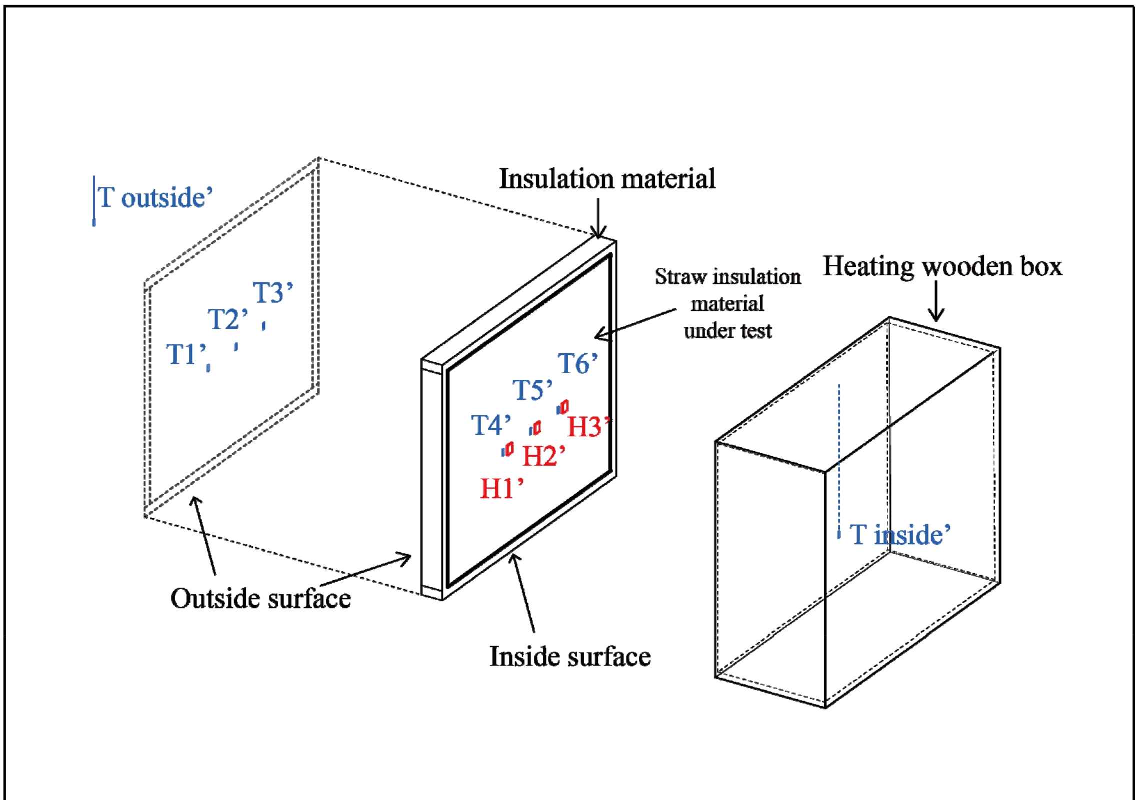


Figure 5.14. Diagram of the experimental test point of rice straw board

5.5.2.Experimental results

Figure 5.15 shows the changes in the air temperature inside and outside the hot box measured during the 11 days. It can be seen that a sharp drop in temperature was on the fourth day. After that, the outdoor temperature remained stable from day 4 to day 11, except for temperature fluctuations caused by the alternation of day and night. From the heating moment, the temperature inside the hot box reaches a stable level of about 70°C higher than the outdoor temperature after one day. Due to the change of outdoor temperature, the temperature inside the box had two times drastic drops and did not stabilize until the seventh day. In order to ensure the accuracy of the test results, we only select the data from Day 8 to Day 10 for statistics and calculations. The statistical results of these two days are shown in Figure 5.15, after the average value. The average inside air temperature is 65.8°C, and the average outside air temperature is 12.8°C, which the difference is 54 °C meeting the requirements.

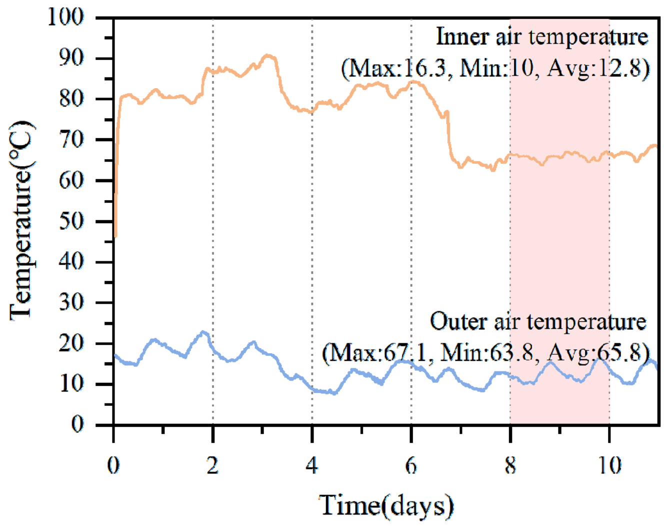


Figure 5.15. The temperature change of the air on both sides of the rice straw board

Figure 5.16 shows the changes in temperature inner the hot box surface measured during the 11 days. The average temperature of the box filled with straw is 58.9°C, which is 6.9°C lower than the inner air temperature and fluctuates with the inner air temperature fluctuation. Only counting the data from Day 8 to Day 10, the average heated surface temperature of the box filled with straw is 58.9°C, which is 6.9°C lower than the inner air temperature and fluctuates with the fluctuation of the inner air temperature. The difference between the maximum and minimum is 3.1 °C.

Figure 5.17 shows the changes in temperature outer the hot box surface measured during the 11 days. Similarly, counting the data from Day 8 to Day 10, the average unheated surface temperature of the rice straw board is 16.9°C, which is 4.1°C higher than the outer air temperature and fluctuates with the fluctuation of the outer air temperature. The difference between the maximum and minimum is 4.3 °C.

Figure 5.18 shows the changes in heat flow inner the hot box surface measured during the 11 days. Only counting the data from Day 8 to Day 10, the average heat flow on the heated surface of the straw board was 69.5 W/m^2, and the difference between the maximum and minimum was 16 W/m^2.

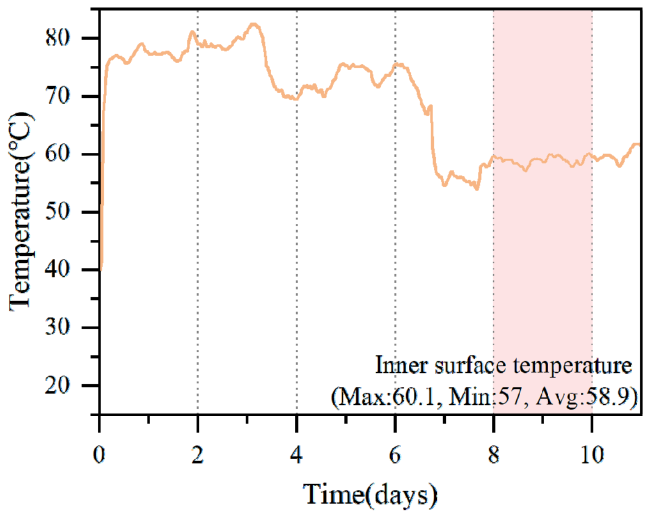


Figure 5.16. The temperature change of the heated surface of the rice straw board

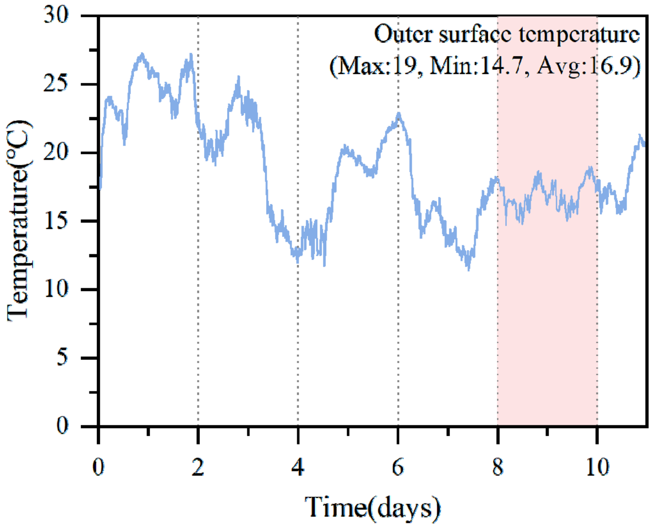


Figure 5.17. The temperature change of the non-heated surface of the rice straw board

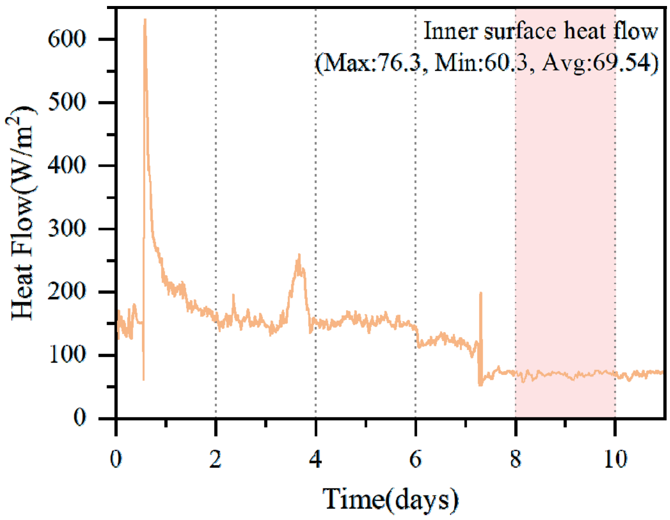


Figure 5.18. The heat flow change of the rice straw board

The data processing method of SHB-HFM is the same as the traditional heat flow meter method. Finally, the heat transfer coefficient of rice straw board can be obtained by the following formula:

$$(3)\ \ R_n = \frac{\sum_{n=1}^{N}(T_{,n,in} - T_{n,out})}{\sum_{n=1}^{N} q_{n,in}}$$

$$(4)\ \ U = \frac{\lambda}{R_n}$$

In the formula, $T_{n,in}$ is the measured temperature of the heated side of the wall (°C); $T_{n,out}$ is the measured temperature of the unheated side of the wall (°C); q_n is the measured value of the heat flow meter (W/m^2); R_n (K·m^2/W) is the thermal heat resistance of material，which can be obtained by $T_{n,in}$, $T_{n,out}$ and $q_{n,in}$. Moreover, λ is the thickness of the material, in this experiment is 0.035 m.

The calculation result is 0.6061 K·m^2/W, which contains the straw's thermal resistance and the wooden board's thermal resistance. After the second calculation to remove the board's thermal resistance, the straw's thermal resistance is 0.4794 K·m^2/W, and the thermal conductivity of straw is 0.073 W/(K·m).

5.6.Summary

The original heat transfer coefficient of the hollow brick material was 1.59 W/(K·m^2). After using the insulating hollow brick filled with rice straw, the heat transfer coefficient was 1.07 W/(K·m^2), reduced by 32%. After using the insulating hollow block filled with reed leaves, the heat transfer coefficient was 1.20 W/(K·m^2), reduced by 24%. After using the insulating hollow block filled with wheat stem, the heat transfer coefficient was 1.12 W/(K·m^2), reduced by 29.5%. After using the insulating hollow block filled with reed stem, the heat transfer coefficient was 1.39 W/(K·m^2), reduced by 12%. After using the insulating hollow block filled with rice shells, the heat transfer coefficient was 1.17 W/(K·m^2), reduced by 26%. It can be seen that among the above materials, the effect of rice straw on thermal performance is the best. The effect of the wheat stem is second. Furthermore, the rice straw and the wheat stem have similar improvements in thermal performance, which are 32% and 29.5%, respectively. And the rice shell and reed leaves have similar improvements in thermal performance, which are 26% and 24%, respectively. However, the effect of reed stem on the thermal performance was far from the previous ones, which is 12% only.

Through the rice straw board experiment, the heat transfer coefficient of straw is 0.073 W/(K·m), which is one-seventh of the heat transfer coefficient of the straw hollow bricks. Using only straw is better than using straw bricks as a composite material for heat preservation, but the straw itself is too loose, and it is not as easy to construct as straw-filled bricks. So in practical applications, straw should be made into the straw board.

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Chapter 6. The energy-saving improvement for the rural houses by numerical simulation

6.1. Introduction

Energy-saving in the building itself requires the application of energy-saving technologies and building envelopes using energy-saving materials to reduce its energy losses. The research and development of new envelope materials is an important technology for achieving energy efficiency in buildings, which can reduce energy consumption while maintaining a comfortable indoor thermal environment [1]. The building envelope is divided into three parts: external walls, roofs, and external doors and windows, and the energy loss through the building envelope accounts for 25% to 35% of the total building energy consumption [2]. Wall insulation technology can be divided into external wall self-insulation, external wall insulation, external wall internal insulation, and external wall sandwich insulation [3]. As an external protective structure covering the top of the building, the roof also impacts building energy-saving. According to statistics, in general, in residential buildings in China, the heat loss from the roof accounts for about 10% of the energy loss of the whole building [4]. At present, standard roof insulation engineering techniques include inverted roof insulation, high roof insulation, water-storage roofing and planted roofing, and other energy-saving insulation techniques [5]. The window and door system accounts for 1/6 to 1/8 of the total area in the building envelope. Still, the energy lost through windows and doors is 5-6 times that of the walls, accounting for about 40% to 50% of the total energy consumption of the building envelope [6]. As an essential part of the building envelope, windows and doors have many factors affecting their heat loss, mainly including heat conduction loss through the window and door frame material and glass, air convection heat loss through the window and door gaps, and heat conduction loss through the window and door frame material and bevelled glass. There are three aspects of shooting losses. Among them, the heat loss due to air infiltration accounts for 25% to 50% of the building heat load [7]; therefore, reducing the air infiltration rate of external doors and windows will inevitably improve the overall energy-saving of the building.

Therefore, this chapter focuses on the influence of the external envelope of rural houses on their thermal insulation performance. Firstly, based on the previous summary of different generations of rural house types in Qingdao, a typical rural residential model in Qingdao is selected, then, combined with the research findings of insulated walls and insulation board filling materials in Chapter 5, the data analysis function of Energy-plus building energy simulation software is used to explore and analysis the forms of renovation and energy-saving of external walls, roofs and external windows, and further, propose the corresponding. Finally, the three indexes of temperature and ePMV of typical rural houses before and after renovation are comprehensively compared, to quantify the efficiency of the external envelope renovation in this chapter.

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6.2.Description of a typical house and local climate

6.2.1.House layout

House 1, measured in Chapter 3, was selected as the study object. This rural house was chosen for the study because it has the largest proportion of all rural houses in Qingdao in terms of age and heating method, as well as the poor insulation performance of the envelope of this rural house and the benefits of its renovation. This rural house was built in 1971 with an L-shaped layout and a total base area of 148.24 m^2. The whole building area is 73.87 m^2, and the entire area of the main house is 43.6 m^2. The main house is divided into three rooms: the living room and two bedrooms.

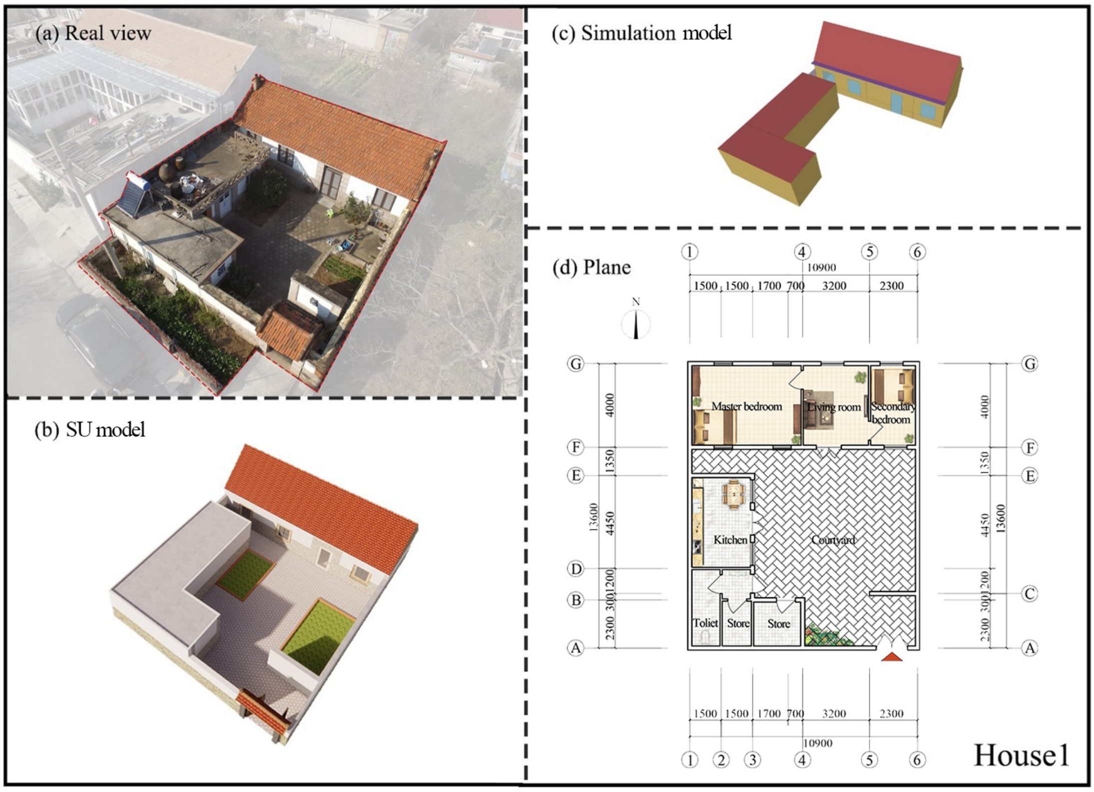


Figure 6.1. Realistic view, SU model, simulation model, and plane of the typical rural house in Qingdao

6.2.2.House envelopes

The external envelope of this rural house is very typical, with walls of mixed masonry with rubble stone in the lower part and brick in the upper part, aluminium window frames, cement floor and heating by the furnace. The parameters of the envelope of this rural house are shown in Table 6.1 and Figure 6.2.

Table 6.1. Statistical table of external envelope parameters of typical rural houses

Name	Construction (outside-inside)	Thickness (mm)	Heat transfer coefficient K ($W/m^2{\cdot}K$)	Thermal inertia D(cal/cm^2-°C-s)
External wall (Lower)	Granite	500	3.13	3.90
	Cement mortar	10		
	Plastering	10		
External wall (Upper)	Plastering	10	1.54	5.35
	Cement mortar	10		
	Solid clay bricks	370		
	Cement mortar	10		
	Plastering	10		
Roof	Red tiles	20	3.04	3.98
	Hanging tile bars	-		
	Protective layer	-		
	Reinforced concrete	100		
	Wooden frame construction	-		
Ceiling	Plasterboard	10		
Windows	Single-pane glass	6	5.70	1.56

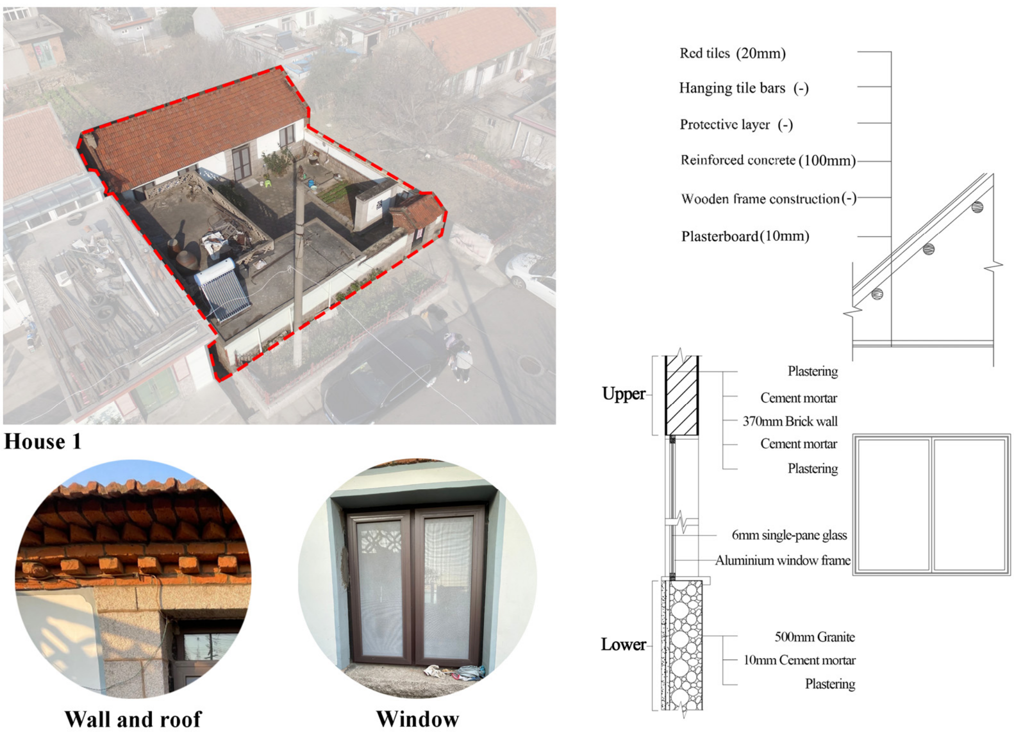


Figure 6.2. The typical rural residential enclosure structure

6.2.3.Indoor parameter setting

In building simulation, the indoor heat source usually refers to the energy allocated to the room by familiar internal heat sources such as personnel and lighting equipment, which largely determines the indoor temperature and thermal comfort for the user.

To obtain a more accurate design temperature for the interior, it is first necessary to understand the climate zones defined by the Chinese government. The city of Qingdao, Shandong Province, belongs to the cold region. About this aspect, some scholars have critically studied the climate zoning in China, for example, Yao Chen et al. [8] proposed a new climate zoning index based on the thermal comfort characteristics of rural residents, and on this basis defined a more refined climate zone in rural areas of China. He argued that the current climate zoning would lead to unreasonable design phenomena of insufficient or excessive insulation in some areas. Rough zoning is not conducive to the implementation of the climate-responsive energy-saving design. However, the prior climate zoning is generally still applicable to most cases studied, so this paper adopts the current Chinese climate zoning criteria and defines Qingdao, Shandong Province, as a cold region.

