DOCTORAL DISSERTATION

Empirical Study on Energy Saving and Thermal Environment Improvement of Existing Residential Buildings After Interior Insulation Retrofit in Chengdu, China

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ABSTRACT

The indoor thermal environment in the hot summer and cold winter (HSCW) region is the worst among the five climate zones in China. Increased demand for indoor thermal environments has led to rapid growth in air conditioning energy consumption, placing significant pressure on the energy efficiency of buildings in the area. Residences in the region are mainly externally insulated and do not perform well in the local pattern of intermittent use of air conditioning in individual rooms. This study proposes that interior insulation is more suitable for such a pattern of air conditioning use. A high-rise residential unit in Chengdu, a typical city in the HSCW region, was selected for the interior insulation retrofit of bedrooms. Comparative experiments were performed during the cooling and heating seasons to quantify the improvement in air conditioning energy consumption and the indoor thermal environment of the retrofitted residence.

Chapter 1, Research Background and Purpose of The Study. International, domestic, and regional background research was conducted to clarify the research background. After that, the definition of interior insulation, the purpose and framework of this study, and its innovation were presented.

Chapter 2, Literature Review. Firstly, the climate and energy use characteristics of the HSCW region (including Chengdu), the physical and indoor environment characteristics of existing residential buildings, and the air-conditioning usage patterns were summarized and presented. Secondly, the building energy codes for residential buildings in this region were collated and shown. Finally, common measures to improve the insulation performance of the existing building envelope were summarized and analyzed. The above literature review showed that interior insulation is a more appropriate approach under the climatic and air-conditioning usage patterns of the HSCW region.

Chapter 3, Research Method. This chapter includes the framework of the research methodology, the description of the selected case study building, the renovation process and the construction of the building envelope, and the description of the experimental conditions.

Chapter 4, Improvements After Interior Insulation Retrofit Under Intermittent Cooling Condition. Under three typical local intermittent cooling modes, actual measurements were conducted in experimental and comparison residences in the summer of 2019. Intermittent cooling comparison experiments were carried out on eight of the hottest days and the main findings are as follows. Firstly, the retrofitted south bedroom showed a good energy-saving effect. The average daily energy-saving rate was 42.09% and the highest daily energy-saving rate was 48.91%. Secondly, compared to the original south bedroom, the renovated one exhibited the following characteristics of the indoor thermal environment when cooling the space. Overall, the indoor temperature was more stable and closer to the setpoint (26 °C). Horizontally, the temperature difference between the indoor temperature and the inner surface of the external wall was much smaller. Vertically, the indoor temperature was more concentrated after the retrofit. Besides, indoor relative humidity was higher and much more stable after the retrofit.

Chapter 5, Improvements After Interior Insulation Retrofit Under Intermittent Heating Condition. Under three typical local intermittent heating models were measured in the winter of 2020 in experimental and comparison homes. The intermittent heating comparison experiment was carried out on 10 of the coldest days and the main findings are as follows. Firstly, the retrofitted room showed a good energy-saving effect. The average daily energy-saving ratio was 41.58%, with a maximum energy savings of 55.53%. Secondly, compared to the original south bedroom, the renovated one exhibited the following characteristics of the indoor thermal environment when heating the space. When the heating temperature was 24 °C, the overall average indoor temperature was 0.7 °C higher after the retrofit. The indoor temperature was well controlled at 1.1 m and 2.7 m but showed a greater range of fluctuations. Besides, indoor relative humidity was lower and fluctuated more after the retrofit.

Chapter 6, Impact of Orientation and Set Temperature on Energy Consumption and Indoor Thermal Environment. In the first part, intermittent cooling experiments in 2019 were carried out in both the north and south bedrooms and the results of the comparison experiments were shown below. The retrofitted south bedroom outperformed the north bedroom in terms of both energy-saving rate and indoor thermal environment, with the average daily energy-saving rate was 28% in the retrofitted north bedroom compared to 41% in the south bedroom. In terms of the temperature difference between the inner surface of the external walls and the indoor temperature, the vertical indoor temperature difference, and the range of temperature fluctuations, the south bedroom was significantly smaller than the north one. In the second part, in the intermittent heating experiment of 2020, three days with the same operating mode were selected to compare the impact of setpoint temperature on the retrofit effect. The results showed that a 2 °C difference in set temperature had a less noticeable effect on energy consumption and indoor temperature.

Chapter 7, Conclusion. The results of every chapter were summarized, and the contribution of this research was presented.

Keywords: interior insulation retrofit; intermittent air conditioning operation; air conditioning load; indoor thermal environment; real-life scenario measurements

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RESEARCH BACKGROUND AND PURPOSE OF THE STUDY

CHAPTER ONE: RESEARCH BACKGROUND AND PURPOSE OF THE STUDY

1.1 Research background

1.1.1 International background

No region of the globe is isolated from the effects of global warming. It is estimated that in the future a rising probability of overheated days and a declining probability of overcooled days will be expected [1]. At least for one season, between one-fifth and two-fifths of the world's population has experienced a warming of more than 1.5 °C [2], as shown in Figure 1-1. Without timely action, it is estimated that by 2050 global average temperatures will rise by 1.7 °C to 2.4 °C above pre-industrial levels [3]. Moreover, the IPCC report shows that global warming of more than 1.5 °C would cause irreversible damage to ecosystems and lead to a huge crisis for vulnerable people and societies [2]. However, limiting global temperature rise to less than 1.5 °C requires an unprecedented global effort and will be more difficult than limiting it to less than 2 °C. Only if we take urgent mitigation action across all sectors right now, will it be possible to curb such a situation [4].

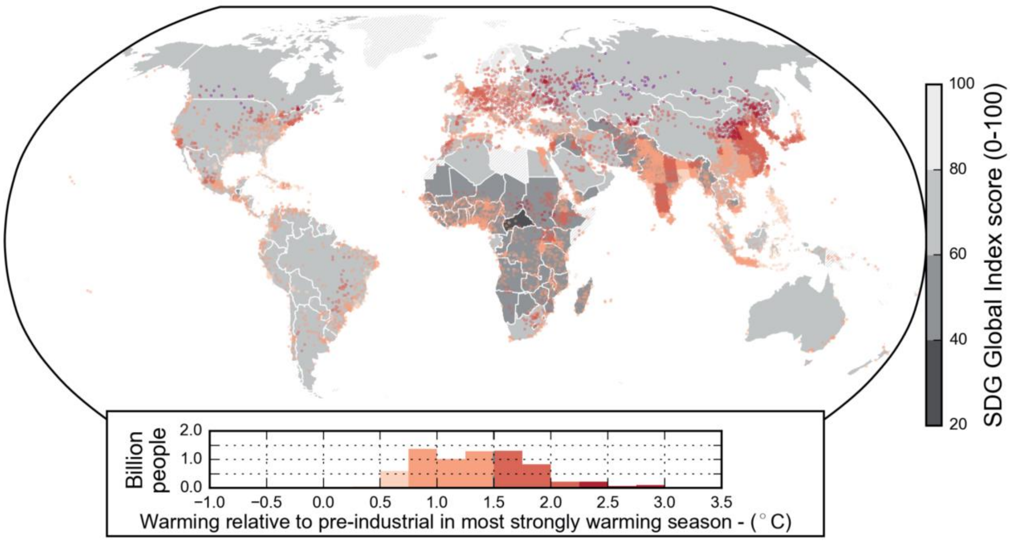

Figure 1-1. Human experience of present-day warming [2]**.**

(Source: IPCC, 2018: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. In Press.)

Of the factors influencing climate, human activity is the dominant one. Rapid global economic growth around the world has caused a dramatic increase in energy consumption. Although all major sectors of the economy saw growth in energy consumption, industry and buildings were responsible for 75% of energy demand growth, as shown in Figure 1-2. Besides, the rate of growth in energy consumption varies by country and region. In the reference case, the majority of the increase in world energy consumption from 2015 to 2040 took place in non-OECD countries. During this period, energy consumption in non-OECD countries increased by 41%, far exceeding the 9% of OECD countries [5], as shown in Figure 1-3.