The Energy Conservation Design Standard for Residential Buildings in Severe Cold and Cold Areas (JGJ26-2018) [9] released in 2018 in China stipulates that the appropriate temperature for heating in severe cold and cold areas in winter should be taken as 18°C. However, relevant studies in recent years have shown that due to the layout of rural houses, some extra rooms, such as kitchens, toilets, and other auxiliary rooms, are usually located in the courtyard, and residents often need to shuttle between the indoor living room and the extra rooms in the courtyard. In addition, residents often go in and out, and indoor living rooms and yards are generally dressed thicker in winter. So if the interior design temperature is too high, residents will have to change their clothes frequently, which is not only inconvenient but also easy to make people feel cold [10].

Table 6.2. The building interior simulation parameters collated table

Name	Value
Interior design temperature	16℃
index door and window permeability	7.5 $m^3/(m^2 \cdot h)$
Indoor airspeed	0.01m/s
Average thermal resistance of clothing	1.98clo
Average metabolic	0.925

As Table 6.2 shows, the interior design temperature is designed to be 16°C [11]. In addition, the door and window permeability was set to 7.5 $m^3/(m^2 \cdot h)$, and the indoor wind speed was 0.01 m/s. According to the Energy Conservation Design Standards for Rural Residential Buildings, the average thermal resistance of indoor clothes in cold regions in winter should be taken as 1.98 clo. The metabolic index is divided into adult male (1.0), adult female (0.85), and child (0.75), and an ordinary room accommodating a pair of adult male and female is taken as an Average metabolic index of 0.925.

6.2.4.Local climate

Qingdao is located in the southeast of Shandong Province, China, bordering the Yellow Sea. It belongs to temperate monsoon climate with hot summers and cold winters, and Qingdao is characterised by maritime climate: slow warming in spring, few hot days in summer, slow cooling in autumn, low temperatures in winter, humid air, moderate precipitation, hot rainy season. Figure 6.3 shows the change of annual temperature and solar intensity of Qingdao. Figure 6.4 shows the annual wind rose of Qingdao. It shows that the south and southeast monsoon dominate in summer, and the north and northwest wind are prevalent in winter. Figure 6.5 shows the annual solar sundial diagram of Qingdao city, reflecting the local solar altitude angle change throughout the year. Qingdao city is located north of the Tropic of Cancer, so the sunlight comes into the room from the south direction throughout the year. The solar altitude angle is higher in summer than in winter, and the solar altitude angle varies more markedly between winter and summer.

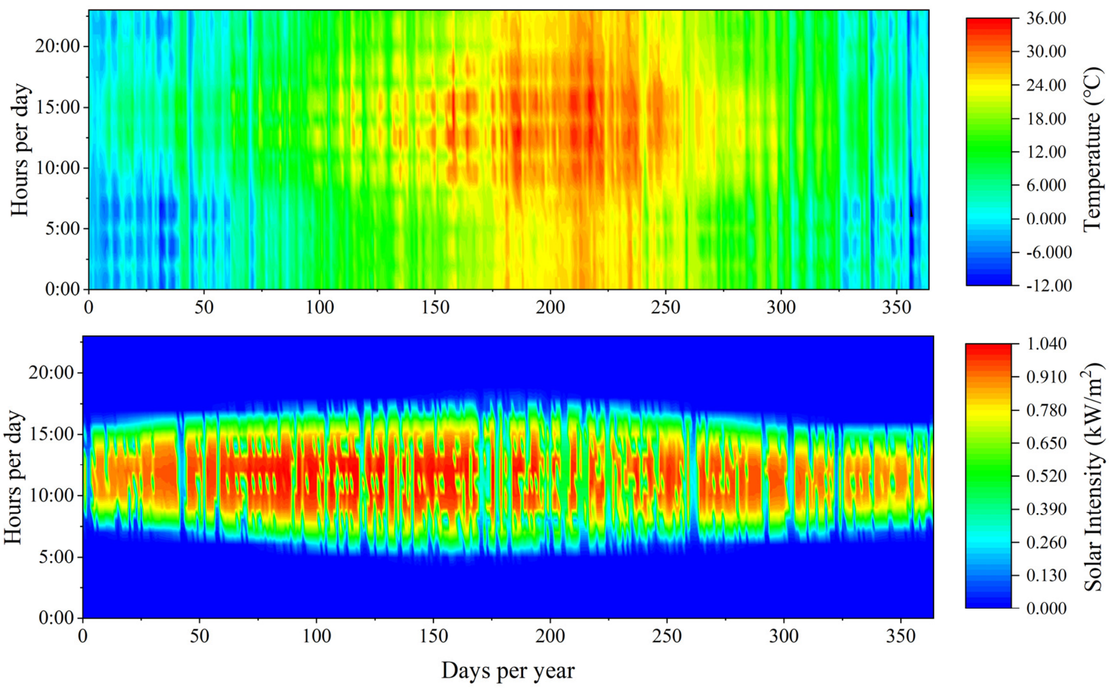


Figure 6.3. Annual temperature and solar intensity change figure of Qingdao

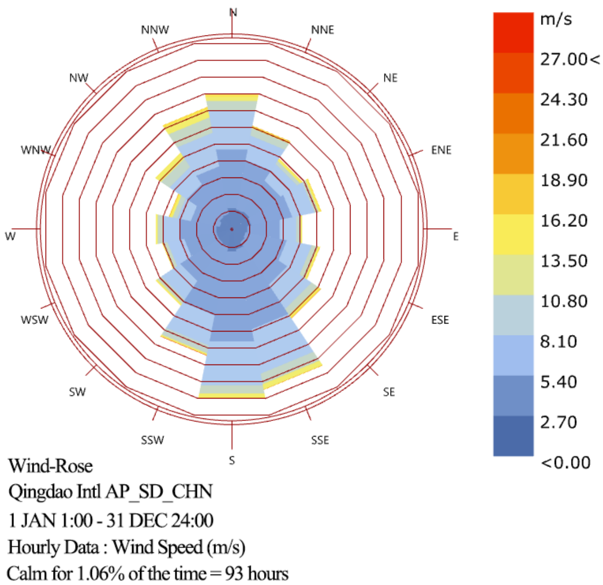


Figure 6.4. The annual wind rose of Qingdao

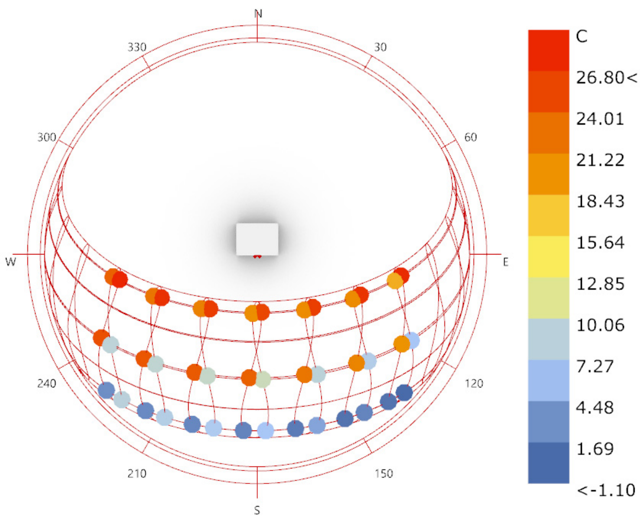


Figure 6.5. Annual sundial chart of Qingdao

These are the typical annual weather figures for Qingdao provided by the "Climate.OneBuilding.Org" website and accurately represent the local weather conditions in Qingdao. Files in epw format recognised by the EnergyPlus software are selected for subsequent simulation.

6.3.Numerical simulation and verification

6.3.1.Numerical simulation method

EnergyPlus building energy simulation software was released in April 2001. It was developed by Lawrence Berkeley National Laboratory, the University of Illinois, the US Army Building Engineering Laboratory, Oklahoma State University and others, with the support of the US Department of Energy.

6.3.2.Experimental verification

The accuracy of building energy simulation software has always been a hot topic of ongoing academic interest. In real life, indoor air conditioning systems do not operate precisely according to the schedule in the software but change daily according to actual conditions. The simulation software can only set values as close as possible to the actual situation but cannot be specified precisely according to the real problem. These two factors can lead to some deviations between the software simulation results and the actual values, so it is necessary to verify the accuracy of this numerical simulation before the formal simulation.

To verify the accuracy of the simulation software, a control experiment was carried out between the simulated and measured bedroom temperatures of a typical house for five days from 23 to 27 December, as shown in Figure 6.6. The results in Figure 6.6 show good agreement between the simulated temperature results and the measured data, with the mean simulated bedroom temperature being 14.3°C and the mean measured bedroom temperature being 14.7°C. The mean difference between the simulated and measured temperatures is only 0.4°C, which is within an acceptable margin of error, so this paper's simulated data using EnergyPlus is a good reference value.

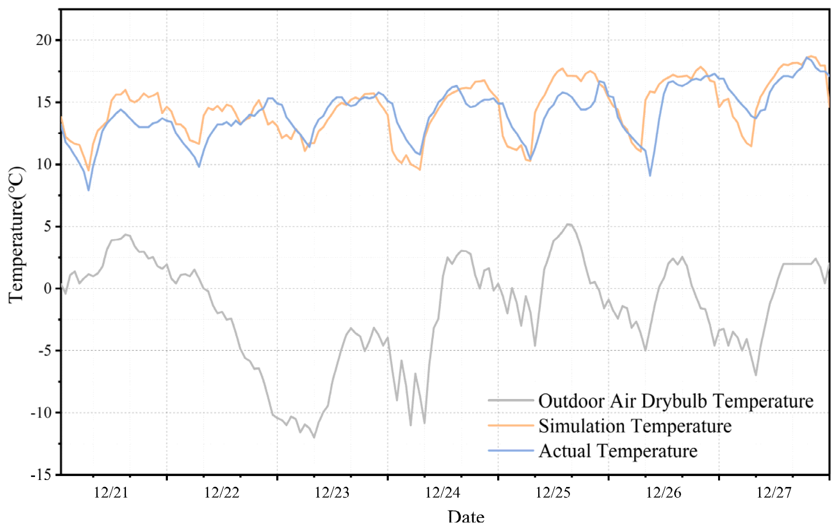


Figure 6.6. Comparison between simulated temperature and measured temperature

6.4.Improvement strategies of house envelopes

In this section, selected rural houses are individually renovated in walls, roofs and windows in conjunction with the experimental materials chosen in the previous quarter. Their thermal and energy-saving are approximated by calculating their heat transfer coefficients, K, to the extremes.

6.4.1.Walls

Insulation systems are divided into three types: internal insulation, external insulation and sandwich insulation. In the case of renovation works in which the walls are not demolished, the only two construction methods available are internal and external insulation. External insulation has an advantage over internal insulation because it prevents heat loss due to cold and heat bridges, etc., caused by discontinuous insulation materials, effectively avoiding condensation resulting from internal and external temperature imbalances. Before the renovation of the walls, an experimental assessment of the walls of the former farmhouse was carried out in chapter 5, and the conclusions were drawn before the walls were renovated accordingly.

For the wall renovation, the best insulating straw-filled sintered porous bricks from the previous section were used as the base renovation material, placed vertically (i.e. 235mm in length, 235mm in width and 110mm in height) used on the walls of the building. Figure 6.7 shows two different masonry solutions for the wall renovation. The first is the direct masonry of straw-filled sintered porous bricks on top of a stone or brick wall, and the second is the addition of a 20mm air interlayer between the porous bricks and the original fence. According to Table 6.3, the pure thermal conductivity of the air layer decreases rapidly with the increase of the thickness of the interlayer, and the change is very significant within 40mm, but it hardly increases above 40mm [12]. When the thickness is increased from 5mm to 10mm, the thermal resistance value is increased from 0.1 to 0.14, an increase of 28%, when the thickness is increased from 10mm to 20mm, the thermal resistance value is increased from 0.14 to 0.17, an increase of 17%, the thickness is increased from 20mm When rising to 30mm, the thermal resistance value increases from 0.17 to 0.18, which is only an increase of 5%. It can be seen that in the range of 40mm, as the thickness increases, the thermal resistance value increase efficiency is getting lower and lower. Due to the shortage of rural residential land, a 20mm air interlayer insulation layer was selected between the original wall and the straw-filled insulation sintered porous block wall.

According to the relevant parameters given in the previous section, the heat transfer coefficients of the whole wall and the two modified walls were calculated. It was found that the heat transfer coefficient K of the brick wall was always smaller than that of the corresponding stone wall. In contrast, the K of both the brick wall and the stone wall were significantly reduced after the sintered porous brick filled with straw masonry, with the stone wall improving from 3.13 W/m^2·K to 1.49 W/m^2·K and the brick wall improving from 1.54 W/m^2·K to 1.00W/m^2·K. The improvement effect of the stone wall is more prominent. In addition, the heat transfer coefficients of both walls were further reduced with the addition of the air interlayer, from 1.49 W/m^2·K to 0.70 W/m^2·K for the stone wall and from 1.00 W/m^2·K to 0.57 W/m^2·K for the brick wall, with a more significant reduction in K for both compared to the stone wall.

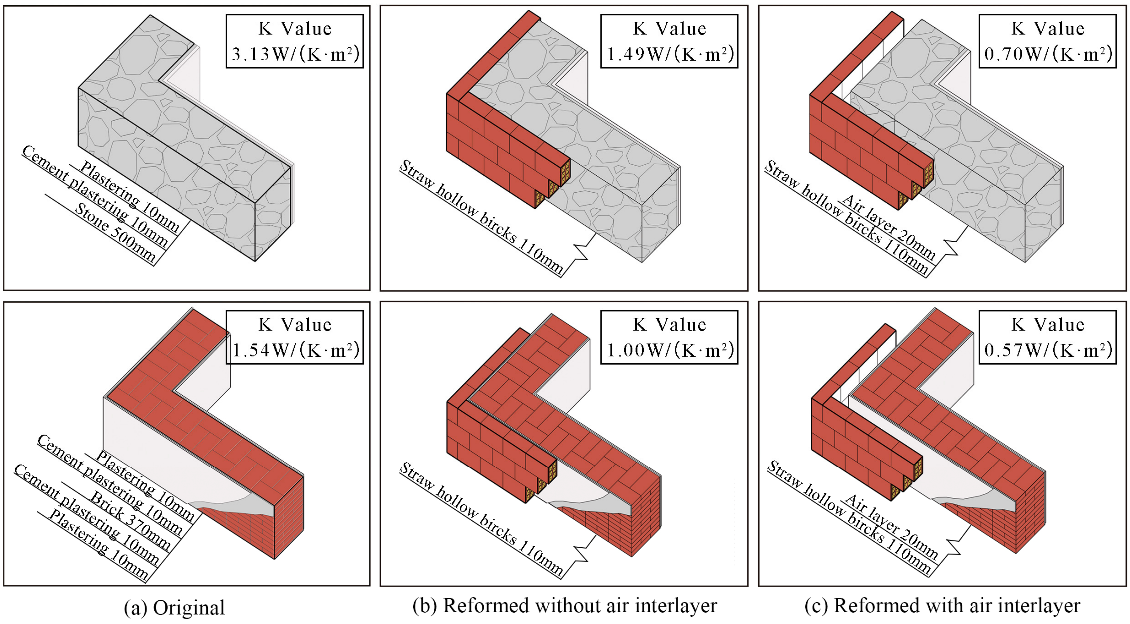


Figure 6.7. The structural form of the external wall before and after renovation

Table 6.3. The thermal resistance of vertical enclosed air interlayer in winter

Vertical air interlayer thickness(mm)	Thermal resistance in winter(㎡ • K/W)
5	0.1
10	0.14
20	0.17
30	0.18
40	0.19
50	0.2
60 and above	0.2

6.4.2.Roofs

This section explores improvement strategies for typical rural residential roofs. In Chapter 5, values such as the heat transfer coefficient K and the thermal inertia D of straw insulation boards were measured through practical experiments. The same straw-filled insulation boards with the best properties from the previous chapter are chosen as the primary improvement material in this chapter. There are three cases for the placement of the roof insulation panels: the case 1 is to place them on the lowest level of the pitched roof, the case 2 is to place them on top of the ceiling, and the case 3 is to use both of the case 1 and case 2. The thickness of the insulation panels is 120mm.

Based on the relevant parameters given in the previous section, the heat transfer coefficients of the entire roof and the three modified roofs were calculated. It was found that the K-values of the roofs of all three modified options were significantly lower compared to those before the modification. K-values were 3.04 W/m^2 for the roofs before the modification, 1.04 W/m^2 for roof case 1, 0.87 W/m^2 for roof case 2, and 0.65 W/m^2 for roof case 3.

6.4.3.Windows

In terms of external window renovation, this section focuses on the impact of the number of glazing layers, the type of gas fill, and the gas layer's thickness on the thermal performance of external windows. A total of four renovation forms were chosen, as shown in the diagram, all renovation options are 6mm glazing, original is single glazed, window case 1 is double glazed with 6mm air built in between the layers, window Case 2 is double glazed with 9mm air produced in between the layers and window Case 3 is double glazed with 9mm argon gas produced in between the layers.

At the same time, the heat transfer coefficients of the original case and the three instances of window renovation were calculated. The K of the original case was 5.7 W/m2·K, the K of window case 1 was 1.6 W/m2·K, the K of window case 2 was 1.48 W/m2·K and the K of window case 3 was 1.35 W/m2·K. The comparison of the values indicates that the K of the three renovation cases are significantly lower than the original ones. However, the change between the K of the three renovation cases is not significant.

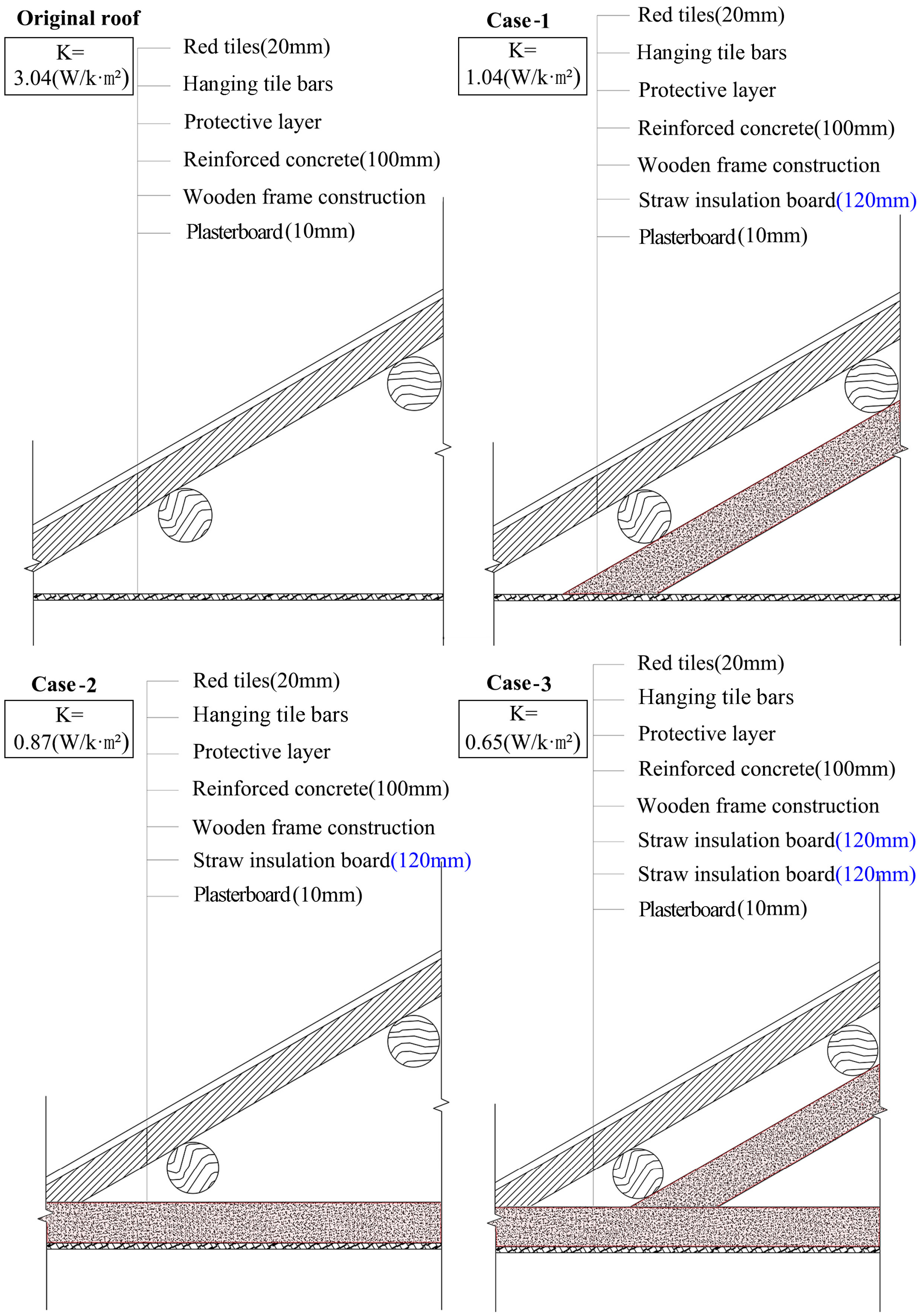
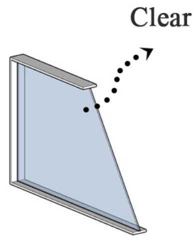
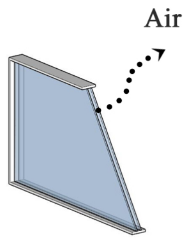
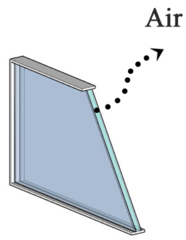
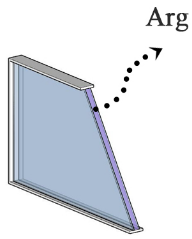
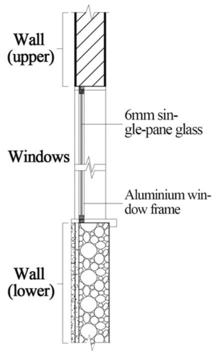
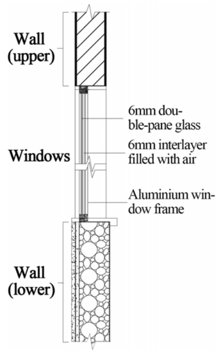
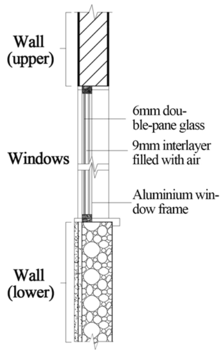
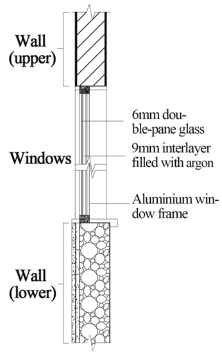


Figure 6.8. Structural hierarchy of the original roof and the roof conversion case

Table 6.4. Structural form of external window before and after reconstruction

	Original	**Case-1**	**Case-2**	**Case-3**
Type	(0)SSP	(1)SDP-Air	(2)SDP-Air	(3)SDP-Arg
Brief figure				
Section				
Air layer thickness (mm)	0	6	9	9
Heat transfer coefficient (W/(m²·K))	5.7	1.6	1.48	1.35

6.5.Improvement efficiency of the envelope optimization

This section adds all of the previously proposed individual renovation cases to selected typical rural houses. They are subjected to a typical week temperature simulation and a month-by-month energy consumption simulation to quantify each renovation Case's efficiency.

6.5.1.Contribution of house walls

Three types of walls were added to the selected typical rural house for the original , case 1 and case 2.Typical weeks (21 December to 27 December) and the whole winter season (November-March) were chosen as two different study periods. Temperature simulations when unheated and heat load simulations when heated were carried out, as shown in Figure 6.9 and Figure 6.10.

(1) Under indoor natural condition

Figure 6.9 shows the typical weekly air temperature trend in each room of the selected farmhouse before and after the wall renovation. Except for 22 December, the daily minimum air temperature for that day was between 6:00 and 8:00. The daily maximum air temperature generally occurred between 13:00 and 15:00. There was a slight temperature improvement at around 18:00 each day. The average change in the three cases shows that the colder the month, the more pronounced the temperature improvement. It can be seen that the temperature improvement in all three rooms is better in case 2 of the wall renovation than in case 1, and Case 1 is also better than the original solution in all cases. The analysis of the temperature changes throughout the winter better reflects the advantages and disadvantages of both solutions. Figure 6.10 shows the air temperature changes in the three rooms throughout the winter. The temperature fluctuations throughout the winter show that the two renovation solutions have approximately the same increase in temperature in each of the five months from November to March, except case 1, which has a lower maximum temperature in November than the previous month. It can be seen that case 2 has a better improvement in indoor temperatures.

Table 6.5 shows the variation in maximum, minimum and average air temperatures for the external wall renovation case during the typical week and winter. During a typical week, the change in air temperature shows that the master bedroom has the lowest average temperature of 6.47°C, followed by the second bedroom with a typical week average of 7.32°C and the living room with the highest average temperature of 7.98°C. For all three rooms, both of two renovations improve the insulation performance of the walls. However, in terms of temperature improvement, case 2 is superior to case 1. In terms of typical weekly indoor thermal gain, the living room, master bedroom and the second bedroom in case 1 improved by 1.06°C, 1.08°C and 1.53°C, respectively. In comparison, the temperatures in these three rooms in case 2 improved by 1.64°C, 1.98°C and 2.39°C, respectively. In terms of the improvement of the indoor thermal environment throughout the winter, the average winter

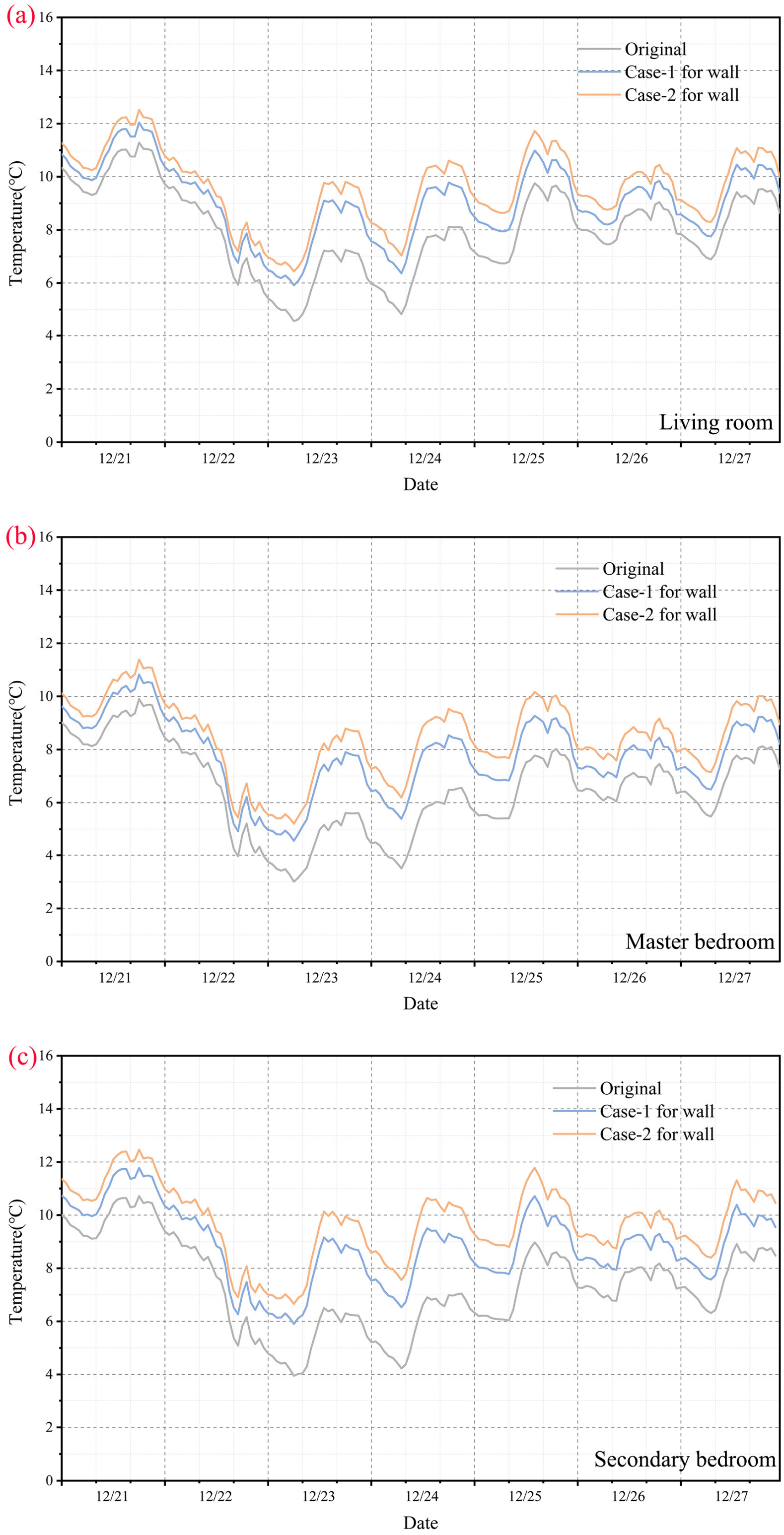


Figure 6.9. Daily variation curve of air temperature in three rooms in the typical week before and after external wall renovation

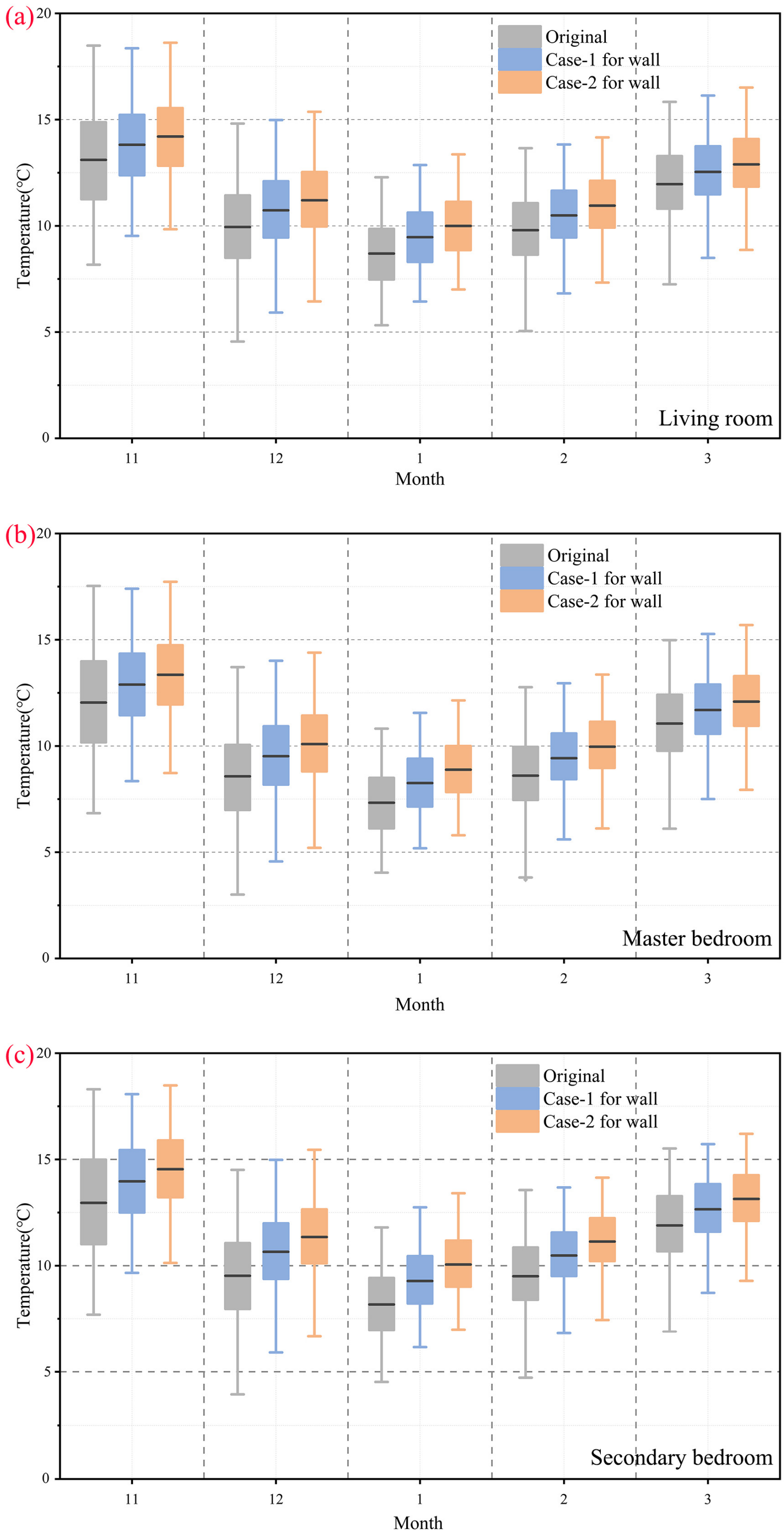


Figure 6.10. Daily variation of air temperature in three rooms in winter before and after external wall renovation

temperatures in the living room, master bedroom and second bedroom in case 1 increased by 0.71°C, 0.84°C and 1.00°C respectively compared to the original, compared to the average winter temperatures in the three rooms in case 2, which increased by 1.15°C, 1.36°C and 1.64°C. This shows that case 2 is better at improving the insulation performance of the walls and is the best choice.

Table 6.5. Compare air temperature in typical weeks and winter before and after external wall renovation

Air temperature	Rural house	Typical week			Winter		
		living room	master bedroom	secondary bedroom	living room	master bedroom	secondary bedroom
Maximum	Origin	11.28	9.90	10.72	18.48	17.53	18.30
	Case-1	12.04	10.30	11.78	18.36	17.40	18.07
	Case-2	12.52	11.39	12.47	18.62	17.73	18.48
Minimum	Origin	4.55	3.00	3.94	4.55	3.00	3.95
	Case-1	5.92	4.14	5.90	5.92	4.56	5.90
	Case-2	6.44	5.21	6.66	6.44	5.21	6.66
Average	Origin	7.98	6.47	7.32	10.70	9.52	10.41
	Case-1	9.04	7.55	8.85	11.41	10.36	11.41
	Case-2	9.62	8.45	9.71	11.85	10.88	12.05

(2) Under the indoor heating condition

The heat load is the heat supplied by the heating system to the building per unit of time to achieve the required room temperature at a given outdoor temperature. It varies with the amount of heat gained or lost from the building. The Figure 6.11 compares the heating load for a typical week and the whole winter season for the three cases. The heating energy consumption of the selected rural house during the specific week period is 211.42kw, with a significant reduction in energy consumption after the wall renovation. The heating energy consumption of this rural house for the whole winter period was 1827.03kw, of which case 1 and case 2 reduced the energy consumption by 733.83kw and 1058.60kw, respectively. Case 1 had building energy-saving rates of 35.8% and 40.2% for the typical week and the whole winter period. In comparison, case 2 had to build 53.3% and 57.9% energy-saving rates for the specific week. Case 2 achieved 53.3% and 57.9% building energy savings during the regular and winter months. Case 2, therefore, has better energy savings over a short period. The energy savings in case 2 also increase with time throughout the winter months.

In summary, of the two wall renovation solutions, case 2 has an overall better temperature improvement effect on the three interior rooms than case 1. The building energy-saving is also higher than that of case 1. Moreover, from the renovation process and renovation cost, the cost and difficulty of case 2 is the same as that of case 1. Therefore, case 2 is chosen as the final wall renovation solution.

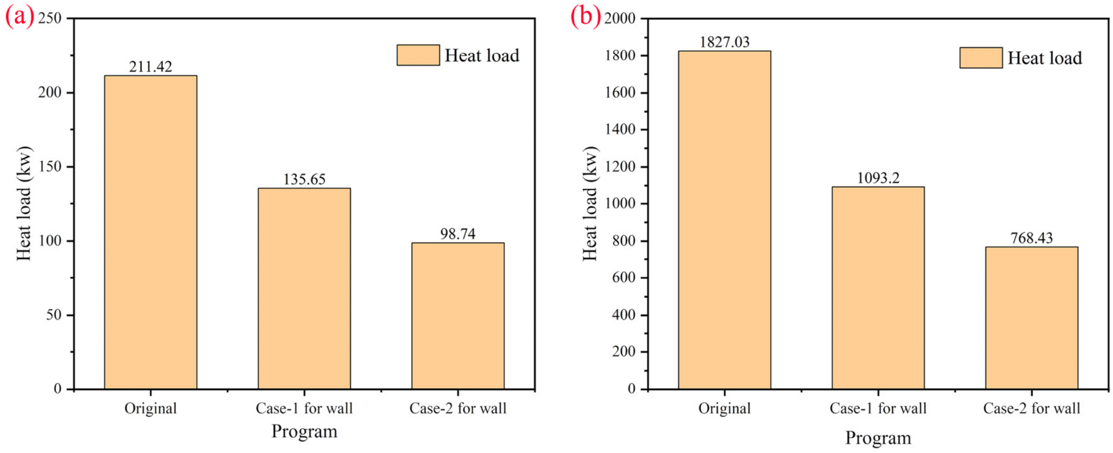


Figure 6.11. Typical weekly and winter heating load histogram of the external wall

6.5.2.Contribution of house roofs

The three roof types from the original, case 1, case2 and case3, were added to the selected typical house. Hour-by-hour temperature simulations were carried out for the living room. Two bedrooms during a typical week when the building was not heated, hour-by-hour temperature simulations were carried out for the living room. Two bedrooms during the winter when the building was not heated, and for a typical week. The heat load simulations were carried out for the building during heating and the construction during winter when heating is provided, as shown in Figure 6.12 and Figure 6.13.

(1) Under indoor natural condition

Figure 6.12 shows the change in air temperature trends for each room before and after the roof modifications during a typical weekly period. Except for 22 and 26 December, the daily minimum temperature for that day was between 6:00 and 8:00. The daily maximum temperature generally occurred between 13:00 and 15:00. There was a small temperature increase between 16:00 and 18:00 each day. Figure 6.13 shows the change in air temperature in the three rooms throughout the winter before and after the roof renovation. In November and March, the maximum values for the original are larger than the three renovation cases.

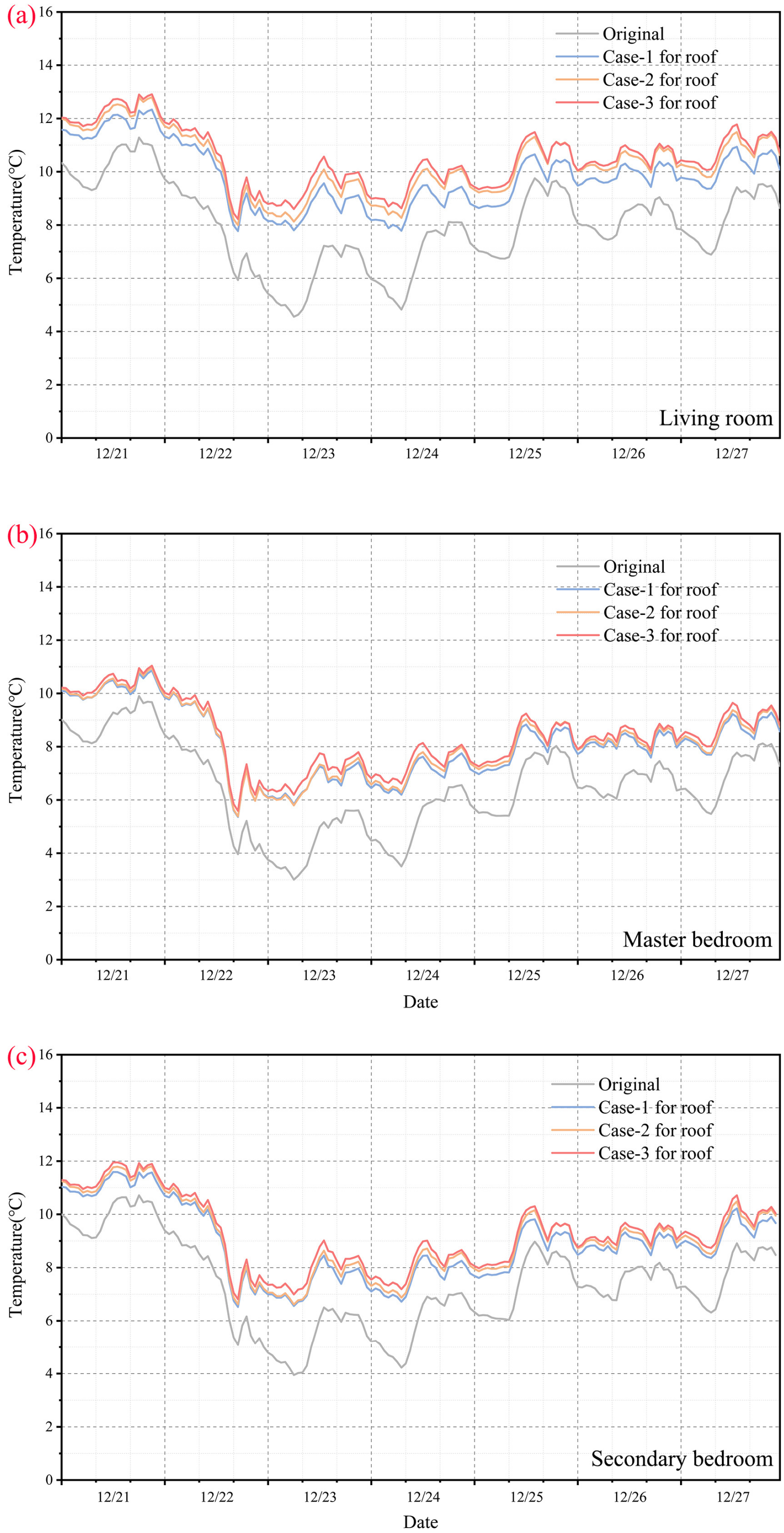


Figure 6.12. Daily variation curve of air temperature in three rooms in the typical week before and after roof renovation

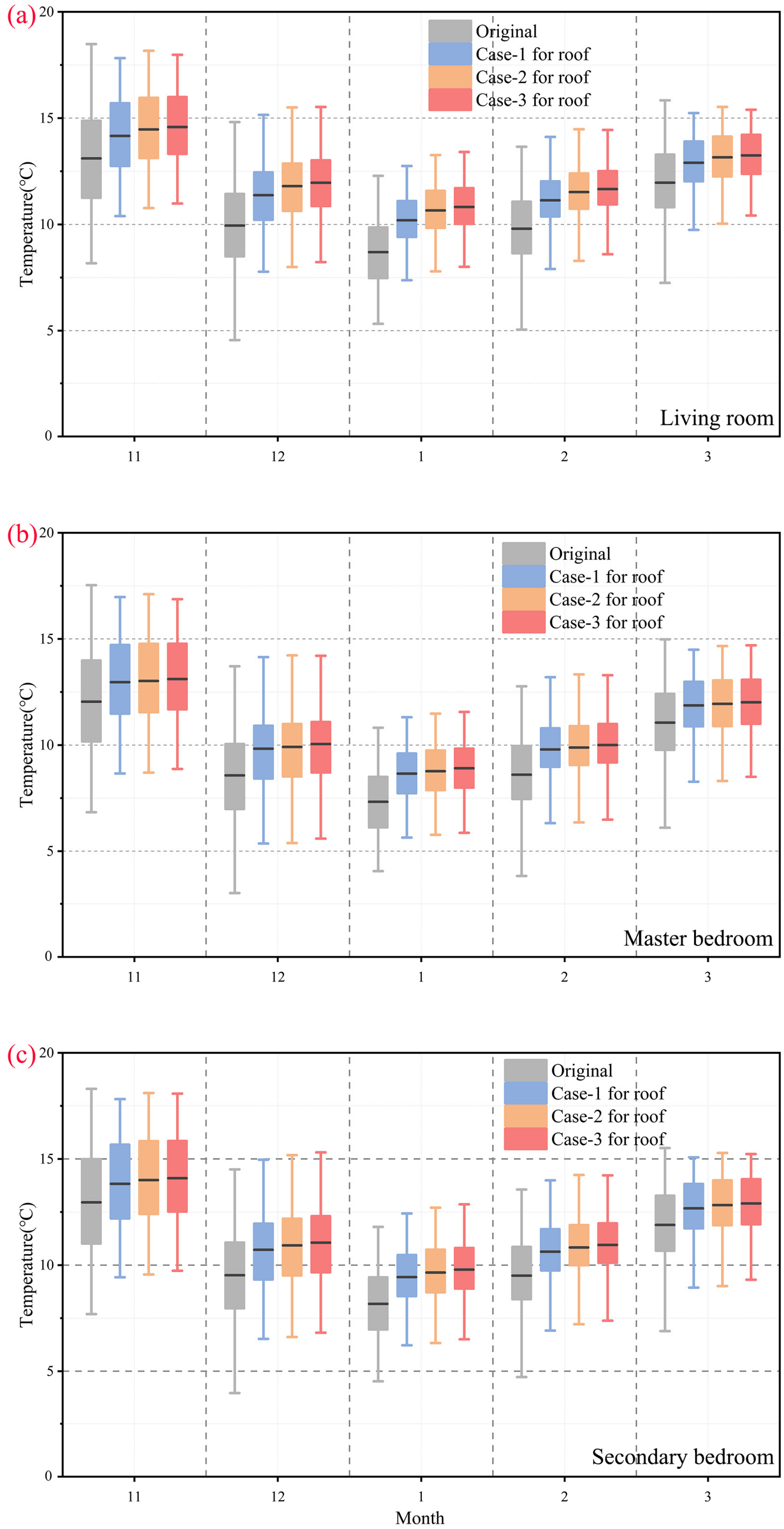


Figure 6.13. Daily variation of air temperature in three rooms in winter before and after roof renovation

This shows the advantage of the three renovation options in reducing the temperature fluctuations throughout the room during the winter when the overall temperature is higher. In addition, the temperature fluctuations throughout the winter months show that the two renovation solutions increase the temperature to a similar extent in each winter month. In contrast, the maximum temperature in November in case 1 is lower than before. In terms of temperature extremes, case 3 > case 2 > case 1 > original.

Table 6.6 shows the changes in maximum, minimum and average temperature for the two roof renovation cases during a typical week and winter period. In terms of temperature improvement during a typical week, case 1 improved the living room, master bedroom and second bedroom by 1.83°C, 1.61°C and 1.54°C, respectively. Case 2 saw an improvement of 2.31°C, 1.72°C and 1.74°C for the three rooms. In contrast, case 3 improved the temperatures in these three rooms by 2.53°C, 1.91°C and 1.92°C, respectively. Regarding temperature change over a typical week, all three renovation options helped improve the roof's insulation.

Table 6.6. Comparison of air temperature in typical weeks and winter before and after roof renovation

Air temperature	**Rural house**	**Typical week**			**Winter**		
		living room	**master bedroom**	**secondary bedroom**	**living room**	**master bedroom**	**secondary bedroom**
Maximum	Origin	11.28	9.90	10.72	18.48	17.53	18.30
	Case-1	12.34	10.86	11.59	17.82	16.97	17.82
	Case-2	12.80	10.95	11.83	18.17	17.11	18.11
	Case-3	12.91	11.04	11.95	17.98	16.87	18.08
Minimum	Origin	4.55	3.00	3.95	4.55	3.00	3.95
	Case-1	7.77	5.36	6.52	7.38	5.36	6.22
	Case-2	8.00	5.38	6.61	7.79	5.38	6.33
	Case-3	8.23	5.59	6.81	8.00	5.59	6.50
Average	Origin	7.98	6.47	7.32	10.70	9.52	10.41
	Case-1	9.81	8.08	8.86	11.95	10.62	11.46
	Case-2	10.29	8.19	9.06	12.32	10.71	11.65
	Case-3	10.51	8.38	9.24	12.45	10.82	11.76

And in terms of temperature changes throughout the winter, the average winter temperatures in the living room, master bedroom and second bedroom in case 1 were 1.25°C, 1.10°C and 1.05°C higher than before the renovation. In comparison, in case 2, the average winter temperatures in the upper three rooms were 1.62°C, 1.19°C, and 1.24°C higher than before the renovation. In comparison, the average winter temperatures in the three rooms in case 3 were 1.75°C, 1.30°C, and 1.35°C higher than before the renovation.

(2) Under the indoor heating condition

Figure 6.14 compares the heating loads for a typical week and the whole winter period for the three cases on the roof. During the regular week period, the heating energy consumption of the three roof renovation cases was reduced by 82.64kw, 96.83kw, and 108.06kw, respectively, compared to the actual energy consumption of the rural house. Case 1 had a building energy saving of 39.1%, Case 2 had a building energy saving of 45.8%, and case 3 had a building energy saving of 51.1%. At that point, the heating energy consumption between the three cases was relatively similar, with energy savings of around 45%. As the period increases from a typical week to the whole winter. The building energy-saving rates for cases 1, 2 and 3 are 39.1%, 45.8% and 51.1%.

Both case 2 and case 3 have improved by over 45% compared to the original. However, Ccase 3 is near twice the cost of case 2, so case 2 is chosen as the final renovation solution. In summary, among the three roof renovation cases, case 3 has an overall better temperature improvement effect on the three indoor rooms than case 1 and case 2. The building energy-saving rate is also higher than both, but in terms of the renovation cost, the renovation cost of case 3 is twice that of case 1 and case 2. In terms of effect, the temperature improvement of case 3 is not significant compared to case 2. Therefore, case 2 is chosen as the final roof renovation solution.

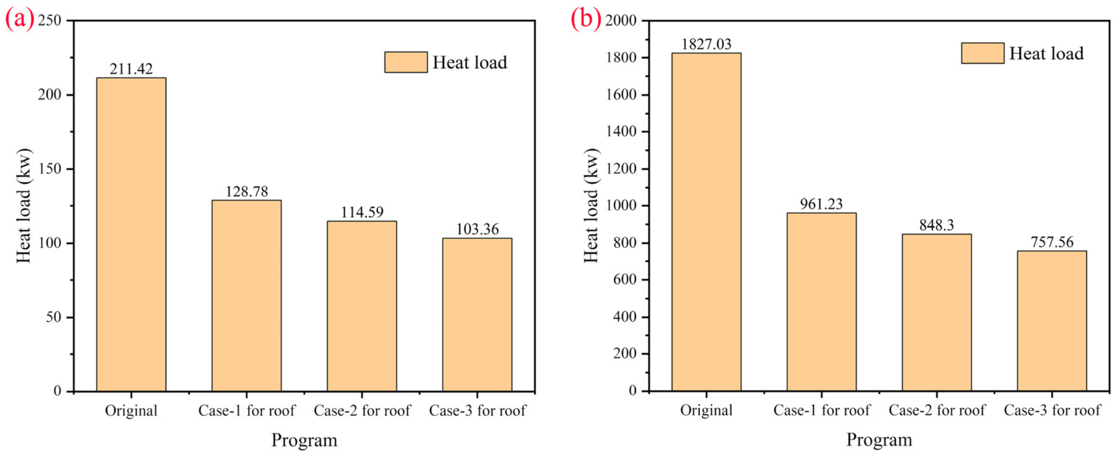


Figure 6.14. Typical weekly and winter heating load histogram of the roof

6.5.3.Contribution of house windows

Similarly, four kinds of windows from the original, Case 1, Case 2 and Case 3, were added to the selected typical rural houses. Two sets of time periods were selected for a typical week and for the whole winter. Day-by-day temperature simulations without heating and load simulations with heating were carried out, as shown in Figure 6.15 and 6.16.

(1) Under indoor natural condition

Figure 6.15 shows the change in air temperature trends for each room before and after the window renovations during a typical week. It can be seen that for all three rooms, the temperature increase in case 3 was better than in cases 1 and 2. Similarly, except for 22 December, the lowest temperature of the day was between 6:00 and 8:00. The day's highest temperature generally occurred between 13:00 and 15:00, with a slight temperature increase around 18:00. It is important to note that although all three renovation solutions could increase indoor temperatures more significantly, the difference between the three renovations was not significant. Figure 6.16 shows the temperature changes in the three rooms throughout the winter, with the average temperature change showing that case 3 was more effective than case 1 and case 2. The difference in temperature extremes shows that the window renovation did not significantly change the temperature extremes, suggesting that the most significant benefit of the external window renovation was the overall increase in indoor temperature, rather than a substantial reduction in the temperature extremes. The values for Case 3 were maximum throughout the winter and always satisfied case 3 > case 2 > case 1 > original.

Table 6.7 shows the changes in maximum, minimum and average temperature for the two window renovation cases over a typical week and winter. In terms of temperature changes over a typical week, the living room, master bedroom and second bedroom in case 1 increased by 1.12°C, 1.82°C and 1.81°C respectively, the temperature in these rooms in case 2 increased by 1.28°C, 1.96°C and 1.94°C respectively, while case 3 saw an increase of 1.87°C, 2.06°C and 2.04°C respectively. In terms of temperature change over a typical week, case 3 showed a better improvement in temperature than both case 1 and case 2. And in terms of temperature changes throughout the winter, the average winter temperatures in the living room, master bedroom and second bedroom in case 1 increased by 1.69°C, 1.75°C and 1.74°C, respectively, compared to the original. Compared to the pre-renovation period, the average winter temperatures in the three rooms mentioned above in case 2 increased by 1.75°C, 1.86°C and 1.85°C, respectively. In contrast, the average winter temperatures in the three rooms mentioned above in case 3 increased by 1.80°C, 1.95°C and 1.93°C. Therefore, compared to the original, case 3 is the most selective in terms of temperature increase. However, case 3 uses rare gas as the filler gas, which is too costly to renovate and not very suitable for a large rural residential population, so case 2 is chosen as the final renovation solution.

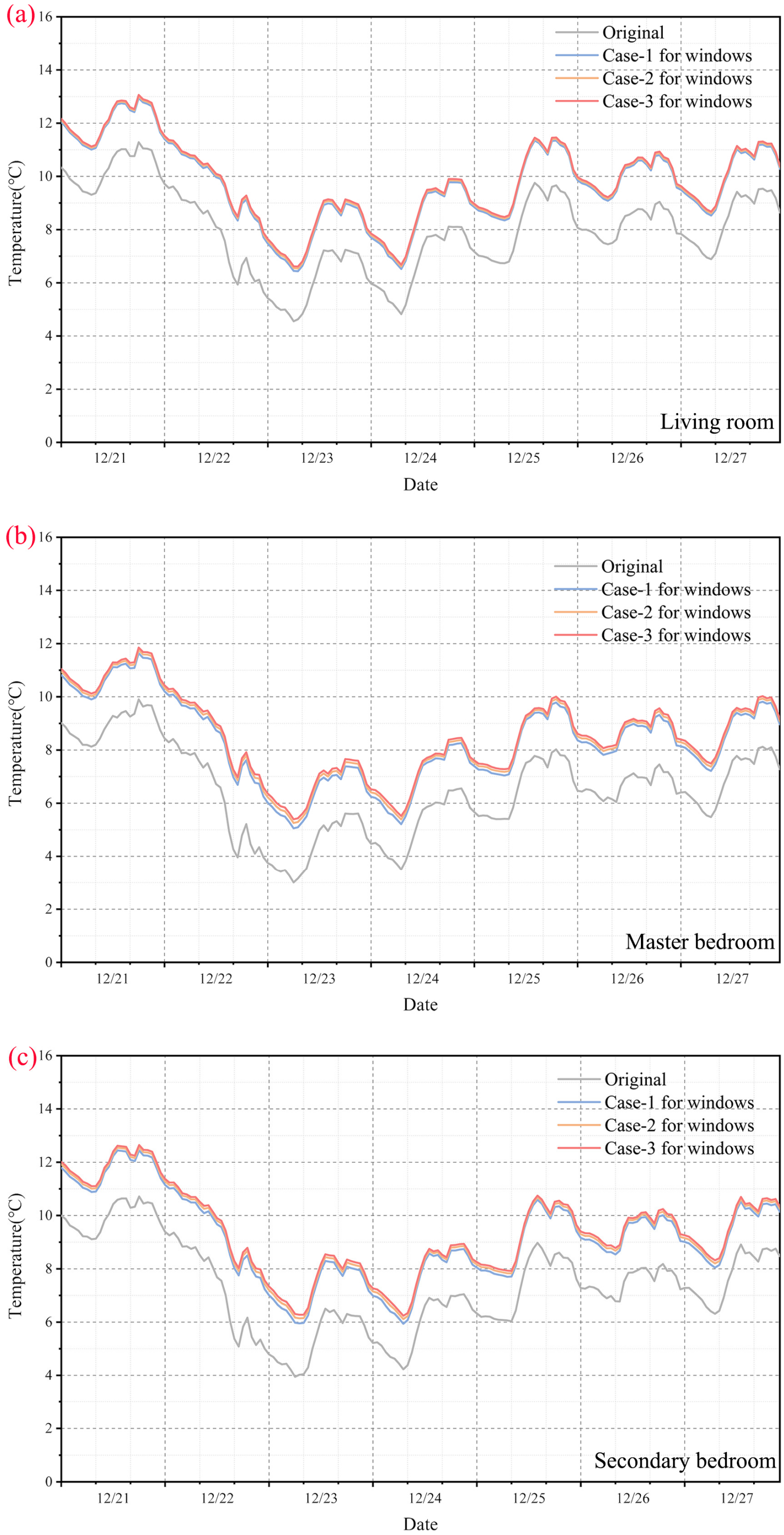


Figure 6.15. Daily variation curve of air temperature in three rooms in the typical week before and after external window renovation

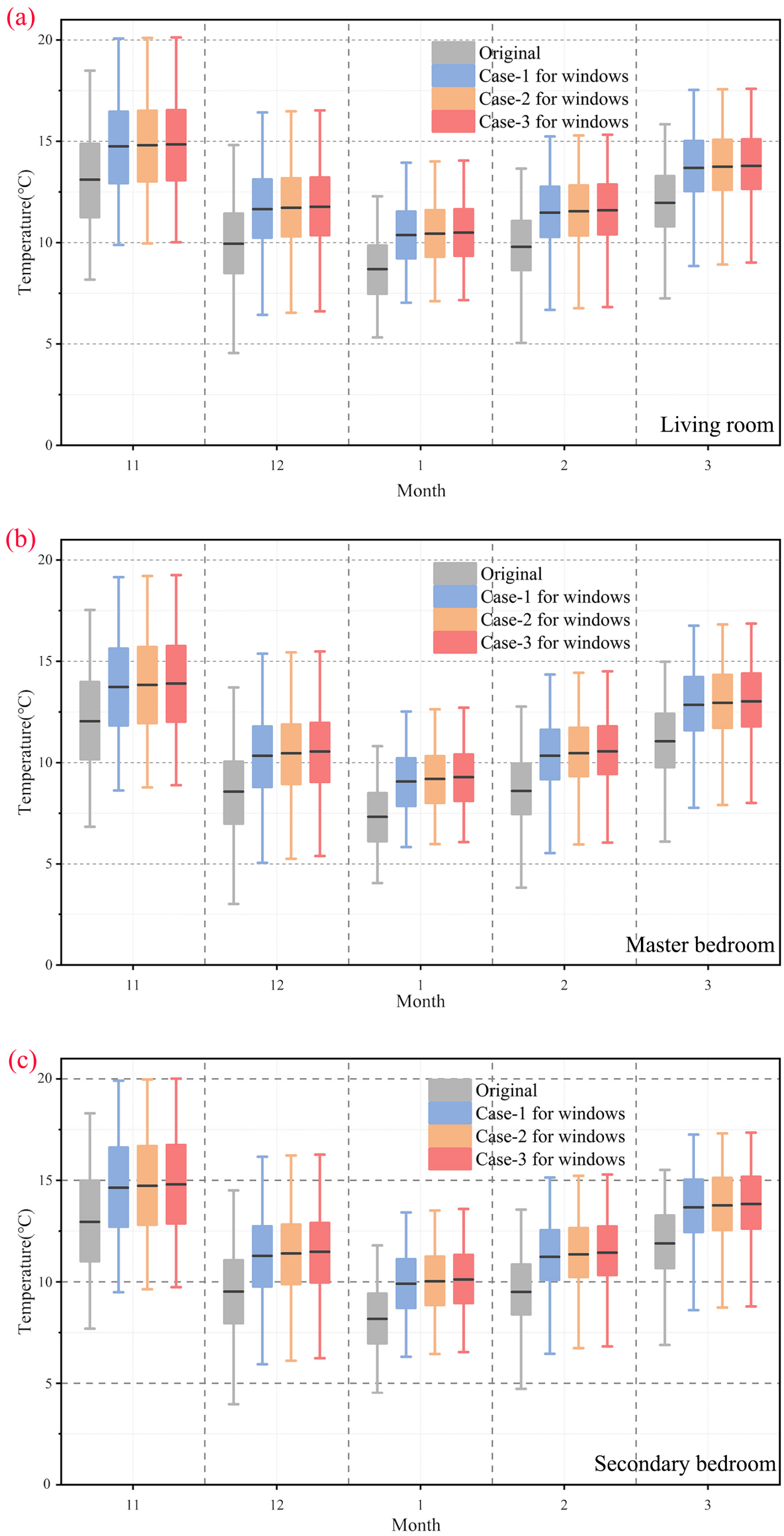


Figure 6.16. Daily variation of air temperature in three rooms in winter before and after external window renovation

Table 6.7. Comparison of air temperature in typical weeks and winter before and after external window renovation

Air temperature	Rural house	Typical week			Winter		
		living room	master bedroom	secondary bedroom	living room	master bedroom	secondary bedroom
Maximum	Origin	11.28	9.90	10.72	18.48	17.53	18.30
	Case-1	12.44	11.64	12.44	20.07	19.15	19.91
	Case-2	12.56	11.76	12.56	20.10	19.21	19.97
	Case-3	13.06	11.85	12.65	20.12	19.25	20.01
Minimum	Origin	4.55	3.00	3.95	4.55	3.00	3.95
	Case-1	5.94	5.06	5.94	6.43	5.06	5.94
	Case-2	6.11	5.25	6.11	6.54	5.25	6.11
	Case-3	6.61	5.39	6.24	6.61	5.39	6.24
Average	Origin	7.98	6.47	7.32	10.70	9.52	10.41
	Case-1	9.13	8.29	9.13	12.39	11.27	12.15
	Case-2	9.26	8.43	9.26	12.45	11.38	12.26
	Case-3	9.85	8.53	9.36	1.50	11.47	12.34

(2) Under the indoor heating condition

Figure 6.17 compares the heating loads for the three renovation cases for a typical week and winter. The heating energy consumption for the three renovation cases is 131.93 kw, 125.05 kw and 121.29 kw for the typical week period. 37.6%, 40.9% and 42.6% building energy savings are achieved for cases 1, 2 and 3, respectively. The building energy-saving rates were relatively similar between the three cases. Over the whole winter, the heating energy consumption of cases 1, 2 and 3 was reduced by 938.68kw, 995.79kw and 1047.34kw, respectively, compared to the actual energy consumption of the farmhouse, and the building energy-saving rates for the three renovation cases were 44.0%, 49.2% and 50.8% respectively. At this point, it can be seen that case 3 has the most significant advantage.

In summary, among the three external window renovation options, case 3 has an overall better temperature improvement effect on the three interior rooms than case 1 and case 2. The building energy-saving is also higher than both of case 1 and case 2, but from the renovation cost point of view, the renovation cost of case 3 is expensive. The temperature improvement effect of case 3 is not significant compared to case 1 and case 2. Therefore, case 2 is chosen as the final external window renovation solution.

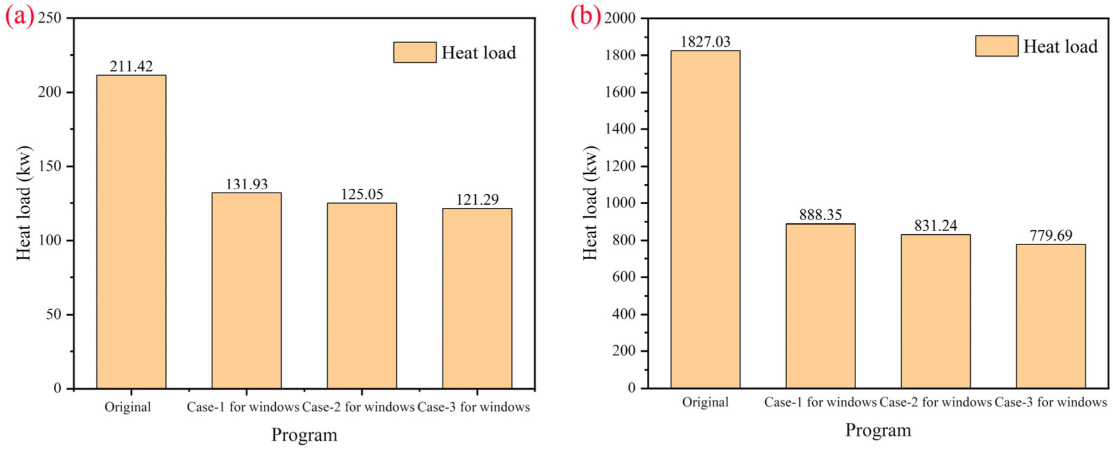


Figure 6.17. Typical weekly and winter heating load histogram of the window

6.6.Improvement efficiency of the whole house

In the previous section, the external wall, roof and window renovation renovations were finalised: the external wall renovation was chosen for external wall case 2, which involved the masonry of straw-filled sintered porous bricks over a stone or brick wall with an additional 20mm air interlayer between them, the roof renovation was chosen for roof case 2, which involved the use of 120mm thick roof insulation panels placed above the original suspended ceiling, the external window renovation was selected from for external window case 2, which involved the use of double 9mm air laminated glass (glass thickness 6mm). The work in this section is to build on the individual renovation in the previous chapter and to simulate parameter indicators such as typical weekly indoor temperature, winter indoor temperature and ePMV for the entire rural house to get a fuller picture of the enhancement effect of the renovation solution on the rural house.

6.6.1.Under indoor natural condition

(1) Variation of indoor air temperature and relative humidity

Figure 6.18 shows the hour-by-hour temperature change curves from 21 December to 27 December before and after the house envelope renovation. The figure shows that the overall temperature of the typical rural house in the renovation house increased by about 5°C compared to the house before the renovation. Using the interior design temperature of 16°C as a reference, it can be found that the indoor temperature of the three rooms was very close to 16°C, proving that the renovation solution proposed in this paper has excellent results. Figure 6.19 shows the monthly temperature fluctuations before and after the envelope renovation throughout the winter. In January, the coldest month, the minimum indoor temperature in all three rooms showed the most significant increase compared to the other months. January was still the most influential in the maximum temperature increase, followed by December. The pre-renovation indoor temperatures in February were similar to those in December. Still, the maximum temperature increase in February was not as effective as in December, probably due to the warming temperatures during part of February. The post-renovation rural houses had a significantly higher temperature than the pre-renovation houses, particularly for the minimum temperatures. In addition, the average temperature in all rooms in the renovated houses was above 16°C in November and March. The average temperature for the rest of the months did not exceed 16°C but was very close to 16°C, again proving the effectiveness of this proposed renovation programme.

Table 6.8 shows the change in maximum, minimum and average indoor temperatures after the envelope renovation solutions in real-time for a typical week and winter. In terms of temperature variation during a typical week, the master bedroom has the lowest average temperature of 6.47°C, the second bedroom has an average temperature of 7.32°C, while the living room has the highest average temperature of 7.98°C. For all three rooms, the integrated solution is proposed in this paper.

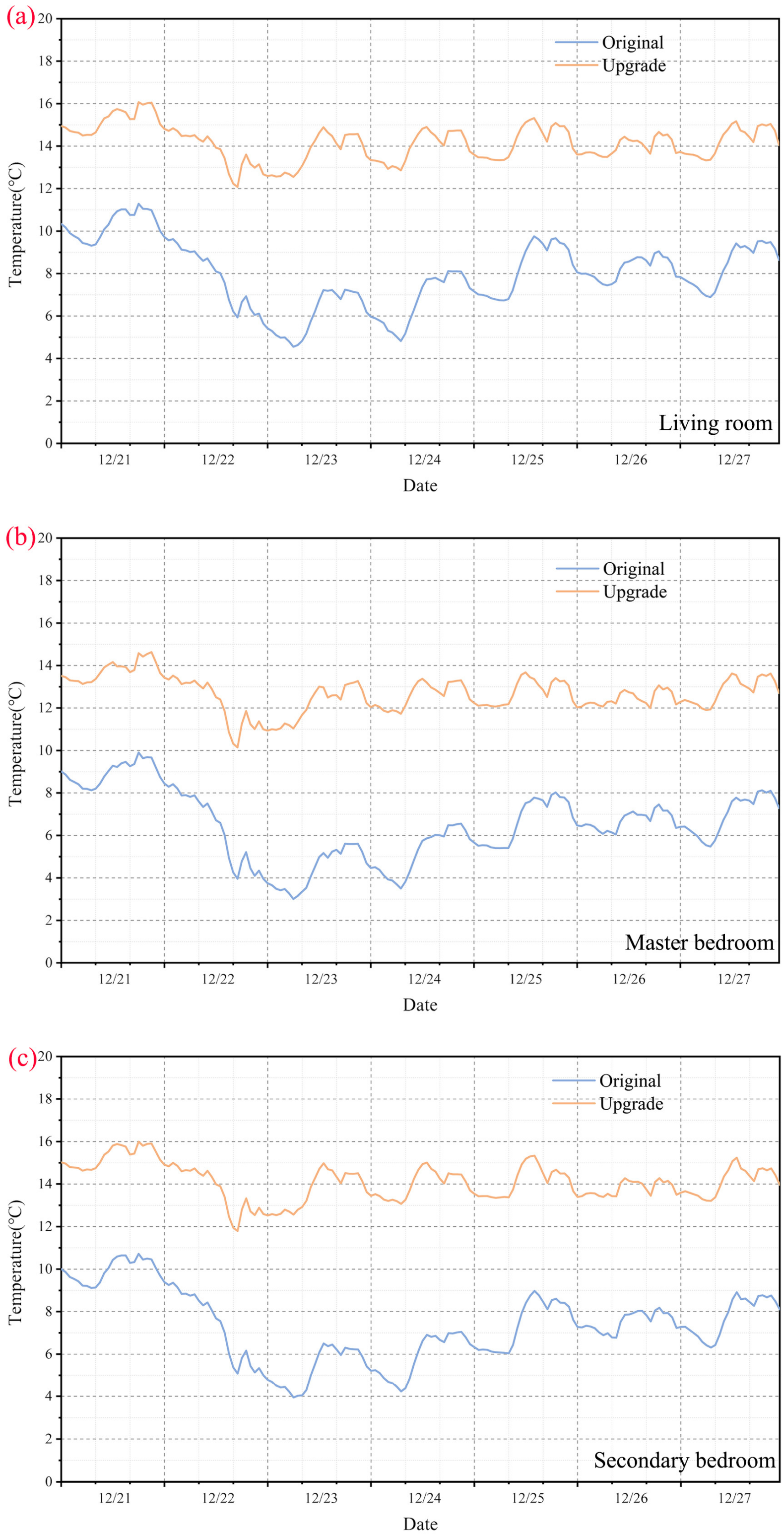


Figure 6.18. Daily variation curve of air temperature in three rooms in a typical week before and after renovation

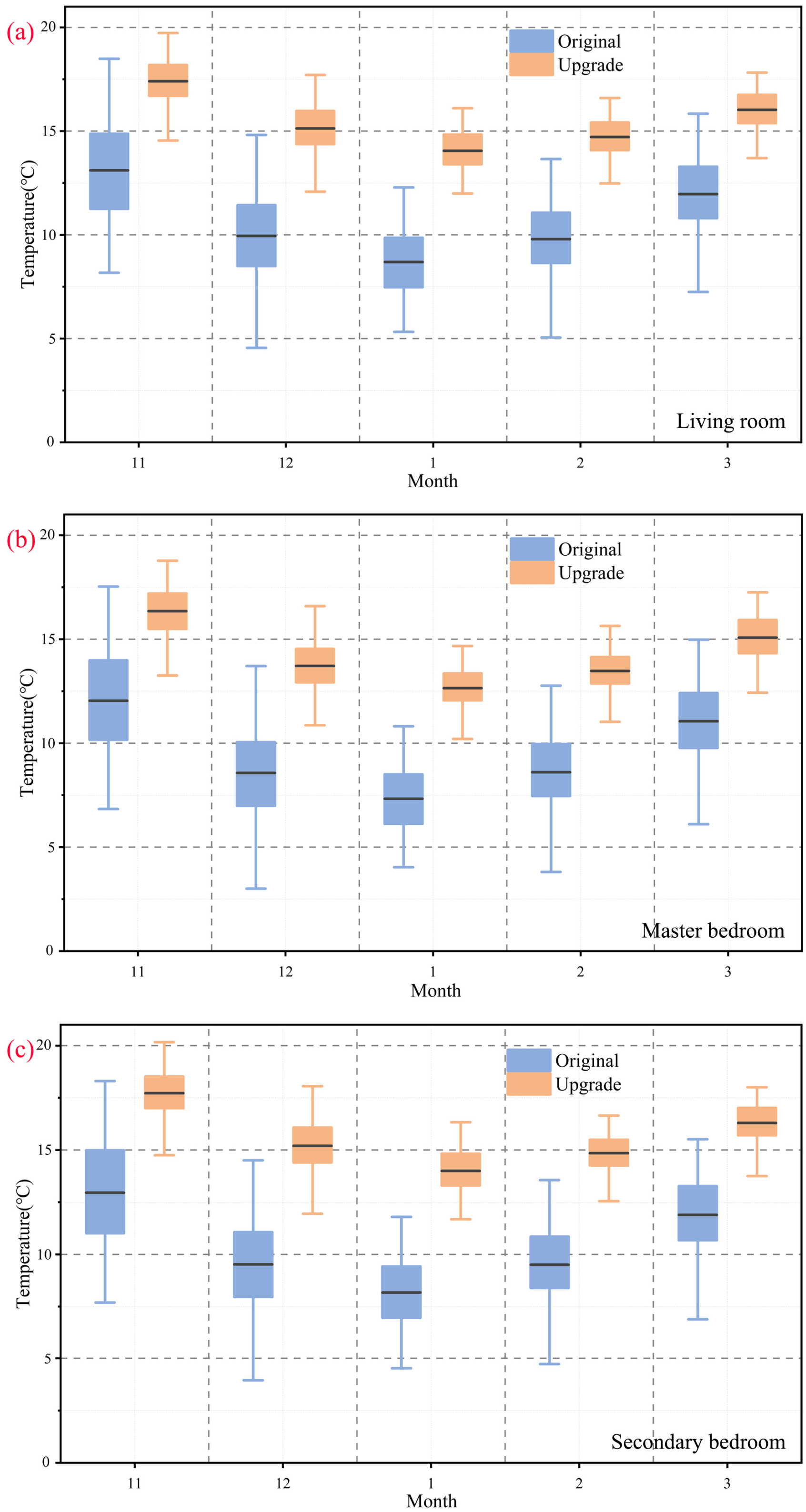


Figure 6.19. Daily variation of air temperature in three rooms in winter before and after renovation

It helps to enhance the overall thermal environment of the building. During a typical week period, the living room, master bedroom and second bedroom improved by 6.19°C, 6.21°C and 6.79°C, respectively. Regarding temperature changes throughout the winter, the average winter temperatures in the living room, master bedroom and second bedroom improved by 4.77°C, 4.73°C and 5.2°C, respectively, compared to the original. This shows that for both the typical week and the whole winter, the most significant temperature increase in all three rooms was in the second bedroom, with the living room and the master bedroom showing almost the same effect.

Table 6.8. Comparison of air temperature before and after renovation in typical weeks and winter

Air temperature	**Rural house**	**Typical week**			**Winter**		
		living room	**master bedroom**	**secondary bedroom**	**living room**	**master bedroom**	**secondary bedroom**
Maximum	Origin	11.28	9.90	10.72	18.48	17.53	18.30
	Upgrade	16.07	10.14	15.99	19.73	18.77	20.16
Minimum	Origin	4.55	3.00	3.95	4.55	3.00	3.95
	Upgrade	12.08	14.63	11.79	11.99	10.14	11.68
Average	Origin	7.98	6.47	7.32	10.70	9.52	10.41
	Upgrade	14.17	12.68	14.11	15.47	14.25	15.61

(2) Variation of indoor ePMV

Figure 6.20 shows the change in ePMV before and after the renovation of the rural residential envelope during a typical week. The summer in Qingdao is a little hot, while the other three seasons are not very hot. The penetration of air conditioning in rural areas of Qingdao is not very high, so the ep was taken to be 0.9. From Figure 6.20, it can be seen that the ePMV of the renovated houses are closer to within the comfort zone (-0.5 to 0.5) compared to those before the renovation. The comfort zone was not met for all periods, but the ePMV did not reach -1 during the typical weekly period. ePMV before the renovation was found to be good. Figure 6.21 reflects the fluctuations in ePMV before and after the renovation of the rural dwelling envelope throughout the winter. All three rooms showed a significant improvement in ePMV throughout the winter, and the overall fluctuation in ePMV levelled off each month after the renovation. This demonstrates that envelope modifications can also positively affect the stability of the indoor thermal environment. The comparison of the three rooms shows that the living room and the master bedroom have similar changes in ePMV. In contrast, the master bedroom cannot have the same effect as the other two rooms after the renovation due to its previous worst ePMV situation, which can also correspond to the temperature changes in the last three rooms.

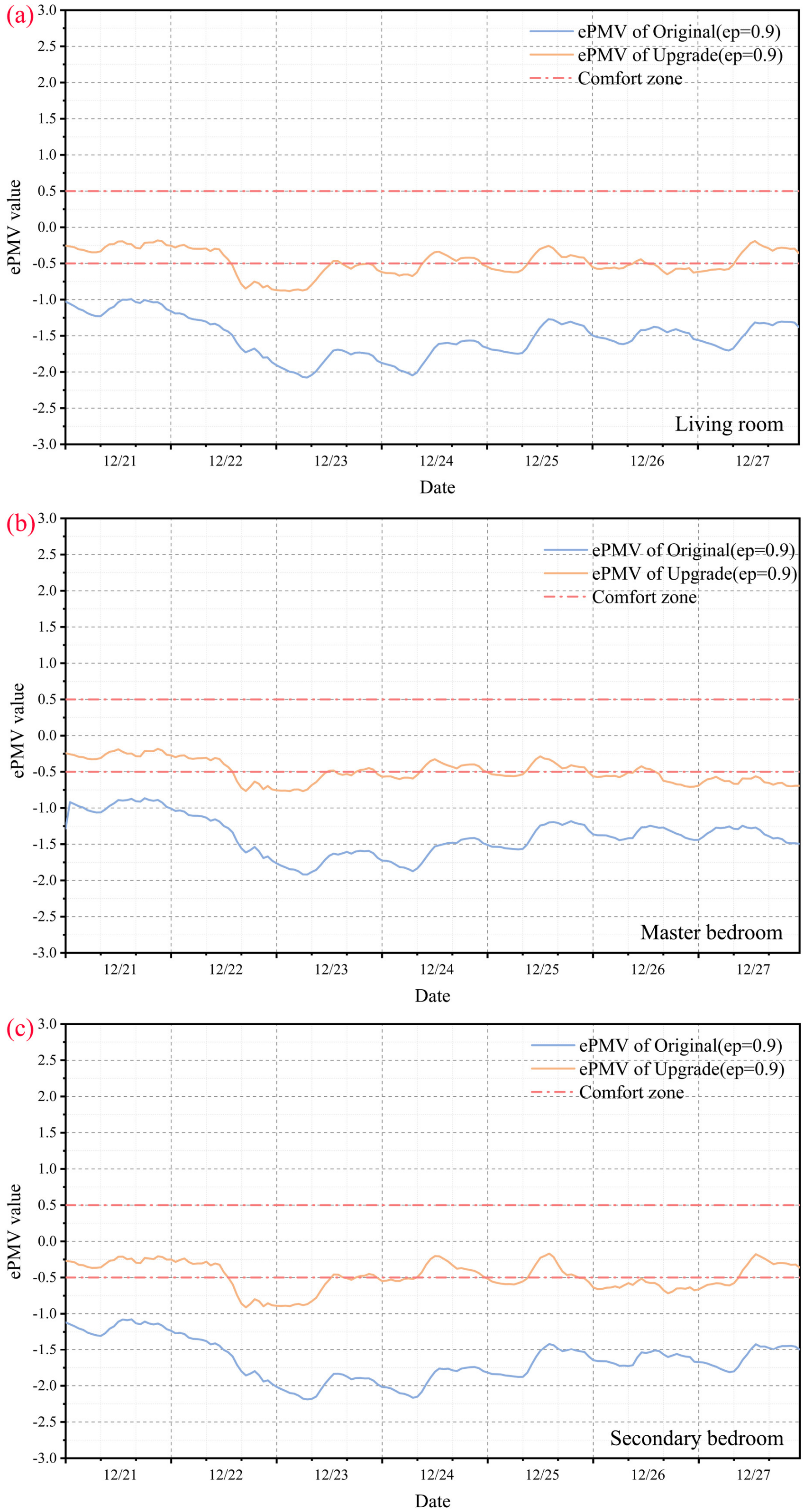


Figure 6.20. Daily variation curve of ePMV in three rooms in a typical week before and after renovation

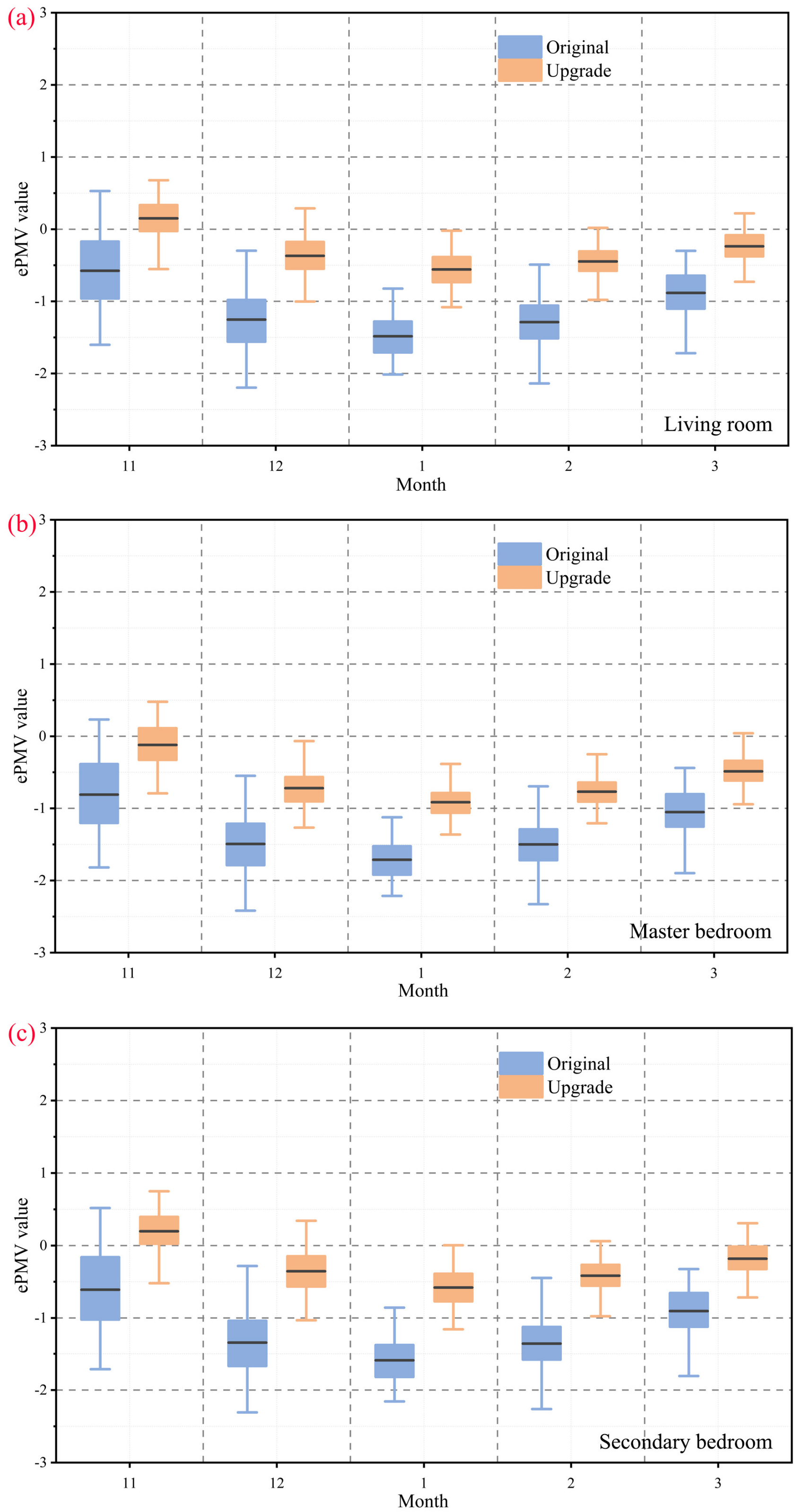


Figure 6.21. Month variation of ePMV in three rooms in winter before and after renovation

6.6.2.Under the indoor heating condition

Figure 6.22 compares the heating loads before and after the renovation of the house during a typical week and throughout the winter. As shown in Figure 6.22(a), during the typical week period, the heating energy value after the envelope renovation was significantly reduced compared to the pre-renovation period, from 211.42 to 43.32kw for a typical week, resulting in a building energy saving of 79.5%. As shown in Figure 6.22(b), the heating energy consumption value after the envelope renovation was reduced from 1827.03kw to 300.45kw throughout the winter season, with a building energy-saving rate of 83.6%. It can be seen that the envelope renovation solution has relatively significant benefits both in the short and long term.

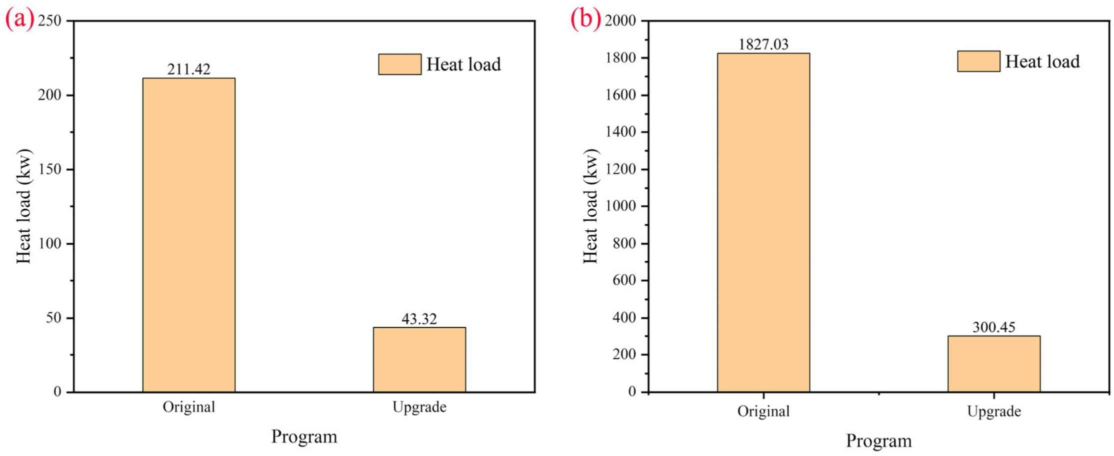


Figure 6.22. Typical weekly and winter heating load histogram of the whole renovation

6.7.Summary

In this chapter, considering various factors such as temperature and heating energy consumption, suitable and reasonable energy-saving renovation technical measures are proposed for three aspects of typical rural houses: external walls, roofs and external windows, and univariate energy consumption simulations are carried out using Energy-plus energy consumption simulation software to calculate the renovation measures for different materials and structures of the external envelope of other residential spaces, and the simulation results obtained are compared with the experimental The simulated results are compared with the experimental results in Chapter 5 to verify the accuracy of the experiments.

(1) In terms of wall renovation, wall case 2 had a better overall temperature improvement effect on the three rooms than wall case 1. The winter energy-saving of wall case 2 was 57.9%, higher than that of wall case 1 (40.2%). Regarding the renovation process and renovation cost, the cost and difficulty of renovation for wall case 2 are also the same as that of wall case 1. Therefore, Wall case 2 was chosen as the final wall renovation solution.

(2) In terms of roof renovation, the overall effect of roof renovation case 3 on the temperature improvement of the three interior rooms was better than that of case 1 and case 2. The winter building energy-saving rate of case 3 was 58.5%, higher than that of case 1 (47.4%) and case 2 (53.6%). In terms of renovation costs, case 3 is twice as expensive as case 1 and case 2. In terms of overall results, the improvement in case 3 is similar to that of case 2, making case 2 the more appropriate choice as the final roof renovation solution.

(3) In terms of external window renovation, window renovation case 3 had a better overall temperature improvement effect on the three interior rooms than case 1 and case 2. The building energy-saving for the whole winter in case 3 was 57.3%, again higher than the 51.4% in case 1 and 54.5% in case 2. However, in terms of the renovation cost, case 3 was expensive to renovate, and in terms of temperature increase, the temperature increase in case 3 was close to that of case 1 and case 2. Therefore, case 2 was chosen as the final external window renovation solution.

(4) Afterwards, the three selected renovation solutions for external walls, roofs and external windows were aggregated and evaluated comprehensively. It was determined that the comprehensive solutions proposed in this paper helped improve the overall thermal environment of the building, with the living room, master bedroom and second bedroom improving by 6.19°C, 6.21°C and 6.79°C, respectively in terms of temperature change over a typical week. Regarding temperature changes throughout the winter, the average winter temperatures in the living room, master bedroom and second bedroom improved by 4.77°C, 4.73°C and 5.2°C, respectively compared to the original. The change in the

indoor thermal environment before and after the renovation was then assessed by the change in ePMV, and it was determined that the renovated rural houses had a good effect compared to the original in terms of ePMV, both for a typical week and for the whole winter. Finally, building energy consumption was calculated for a typical week and the whole winter season, resulting in a significant building energy-saving of 79.5% and 83.6% before and after renovation respectively.

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Chapter 7. Application of Sunroom to Improve Indoor Thermal Environment in Winter.

7.1.Introduction

The sunroom is a building method of using solar energy for air conditioning or heating. Take this measure to use solar energy to replace some conventional energy sources so that the ambient temperature can meet specific requirements for use [1]. Sunrooms come in various forms and can be divided into two main categories, active and passive, depending on whether they require mechanical power. Active sunroom heating systems require an auxiliary heat source and solar heating equipment due to the instability of solar resources and economic considerations. However, this kind of sunroom equipment is complicated, the initial investment is high, and extra energy is still required. In application, the hot water collection system of the active sunroom needs to be protected from freezing during winter heating. For the above reasons, it is challenging to promote and apply the active sunroom on a large scale in China [2]. Passive sunrooms mainly use the building structure, such as walls and floors, for heat collection and storage to maintain a better thermal comfort in the room. Compared to an active sunroom, a passive sunroom does not require the erection of special solar collectors, the installation of complex systems, and no running costs. Therefore, a passive sunroom house is very cheap to build. Only about 10% costs more than an ordinary house [3].

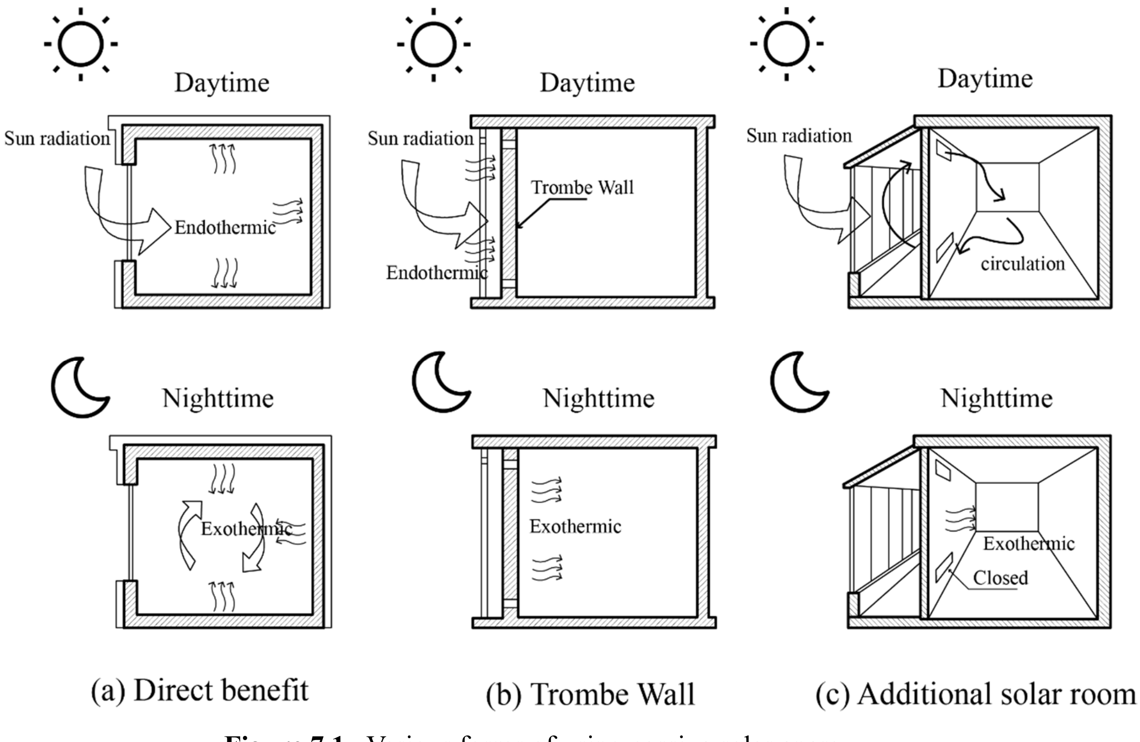

Figure 7.1. Various forms of using passive solar energy

Figure 7.1 shows the three primary forms of passive sunrooms are the direct benefit, the Trombe Wall and the additional sunroom [4]. The direct benefit type (a) is almost the same as the ordinary house and relies mainly on increasing the glass area to allow more solar radiation into the room. The Trombe

Wall type (b) is a composite wall formed by the layer of glass covering the surface of the wall and forming an air layer between them. The layer of air between the glass and the original wall raises its temperature through sunlight and prevents heat from escaping [5].

The additional sunroom type (c) is a mixture of the direct benefit type (a) and the Trombe Wall type (b). This passive solar measure has a sunroom on the south wall. It uses the floor and south wall surface in the sunroom to absorb solar radiation during the day and conduct heat to the interior through the opening ventilation on the south wall. All the ventilation are closed at night, and the south wall dissipates heat into the room. Because of the larger window area, the sunroom can achieve higher temperatures than the direct benefit type during the day. Even when the outdoor temperature is low, better thermal comfort can be completed in the sunroom. In addition, whether in the day or at night, the temperature inside the sunroom is higher than the outdoor temperature. The sunroom also serves as a certain amount of insulation [6].

In practical implementation, each passive-house has its specific boundary conditions, leading to different technical solutions to meet the requirements of the passive-house standard [7]. In the analysis of the results of the climatic suitability zone for sunroom construction, the eastern part of Shandong (including Qingdao) is a climatically suitable region for passive solar heating. Furthermore, in the Shandong area, although the Trombe Wall type achieves the highest indoor average temperature (compared to the direct benefit type and the additional sunroom type), it causes the most significant room temperature fluctuation. Because temperature fluctuation is a factor of great weight, the additional sunroom is suitable for the Shandong area [8]. Therefore, based on the renovation of the envelope in Chapter 6, the additional sunroom type is adopted in Chapter 7 to renovate the house further.

7.2.Description of sunroom

7.2.1.Plan layout

The scope of this additional sunroom is shown in Figure 7.2, with a T-shaped plan added to the renovation result in Chapter 6. The sunroom connects the main living space (north side) with the additional function room space (west side) for the following three main reasons:

(1) Respect the prototype. The rural houses in this study are mainly courtyard style. Demolition of buildings shall be avoided, and the local particular architectural layout shall be respected as far as possible. Most of the rural houses have only one floor. With the increase of economy and population, farmers' demand for space areas becomes larger. On the premise of not changing the number of floors and plane layout of the original building, a functional sunroom is selected. The original building had only about 40 m^2 of indoor use space. The addition of the sunroom has 26 m^2, a 65% increase in the area of usable space and allows for a greater variety of uses that were not previously available between the original indoor and the courtyard space.

(2) Functional perspective. The functional sunroom is larger than the ordinary one, suitable for rural houses and private courtyards. The depth of the sunroom near the auxiliary function room on the west side is 2.3 m. This part of the space can be used as a small dining room in combination with the adjacent kitchen and a leisure house, chess and card room. In winter, because the side room has a flat roof, its height is not greater than that of the sunroom. Sunlight can enter the sunroom through the roof. At this time, the side room will not block the sunroom. In coastal areas, under the condition of high solar radiation, the current transformation form can meet the needs of main activity rooms. At the same time, it is easier for residents to move between the living space and the additional function rooms in some bad weather. In summer, the sunroom can be equipped with a unique ventilation device and sunshade system to make it more functional, convenient, and practical.

(3) Energy-saving perspective. The building body coefficient is the ratio of the outer surface of the building in contact with the atmosphere to the volume enclosed by the atmosphere. The smaller the body coefficient, the smaller the outer surface area per unit of building area, and the smaller the heat transfer loss of the building [9]. The practice has proved that for every 10% increase in the body shape coefficient, the building energy consumption increases by 5%-10% [10]. Most of the rural houses in Qingdao are single-story houses with sloping roofs, which is not conducive to building energy-saving. Residents have adopted measures to reduce the building body coefficient, like the joint-row layout [11]. Furthermore, we reduce the building body coefficient by constructing the sunroom. Before adding the T-shaped sunroom, the body coefficient of the whole building was 1.07; after adding the sunroom, the body coefficient of the entire building became 0.84, a reduction of nearly 30%.

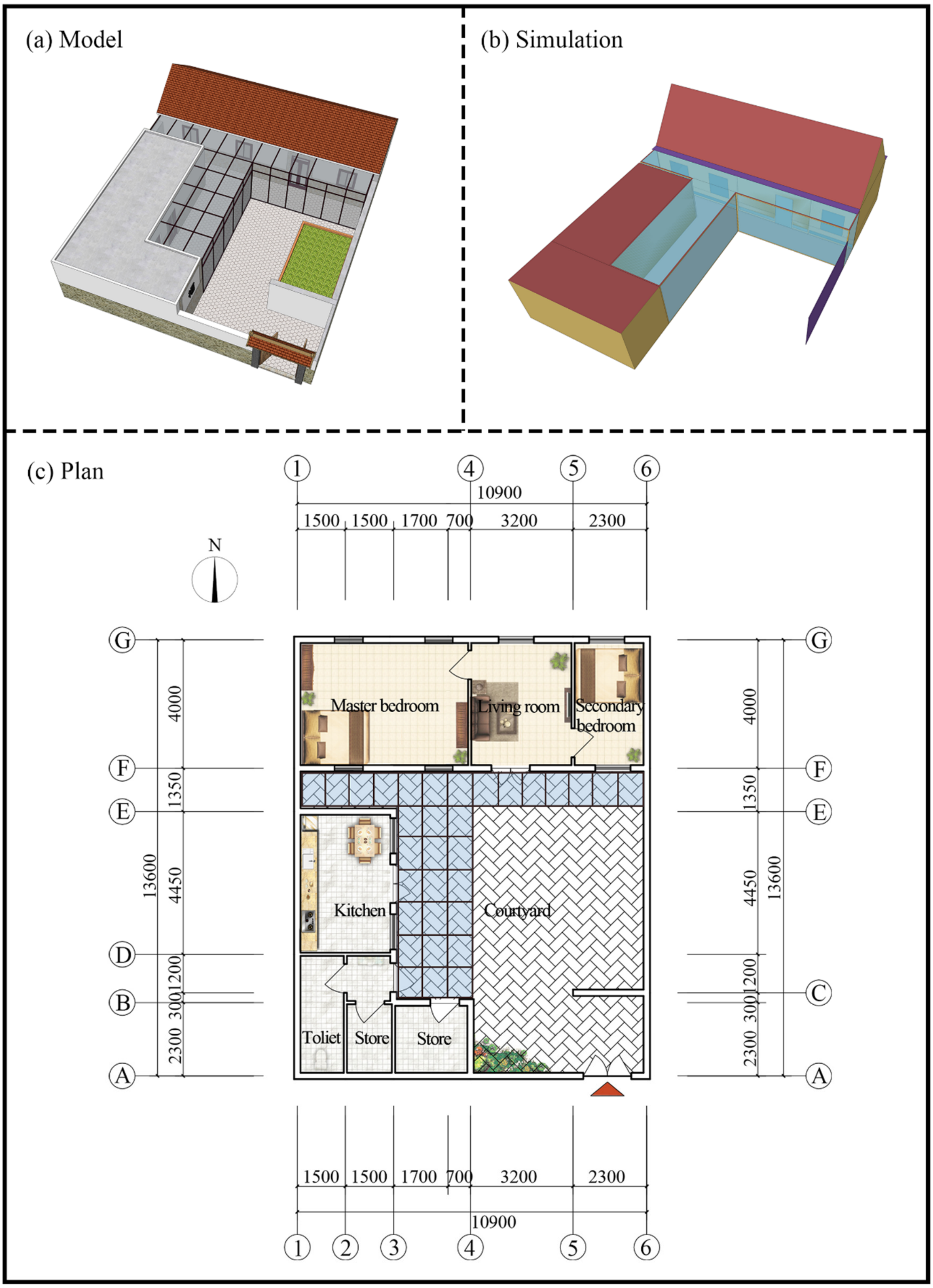

Figure 7.2. Renovation plan through the sunroom

According to the passive building design recommendations, the depth of the sunroom shall be in the range of 0.6-1.5m. From the perspective of energy-saving, the depth of the sunroom, which is used as a heat collecting component, shall be reduced to about 0.6m as far as possible without affecting the light transmission surface. However, to meet the functional requirements of cold areas, the depth is generally 0.9-1.5m [12]. Moreover, in our plane, the depth of the additional sunroom near the main living space is 1.35m fitting this range. The depth of the sunroom near the auxiliary function room on the west side is 2.3m, which is beyond this range but considering the overall reduction in the building body coefficient, which is still reasonable.

7.2.2.Materials

Koyunbaba et al. compared the energy performance of single glass, double glass and translucent photovoltaic modules used in Trombe Walls. The results show that double glass has higher thermal insulation properties, while single glass provides more heat for winter heating at night. Moreover, the air temperature in the ducts of the PV modules was lower than that of double glass and single glass [13]. Combining the results of the different glass simulations in Chapter 6, we finally used 9mm double glass as the glass material for the sunroom.

7.2.3.Ventilation openings

The thermal efficiency of the thermal storage wall is higher when two or three ventilations are at the top and bottom, respectively. Moreover, the thermal efficiency of the thermal storage wall will be higher if the ventilation area is 1% to 2% of the wall area [6].

The south wall of the master bedroom is 12 m^2, the total area of the ventilation should be between 0.12 m^2 - 0.24 m^2, and the area of the single ventilation is between 0.03 m^2 - 0.06 m^2. The size of the south wall of the living room is 10 m^2, the total area of the ventilation should be between 0.1 m^2 - 0.2 m^2, and the area of the single ventilation is between 0.025m^2 - 0.05 m^2. The area of the south wall of the secondary bedroom is 6 m^2, the total area of the ventilation should be between 0.06 m^2 - 0.12 m^2, and the area of the single ventilation is between 0.03 m^2 - 0.06 m^2. In order to facilitate the building renovation, the area of the single ventilation is taken as the intersection of the above areas, which is 0.04 m^2.

When the upper and lower centre distance of the ventilations is farther, the longer the heat exchange time between the air flowing through the outer surface of the sunroom and the heat storage wall, the more significant the temperature difference between the upper and lower ventilation of the heat storage wall, and the more significant the density difference, thus, the air velocity in the air interlayer will be more incredible. Therefore, increasing the centre distance between the upper and lower ventilation holes can improve the heat collection and storage wall [14].

Therefore, to ensure the heat gain efficiency of the sunroom, the space between the upper and lower Ventilation should be enlarged as much as possible. The specific way of opening the ventilation method in this sunroom is shown in Figure 7.3.

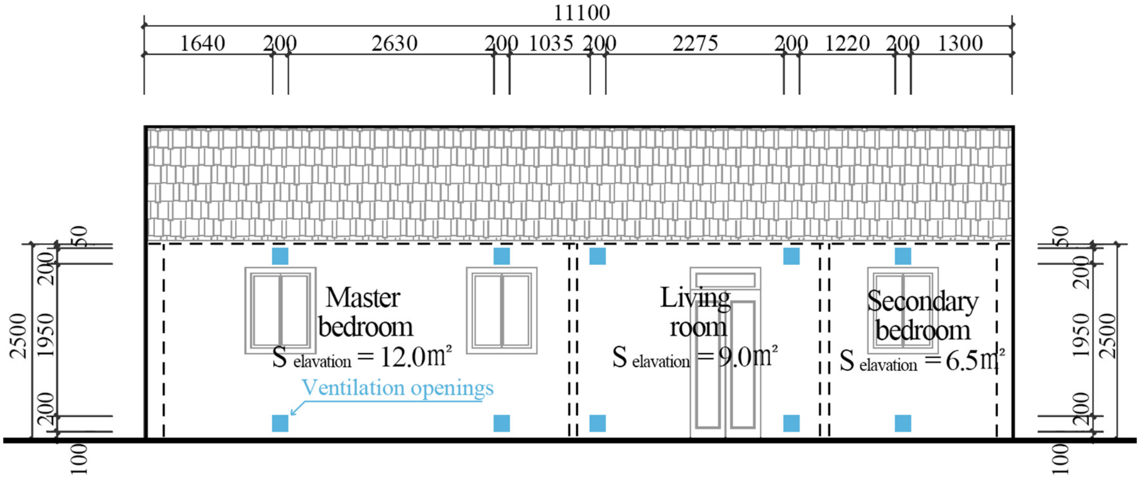

Figure 7.3. Sunroom ventilation locations and dimensions

Sunroom ventilation is opened two hours after sunrise and closed one hour before sunset, which is the most potent heat insulation type for the whole building [15]. Moreover, heat dissipation at night is necessary to release the excess heat gained by the sun during the day and keep the indoor air temperature at the required level [16]. So, the last opening time of ventilation is from 9:00 to 16:00 every day.

7.3.Numerical simulation and verification

7.3.1.Actual measurement data

The validated solar house room in this paper is located in Liudouhe Village, Bohai Town, Huairou, Beijing, and the building plan and model are shown in Figure 7.4 [17]. During the test, the sunroom was unoccupied. The indoor lighting and equipment were not turned on, and the building was set up with natural ventilation.

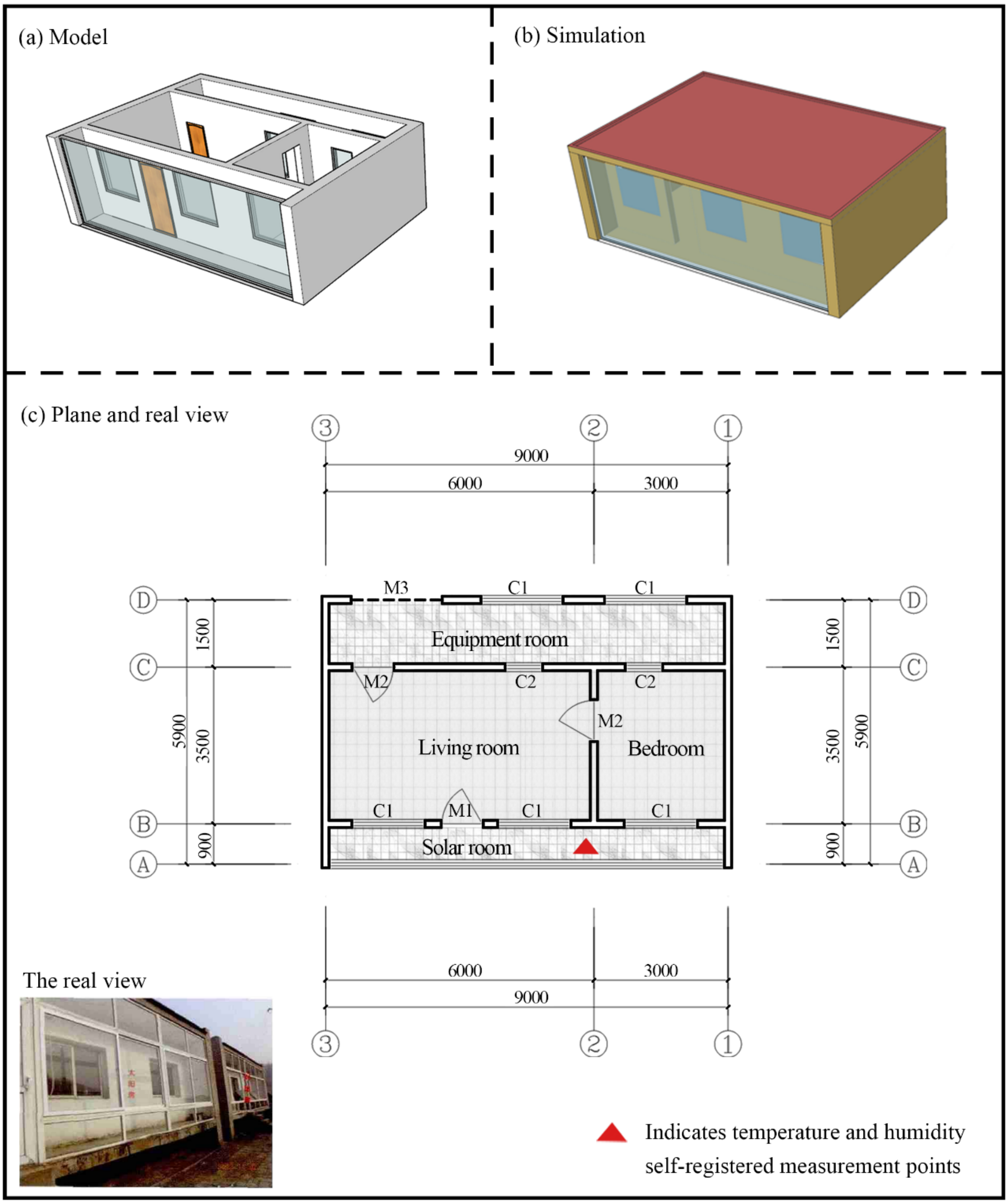

Figure 7.4. Simulation of validated sunroom plan and model

The original paper shows the material and heat transfer coefficients of the solar house in Table 7.1. The form of the solar house is a north-south single-storey residence. The lower part of the floor is supported by 50cm×50cm reinforced concrete columns with a floor height of 3m, and the construction area is 59.5 m^2. The south-facing glass window of the sunroom is 18.2 m^2, the size of window C1 is 1.5m×1.2m, window C2 is 0.8m×0.45m, and the heat transfer coefficients are 5. 70 W/(m^2·K). The door M1 and M3 are 1m×2m and 2m×2m, and M2 is 0.8m×1.9m, and the heat transfer coefficients are 5.70 W/(m^2·K). The south external wall is a 370mm brick wall with a heat transfer coefficient of 1.55 W/(m^2·K), and the rest of the external walls are 370mm brick walls plus 5cm extruded plastic board with a heat transfer coefficient of 0.4 W/(m^2·K); the interior walls are 240mm brick walls with a heat transfer coefficient of 1.73W/(m^2·K); the floor is a prestressed concrete hollow slab with a heat transfer coefficient of 3.16 W/(m^2·K); the roof is 12cm reinforced concrete plus 15cm of powdered polystyrene insulation and waterproofing layer with a heat transfer coefficient of 0.35W/(m^2·K).

Table.7.1. Size and type of components of the simulated house

Component name	**Window C1**	**Window C2**	**Door M1**	**Door M2**	**Door M3**
Size & Type	1.5m*1.2m	0.8m*0.45m	1m*2m	0.8m*1.9m	2m*2m
K（W/m²·K）	5.7	5.7	5.7	5.7	5.7
Component name	**External walls**	**South façade**	**Inner wall**	**Ground floor**	**Roof**
Size & Type	37 brick wall + 5cm extruded plastic panel	37 brick wall	24 brick wall	Prestressed concrete hollow core slabs	12cm reinforced concrete + 15cm of powdered polystyrene insulation + waterproofing layer
K（W/m²·K）	0.4	1.55	1.73	3.16	0.35

7.3.2.Experimental verification

The results of the original author's actual measurements, the original author's simulation results using DeST, and the consequences of our simulation using EnergyPlus to verify the accuracy of the results are compared in Figure 7.5.

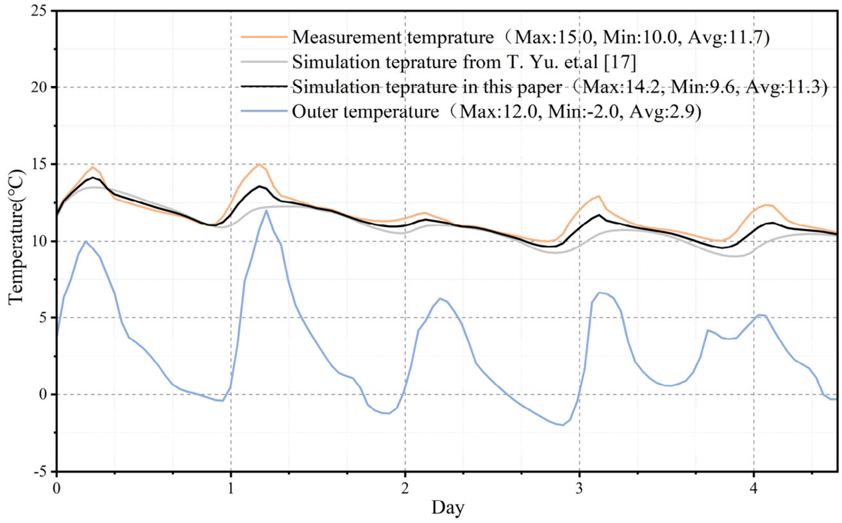

Figure 7.5. Comparison of simulated and measured temperatures

The results in Figure 7.5 show that the simulated temperature results agree with the measured data, with the average of the sunroom measurements being 11.7°C and the standard of the simulated sunroom temperatures being 11.3°C. The average difference between the simulated and measured temperatures is only 0.4°C, which is within an acceptable margin of error. Moreover, the fluctuating trend is the same, so the simulated data from EnergyPlus used in this paper is a good reference value.

7.4.Description of local climate

Qingdao is located in the southeastern part of the Shandong Peninsula in China, with cold winters and a maritime climate with humid air.

Figure 7.6 shows the daily temperature variation curve of the sunroom during a typical week. As the graph shows, the maximum outdoor temperature during a typical week (21 December to 27 December) was 5.2°C, the minimum temperature was -12°C, and the average temperature was -1.7°C. During a typical week (21 December to 27 December), the maximum sunroom temperature was 18.8°C, the minimum was temperature 4.0°C, and the average temperature was 10.2°C. Except for 22 December, the daily minimum temperature for one day was between 6 a.m. to 8 a.m., and the daily maximum temperature generally occurred between 1 p.m. to 3 p.m., with a slight temperature increase around 6 p.m. each day. In contrast, the trend of sunroom temperatures was similar to outdoor temperatures, with the average sunroom temperature being 11.9°C higher than the outside temperature.

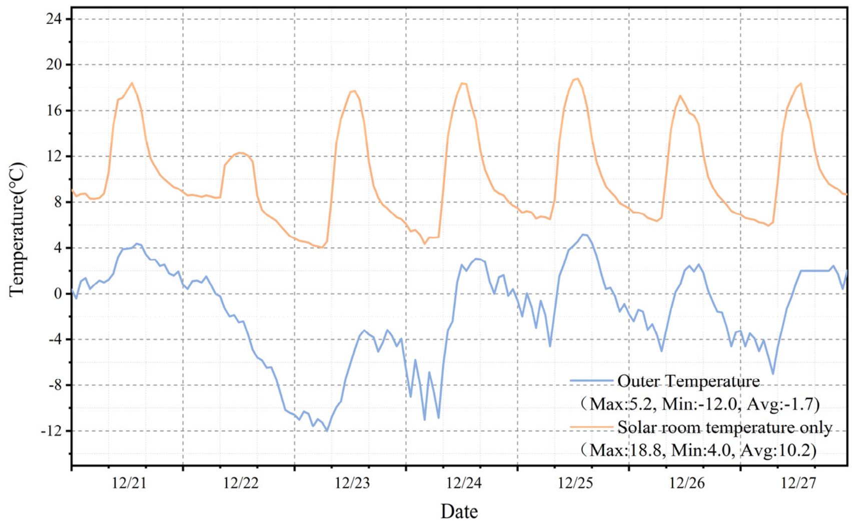

Figure 7.6. Variation curve of temperature in typical week

Figure 7.7 shows a monthly box plot of the winter temperatures in the sunroom and outside. Outside temperatures trend downwards in November, dropping to a low point in January and gradually increasing to March. The trend in sunroom temperatures is similar to that of the outside, but the sunroom is overall warmer than the outside. We can also see from the figure that the temperature change range of the sunroom is smaller than that of the outdoor environment, indicating that the sunroom has a particular anti-interference ability against changes in the outdoor environment temperature.

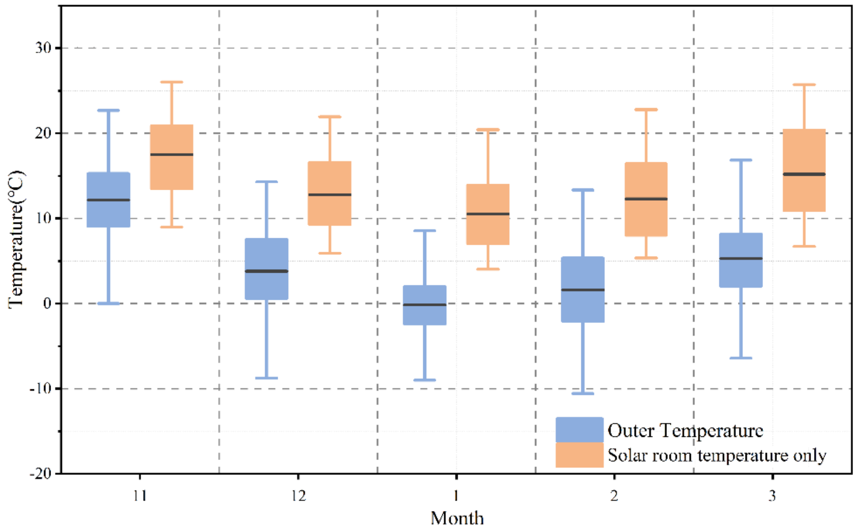

Figure 7.7. Monthly box plot of temperature in winter

Table 7.2 shows the statistics of the box plot diagram of the sunroom and outside throughout the winter. From the table, we can obtain the changes of temperature maximum, minimum and average values of the sunroom and outside. The highest outdoor temperature in November was 12.15℃ on average, while the average temperature in the sunroom was 20.98℃ in the same period, and the average temperature increased by 8.83℃, the lowest average outdoor temperature was -0.16℃ in January, and the average temperature in the sunroom was 15.51℃, and the average temperature increased by 15.67℃. Moreover, the average temperature increase inside the sunroom in other months (December, February and March) was 13.98℃, 15.67℃ and 14.89℃, respectively.

Table.7.2. Max. Min. and Avg. of temperature in winter

(℃) Month	Outdoor			Sunroom		
	Max	Min	Avg	Max	Min	Avg
Nov.	23.79	-0.42	12.15	30.34	13.95	20.98
Dec.	14.29	-8.75	3.79	26.94	10.92	17.77
Jan.	9.58	-12.00	-0.16	25.41	9.03	15.51
Feb.	13.33	-10.58	1.61	27.79	10.37	17.28
Mar.	19.42	-6.42	5.30	30.71	11.70	20.19

7.5.Numerical results and analysis

7.5.1.Indoor air temperature variation during the typical week

Figure 7.8 shows a comparison of the hour-by-hour temperature simulations for a typical week (21 December to 27 December) between the envelope renovation in Chapter 6 and the application of a sunroom based on the results of Chapter 6. The trend was the same for the house with and without the sunroom, in which the lowest temperature of the day generally occurring between 6 a.m. and 8 a.m., the highest temperature of the day generally occurring between 1 p.m. and 3 p.m. However, the overall temperature of application of the sunroom is higher than without the application of a sunroom, except during dramatic weather changes（22 December). With the application of a sunroom, the daily temperature fluctuations become even more significant, with a dramatic rise in temperature at noon, leading to a maximum temperature of almost 19°C. At night when the Ventilations are closed, the sunroom still has an insulating effect on the building, keeping the temperature higher than the renovation of the envelope only without application of the sunroom.

Among the three rooms (Living room, Master bedroom and Secondary bedroom), before the application of the sunroom, there was a big difference between their maximum temperatures, which were 16.1°C, 15.3°C and 16.0°C, respectively, with extreme contrast of 0.8°C. After the application of the sunroom, the maximum temperatures were 18.8°C, 18.8°C and 18.7°C, respectively, with a bit of difference of 0.1°C only. At noon, the sunroom raised the temperature in these three rooms to the same degree (18.8°C or 18.7°C). Similar to the maximum temperature change, the difference between the minimum temperature values has reduced, from 0.5°C to 0.3°C. The average temperature in the living room raised from 14.2°C to 15.6°C, an increase of 1.4°C; the average temperature in the master bedroom raised from 13.8°C to 15°C, an increase of 1.2°C; the average temperature in the secondary bedroom raised from 14.1°C to 15.6°C, an increase of 1.5°C. In short, the average temperature raised by 1.37°C.

7.5.2.ePMV variation during the typical week

Figure 7.9 shows the changes in ePMV before and after the renovation of the house by sunroom during a typical week. Because only summer in Qingdao is hot, while the other three seasons are not very hot. Moreover, the prevalence of air conditioners in rural areas of Qingdao is not very high, so the ep value is taken to be 0.9. From Figure 7.9, it can be seen that the application of the sunroom to the house can make the indoor environment, which was slightly colder before, become entirely suitable (in the range of -0.5 to 0.5). The situation is similar in the living room and secondary bedroom, where thermal comfort is achieved suitable when using a sunroom, while the average value of ePMV is -0.6 when only the external envelope is renovated, which is slightly colder. After using the sunroom, the overall average value of ePMV in the living room becomes -0.02, which is thermally suitable. The maximum value of ePMV is 0.42, and the minimum value is -0.4, which is in the comfort zone of thermal perception overall in the living room. With an overall average value of ePMV becoming -0.01, the secondary bedroom is thermally suitable, too. The secondary bedroom has a maximum value of 0.41 and a minimum of -0.34, all in the thermal comfort zone. The master bedroom, which did not reach the comfort zone when only the envelope was renovated, had a slightly mean average value of -0.96 ePMV. After the sunroom was used based on the renovation of the envelope, the overall ePMV became -0.16, and the maximum value of ePMV was 0.39, which satisfied the thermal comfort zone. Although the minimum value of -0.54 was slightly out of the thermal comfort zone, it was during the coldest hours of the morning on the coldest days (7 a.m. on 23 December and 7 a.m. on 24 December). In summary, the master bedroom was also in the thermal perception comfort zone overall.

7.5.3.Indoor air temperature variation during the winter.

Figure 7.10 shows the change in air temperature in the three rooms (living room, master bedroom and secondary bedroom) throughout the winter season for the two renovation options (renovation by the envelope only and renovation by sunroom and the envelope). The temperature fluctuations throughout the winter show that the two renovation plans for the three rooms are essentially the same for the five months, from November to March, starting with a decrease in November and then reaching a minimum in January. After January, the temperature begins to increase. When only the envelope was renovated, only in November and March did the average temperature in the room reach 16°C. With the application of the sunroom, the average monthly temperature in all three rooms of the simulated temperature was above 16°C, and the temperature with the application of the sunroom was approximately five degrees warmer than the temperature with the renovation of the envelope only. The average temperature in the living room and secondary bedroom is higher than in the master bedroom.

The temperature difference can be seen more concretely in Table 7.3. The living room with a sunroom based on the renovated envelope is 3.3°C warmer than the renovation of envelope only. The master bedroom with a sunroom based on the renovated envelope is on average 3.9°C warmer than the renovation of envelope only. The secondary bedroom with a sunroom based on the renovated envelope is 3.3°C warmer than the renovation of envelope only during the whole winter. The lower the temperature in the renovated envelope only room, the more significant the increase in temperature after adding the sunroom.

The difference in temperature between the living room and secondary bedroom is slight, with the most significant difference of 0.43°C and the slightest difference of only 0.01°C. Moreover, in terms of average temperature, both renovation of the envelope only and adding a sunroom based on the envelope increased by 3.3°C, thus the temperature changes in the living room and secondary bedroom much closer.

The differences between the temperature of the master bedroom and the living room (or secondary bedroom) are complex. Before the application of the sunroom, the maximum temperature of the living room was, on average, 1 °C warmer than the maximum temperature in the master bedroom. The maximum temperature of the secondary bedroom was 1.25°C warmer than the maximum temperature in the master bedroom; however, after the application of the sunroom, the maximum monthly average temperature in the master bedroom was 0.09°C and 0.12°C higher than that in the living room and secondary bedroom, respectively.

The difference in temperature between the monthly minimum values and the monthly average values also become smaller. The mean of the minimum temperature was 1.54°C and 1.49°C higher in the living room and secondary bedroom, respectively, than that in the master bedroom before the application of the sunroom. After applying the sunroom, the mean of the minimum temperatures was 0.44°C and 0.60°C higher in the living room and secondary bedroom, respectively, than that in the master bedroom before the application of the sunroom. The average monthly mean temperatures were 1.21°C and 1.36°C higher in the living room and secondary bedroom, respectively than in the master bedroom before the application of the sunroom. After applying the sunroom, the average of the minimum values was 0.56°C and 0.70°C higher in the living room and secondary bedroom, respectively, than in the Master bedroom before the application of the sunroom. As can be seen, the sunroom further increases the temperature of the space used indoors and reduces the difference in temperature between rooms, which means the higher the lift for the temperature of rooms with poorer original thermal performance.

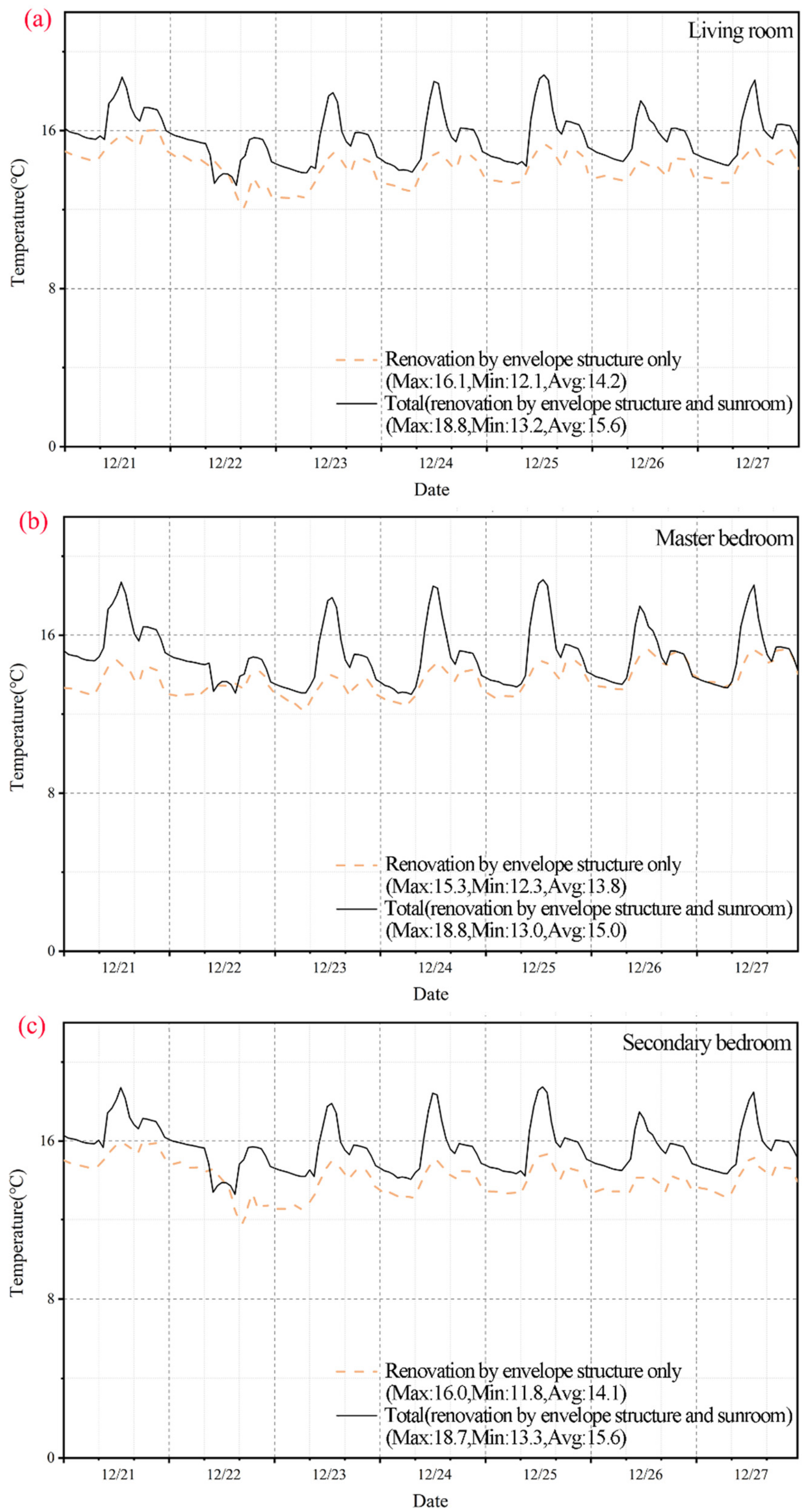

Figure 7.8. Daily variation curve of temperature in the typical week

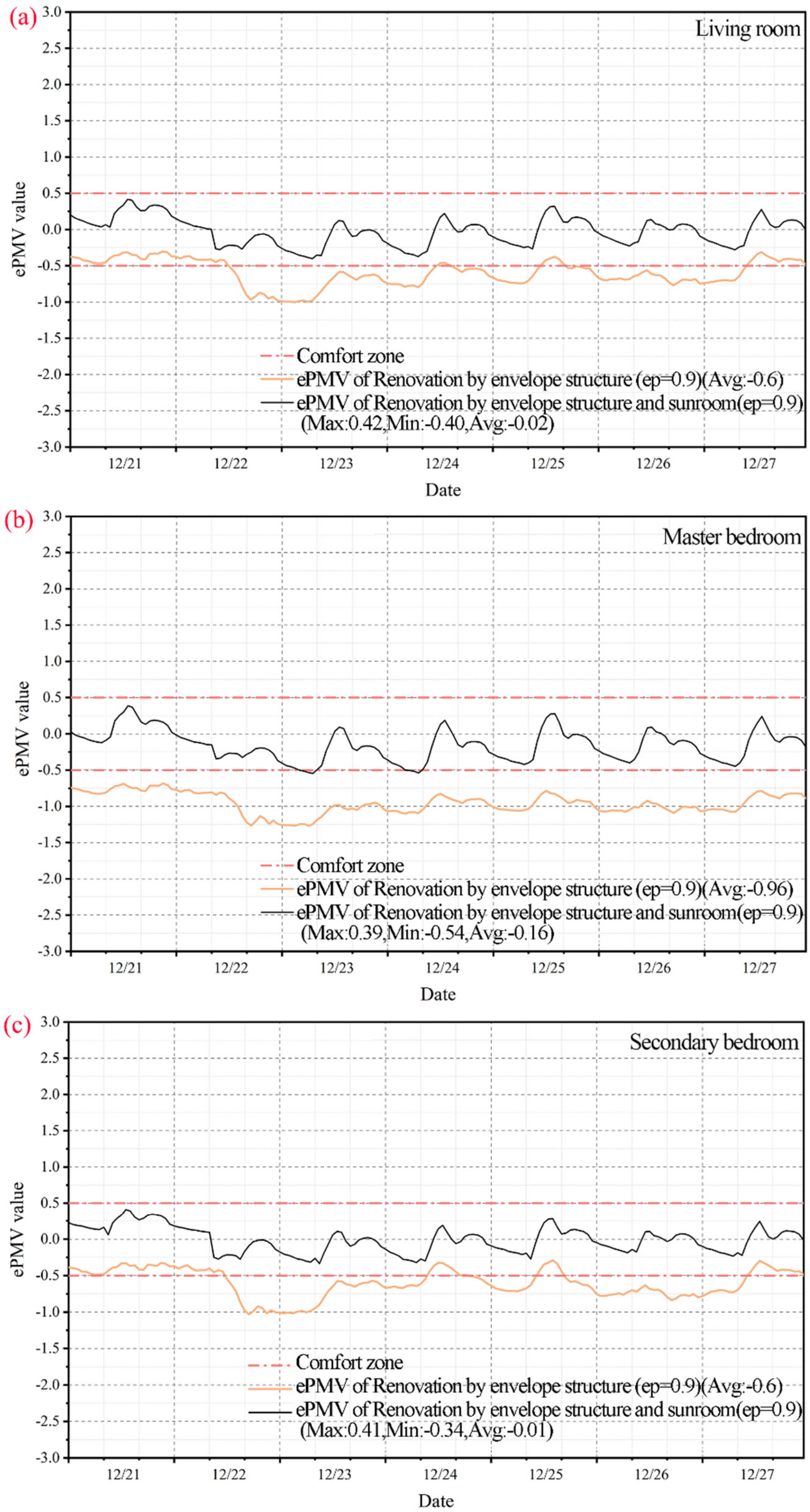

Figure 7.9. Daily variation curve of ePMV in the typical week

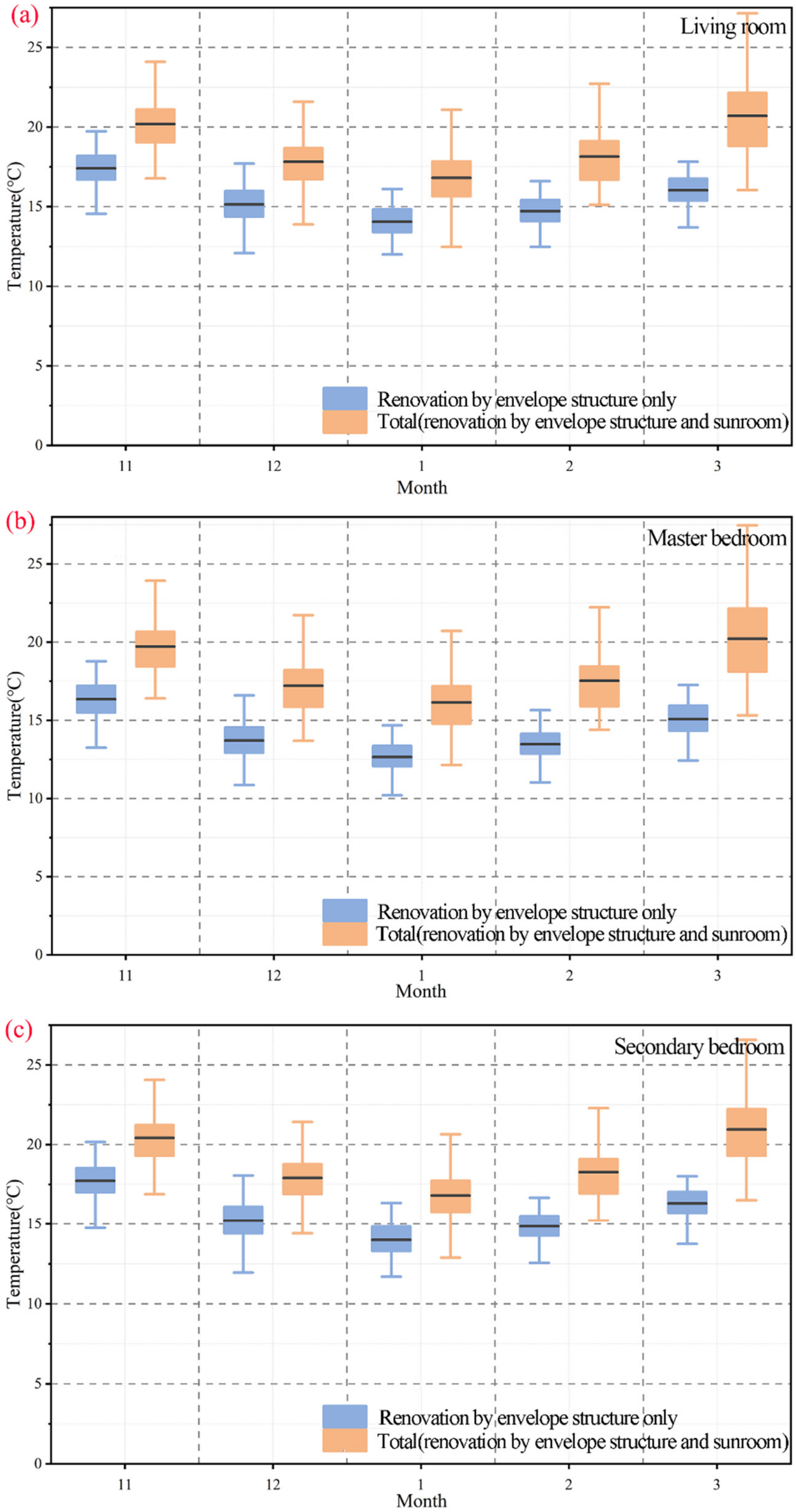

Figure 7.10. Monthly box plot of temperature in winter

Table.7.3. Comparison of monthly of temperature in winter between whether construction of the sunroom

Living room						
Month	**Renovation by envelope only**			**Renovation by envelope and sunroom**		
	Max	Min	Avg	Max	Min	Avg
Nov.	19.73	14.55	17.40	26.05	16.77	20.19
Dec.	17.70	12.08	15.13	22.87	13.88	17.82
Jan.	16.11	11.99	14.05	21.61	12.35	16.81
Feb.	16.59	12.48	14.71	23.79	15.11	18.14
Mar.	17.82	13.70	16.02	27.33	16.03	20.69

Master bedroom						
Month	**Renovation by envelope only**			**Renovation by envelope and sunroom**		
	Max	Min	Avg	Max	Min	Avg
Nov.	18.77	13.26	16.35	26.19	16.40	19.72
Dec.	16.59	10.14	13.71	22.92	13.69	17.21
Jan.	14.67	10.20	12.65	21.64	12.15	16.15
Feb.	15.64	11.03	13.47	23.87	14.39	17.54
Mar.	17.25	12.43	15.07	27.48	15.32	20.22

Secondary bedroom						
Month	**Renovation by envelope only**			**Renovation by envelope and sunroom**		
	Max	Min	Avg	Max	Min	Avg
Nov.	20.16	14.75	17.72	26.03	16.87	20.42
Dec.	18.06	11.79	15.20	22.86	13.96	17.90
Jan.	16.33	11.68	14.00	21.55	12.39	16.80
Feb.	16.65	12.55	14.85	23.75	15.22	18.27
Mar.	18.01	13.75	16.30	27.30	16.50	20.94

7.5.4.ePMV variation during the winter

Figure 7.11 shows the change in ePMV for the three rooms (living room, master bedroom and secondary bedroom) for the two renovation plans (renovation by the envelope only and adding a sunroom based on the renovation of the envelope) throughout the winter. The change in ePMV over the winter season shows that the trend in ePMV for the two renovation plans of the three rooms is essentially the same as is the temperature in winter. The living room is similar to the secondary bedroom, with an average ePMV in the thermal comfort range in November, December, February and March before the application of the sunroom, and slightly colder in January, after the application of the sunroom, the average ePMV is in the thermal comfort range in December, January and February, and warmer in November and March. Master bedroom average ePMV was in the thermal comfort range in November and March before the application of the sunroom, slightly more relaxed in December, January and February, after the application of the average sunroom, ePMV was in the thermal comfort range in December, January and February, warmer in November and March.

As shown in Table 7.4, the average ePMV for the coldest month (January) before adding the sunroom was -0.56, -0.96 and -0.59 for the living room, master bedroom and secondary bedroom, respectively, all of which were on the cold side. After adding the sunroom, the average ePMV in the coldest month (January) for the living room, master bedroom and secondary bedroom was -0.1, -0.23 and -0.1, respectively, achieving thermal comfort. The average maximum ePMV for the coldest months in the living room, master bedroom and secondary bedroom were 0.52, 0.49 and 0.5, respectively, within the thermal comfort range. However, the average minimum ePMV for the coldest month in the living room, master bedroom and secondary bedroom was -0.85, -0.94 and -0.88, respectively, which is still on the cold side.

In addition, the average ePMV for the living room, master bedroom and secondary bedroom in March before the application of the sunroom was -0.21, -0.49 and -0.15, respectively, all within the thermal comfort range. However, after adding the sunroom in March, the average ePMV for the living room, master bedroom and secondary bedroom were 0.69, 0.58 and 0.74, respectively, outside the thermal comfort range (-0.5 to 0.5) on the warm side. Even at midday, the average ePMV in the living room, master bedroom and secondary bedroom was 1.52, 1.51 and 1.53, respectively, outside the thermal comfort range (-0.5 to 0.5) with little hot. Overall, applying a sunroom increases the ePMV based on the renovation of the envelope by approximately 0.5 in value. In extreme cases, the application of sunroom can create a situation where the body's thermal perception goes from being on the cool side to being thermally comfortable or from being thermally comfortable to being a little warm.

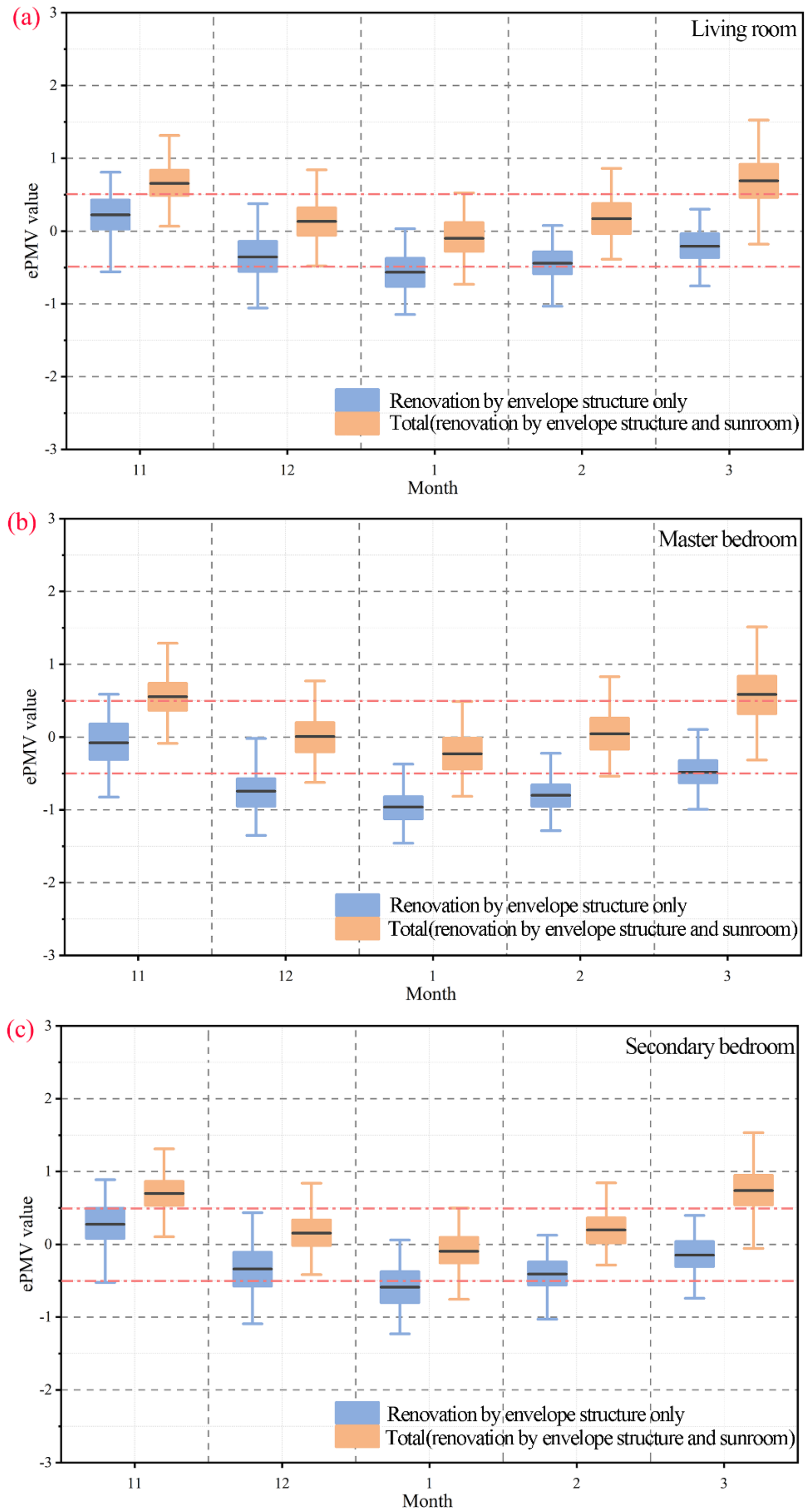

Figure 7.11. Monthly box plot of ePMV in winter

Table.7.4. Comparison of monthly box plot of ePMV in winter between whether construction of the sunroom

Living room						
ePMV	**Renovation by envelope only**			**Renovation by envelope and sunroom**		
Month	Max	Min	Avg	Max	Min	Avg
Nov.	0.81	-0.47	0.22	1.43	-0.06	0.66
Dec.	0.38	-0.94	-0.36	0.84	-0.6	0.13
Jan.	0.03	-1.03	-0.56	0.52	-0.85	-0.1
Feb.	0.08	-0.93	-0.44	0.86	-0.51	0.17
Mar.	0.3	-0.63	-0.21	1.52	-0.3	0.69

Master bedroom						
ePMV	**Renovation by envelope only**			**Renovation by envelope and sunroom**		
Month	Max	Min	Avg	Max	Min	Avg
Nov.	0.59	-0.7	-0.08	1.42	-0.21	0.55
Dec.	0	-1.23	-0.74	0.82	-0.74	0.01
Jan.	-0.35	-1.34	-0.96	0.49	-0.94	-0.23
Feb.	-0.22	-1.17	-0.8	0.83	-0.66	0.05
Mar.	0.1	-0.87	-0.49	1.51	-0.43	0.58

Secondary bedroom						
ePMV	**Renovation by envelope only**			**Renovation by envelope and sunroom**		
Month	Max	Min	Avg	Max	Min	Avg
Nov.	0.89	-0.44	0.27	1.44	-0.02	0.7
Dec.	0.43	-0.97	-0.34	0.84	-0.54	0.15
Jan.	0.06	-1.11	-0.59	0.5	-0.88	-0.1
Feb.	0.12	-0.91	-0.41	0.84	-0.4	0.2
Mar.	0.4	-0.62	-0.15	1.53	-0.18	0.74

7.6.Summary

This chapter uses the passive solar principle to add a sunroom based on Chapter 6. It uses Energy-Plus energy simulation software to simulate the indoor temperatures and ePMV in different residential spaces. Compare the obtained simulation results of the sunroom application based on Chapter 6 with the results of renovated envelope only in Chapter 6 and analyze the data results.

In terms of temperature changes over a typical week, the average temperatures in the living room, master bedroom and secondary bedroom increased by 1.4°C, 1.2°C and 1.5°C, respectively, after the application of the sunroom, which relied mainly on the midday period, as shown by the maximum temperature increases of 2.7°C, 3.5°C and 2.7°C, respectively, while the minimum temperatures only increased by 1.1°C, 0.7°C and 1.5 °C, respectively. The change in ePMV over a typical week shows that the ePMV in the living room, master bedroom and secondary bedroom reached thermal comfort from the original cooler side after applying the sunroom.

Regarding the temperature changes throughout the winter months, the average winter temperatures in the living room, master bedroom and secondary bedroom increased by 3.3°C, 3.9°C and 3.3°C, respectively, compared to the renovated envelope. After calculations before and after the application of the sunroom, the comprehensive improvement in building temperature over the entire winter range from November to March was 18.6%, and the building energy efficiency was satisfactory. The change in the indoor thermal environment before and after the application of the sunroom was assessed by changing ePMV values. The application of the sunroom in the coldest months allowed the thermal performance to reach the thermal comfort from the cooler side, and in November and March, the indoor thermal environment will change from thermally neutral to warmer.

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Chapter 8. Conclusions and prospects

8.1.Conclusions

The energy-saving design of buildings effectively reduces heating energy consumption, improves indoor environmental problems in rural areas, and plays an essential role in alleviating the increasingly severe environmental and energy problems. This study reviews the status of research on building energy-saving renovation and environmental improvement in various countries and summarizes their relevant research experiences. It also introduces the theories and methods of survey, experiment and numerical simulation to provide a theoretical basis for energy-saving renovation and environmental improvement of rural houses. This research is based on the coastal rural houses in Qingdao, and the problems of rural houses are identified through in-field investigation. Then, through experimental simulations, the application and efficiency of different straw materials in the thermal performance improvement of the envelope is explored. In addition, the renovation of rural houses in terms of energy-saving and environmental improvement is proposed from both the envelope renovation and sunroom design. The conclusions of this study are as follows.

In chapter one, **Background and Purpose of This Study**, global climate change and energy shortage have become hot issues worldwide. According to statistics, building energy consumption accounts for 36% of global energy consumption, and carbon emissions account for 39% of global carbon emissions. They are the main factors limiting global climate and energy issues. In both China and Qingdao, the building area of rural houses accounts for a large proportion, and traditional rural houses have high energy consumption and severe pollution in winter heating. In order to solve the above problems, solutions for energy-saving and environmental improvement of rural houses are proposed.

In chapter two, **Literature Review of Energy-saving and Environmental Improvement in Rural Houses**, the status of research on energy-saving and environmental improvement of rural houses in various countries is reviewed from three aspects: thermal comfort of rural houses, the air quality of rural houses, and energy-saving design of rural houses. Comparing the research on energy-saving and environmental improvement of rural houses in different countries and regions reveals that all countries have generally perfected their research in terms of theoretical research and evaluation systems. However, the existing research is primarily region-specific, with distinct regional characteristics and climatic features in practice.

In chapter three, **Methodology of In-site Survey, Experiments, and Simulations**, describes the methodology of field survey testing, thermal performance experiment of the envelope and numerical simulation of building a thermal environment of rural houses in Qingdao. The field survey methods include interviews, questionnaires and field tests. Data on indoor and outdoor temperature, relative humidity, indoor pollutant gases, envelope dimensions and other parameters were measured by these methods in a typical rural area of Qingdao, Shandong Province. SHB-HFM method combines the advantages of the most common methods, the guard hot box method (GHB) and the heat flow meter method (HFM). In the experiment, using this method to test the thermal conductivity of different materials saves costs and obtains accurate data, which has good results. This chapter also introduces the software and principles of building thermal environment simulation. In this paper, EnergyPlus uses the regional air heat capacity method for the air heat balance. In contrast, EnergyPlus uses the CTF (Conduction Transfer Function) method for solving the opaque enclosure heat transfer. Meanwhile, the parameters used in this paper for the evaluation of simulation experiments include temperature, ePMV.

In chapter four, **Status of Coastal Rural Houses and Indoor Environment in Qingdao**, this present study surveyed the thermal performance of building envelope, indoor thermal environment and air quality in the typical coastal villages of Qingdao during the heating period. The results of the study are as follows. (1) Over 90% of the buildings surveyed employed the coal-fired stove in the main room as the primary source of indoor heating. The thermal performance of the envelope does not comply with the relevant standards. (2) The neutral temperature and humidity of local residents were about 13°C and 40%, respectively, which were 2.18°C and 6.3% lower than that of volunteers. The average indoor air temperature and black bulb temperature of the rural buildings investigated were only 14.1℃ and 16.3℃, which are lower than the standard values of the indoor air temperatures during the heating period. (3) The average indoor odor experience scores were 1.1 (more than ″slight odor″) and 0.68 (between ″Neutral″ and ″Slight odor″) with and without the use of a stove in the main room, respectively, which indicated that employing a coal-fired stove for indoor heating is the primary source of indoor odor due to the combustion of coal. All the collected data show that the indoor CO_2, $PM_{1.0}$, $PM_{2.5}$ and PM_{10} of some coastal villages have very high results compared with the allowable concentration of IAQ standards.

In chapter five, **Thermal Performance Enhancement of Building Envelopes by Using Crop Straw**, five different straw materials filled with hollow bricks are selected for controlled tests to investigate the application and efficiency of different straw materials on the thermal performance improvement of envelopes. The original heat transfer coefficient of the hollow brick was 1.59(W/K·m^2). After filling with rice straw, reed leaves, wheat stem, reed stem and rice shell, the heat transfer coefficients of the hollow brick were 1.07(W/ K·m^2), 1.20(W/ K·m^2), 1.12(W/ K·m^2), 1.39(W/ K·m^2), 1.17(W K·m^2), reduced by 32%, 24%, 29.5%, 12%, 26%. The results of the experimental simulations show that the effect of rice straw on thermal performance is the best. The effect of the wheat stem is second. Through the second experiment, the heat transfer coefficient of straw is 0.073W/K·m, which is one-seventh of the heat transfer coefficient of the straw hollow bricks (0.32 W/K·m-0.46 W/K·m).

Using only straw is better than using straw bricks as a composite material for heat preservation, but the straw itself is too loose, and it is not as easy to construct as straw-filled bricks. So in practical applications, straw should be made into the straw board.

In chapter six, **The Energy-saving Improvement for The Rural Houses by Numerical Simulation**, considering various factors such as temperature and heating energy consumption, suitable and reasonable energy-saving renovation technical measures are proposed for three aspects of typical residential buildings: external walls, roofs and external windows. The EnergyPlus energy consumption simulation software was used to carry out univariate energy consumption simulations of the envelopes for rural houses, and case 2 was selected as the final renovation solution. The winter energy efficiency of the walls, roof and windows were 57.9%, 53.6% and 54.5%. Afterwards, the three selected renovation solutions for external walls, roofs and external windows were aggregated and evaluated comprehensively. The study results showed an increase in temperature change of 6.19℃ in the living room, 6.21℃ in the master bedroom and 6.79℃ in the second bedroom during a typical week. During the whole winter, the average winter temperatures in the living room, master bedroom and second bedroom increased by 4.77℃, 4.73℃ and 5.2℃. Finally, building energy consumption was calculated for a typical week and the whole winter season, resulting in a significant building energy efficiency of 79.5% and 83.6% before and after renovation.

In chapter seven, **Application of Sunroom to Improve Indoor Thermal Environment in Winter**, uses the passive solar principle to add a sunroom based on Chapter 6. It uses EnergyPlus energy simulation software to simulate the indoor temperatures and thermal comfort lines in different residential spaces. In terms of temperature changes over a typical week, the average temperatures in the living room, master bedroom and secondary bedroom increased by 1.4°C, 1.2°C and 1.5°C respectively after the addition of the sunroom. The change in e-PMV over a typical week shows that the e-PMV in the living room, master bedroom and secondary bedroom reached thermal comfort from the original cooler side after the addition of the sunroom. Compared to the previous renovation, the living room, master bedroom and second bedroom had an average temperature increase of 3.3°C, 3.9°C and 3.3°C during the entire winter. The addition of the sunroom resulted in a combined increase in building temperature of 18.6% from November to March, while the energy efficiency of the building remained fine.

8.2.Prospects

This research focuses on the energy-saving renovation and environmental improvement of coastal rural houses in Qingdao, which is of great significance for the future development of energy-saving rural houses in cold northern regions. Due to the limited space and time available for writing the thesis, there are still many aspects of the article that need to be studied in-depth and in detail, extrapolated and tested in practical engineering. The study of residential energy-saving has a certain complexity, so the research needs to be further improved and can be carried out in the future from the following aspects.

(1) Due to the extensive geographical area of the cold northern region and the fact that the actual research scope is limited to the coastal rural area of Qingdao, the number of sample villages is not comprehensive enough to reflect the whole situation of coastal rural houses in the cold region. In the future, we will consider further expanding the survey scope and adding new villages for research to enrich and update the primary data and improve the accuracy and scientificity of the research results.

(2) This research focuses on comparing the renovated rural houses with the original houses through software simulation analysis. The results show that the renovated rural houses show significant improvements in temperature and energy consumption. However, the renovated houses were only simulated by software data and were not applied in practice. In future work, it is hoped that the results of the theoretical research and analysis can be applied to practical projects, where their efficiency can be further verified, and the technology of energy efficiency in rural houses can then be promoted.

(3) This research has explored the possibilities of straw materials for building insulation applications, expanding the uses of straw materials. However, due to the complexity of straw performance and production technology, it is hoped that future simulations of straw material insulation performance can be further refined to investigate the relationship between straw insulation efficiency and density and other elements, which will expand the application of straw materials for building construction.