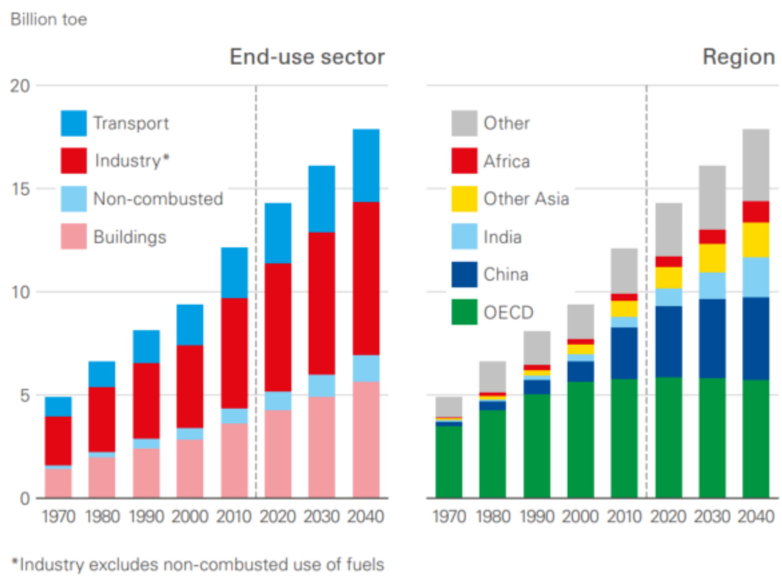

Figure 1-2. Primary energy demand [6]**.**

(Source: Dudley B. BP energy outlook. Report–BP Energy Econ UK 2019;9.)

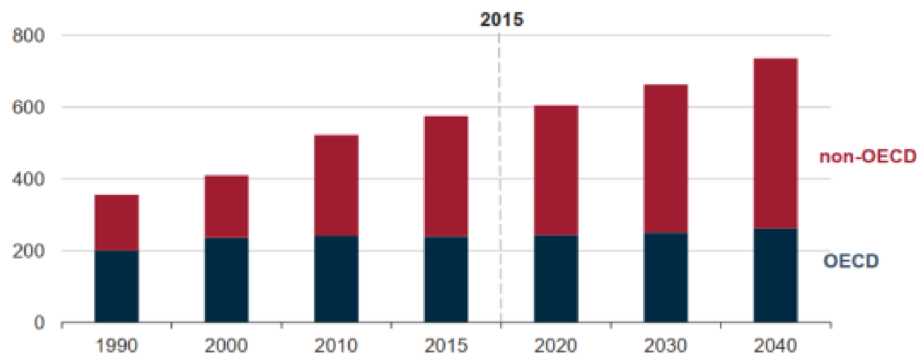

Figure 1-3. World energy consumption [5]**.**

(Source: US Energy Information Administration (EIA). International Energy Outlook 2017 Overview. Int Energy Outlook 2017 2017; IEO2017:143.)

In fact, more than four-fifths of world output growth is contributed by developing economies. It is indicated from Figure 1-4 that China and India, in particular, contributed significantly to the growth in energy demand, accounting for about 50% of that growth [6]. In the context of global warming, it is estimated that demand for air conditioners in developing economies will expand further in line with potential local income and population growth. Africa is predicted to host 34% of the world's new population by 2030, and Asia's share is a staggering 52% [7].

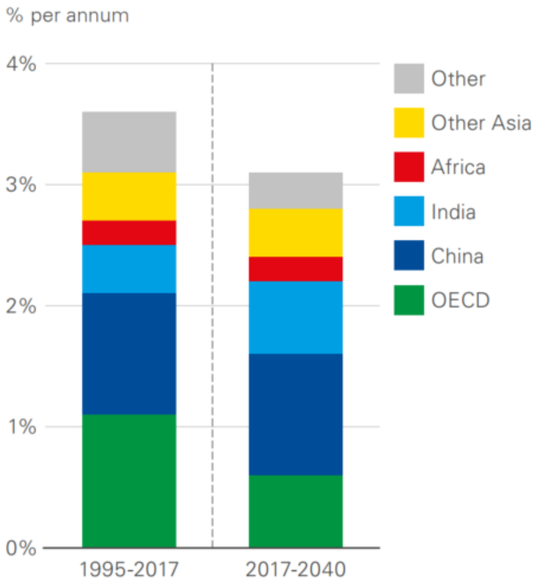

Figure 1-4. Global GDP growth and regional contributions [6]**.**

(Source: Dudley B. BP energy outlook. Report–BP Energy Econ UK 2019;9.)

As the world's economic and population growth becomes increasingly concentrated in hotter countries, the rate of growth in global energy consumption for space cooling needs will continue to increase. In recent years, global energy consumption for space cooling needs has grown faster than in other parts of the building sector. Currently, out of the total electricity used for cooling in buildings worldwide, air conditioners and fans consume almost 20% of that [8]. Globally, annual sales of air conditioners in 2016 almost quadrupled based on 1990 [9]. By the end of 2016, two countries accounted for more than half of the 1.6 billion air conditioners in use worldwide. They are China and the United States, occupying 570 million units and 375 million units respectively, as shown in Figure 1-5 [9]. Within this, residential air conditioners account for the vast majority. In China, for example, residential air conditioners are responsible for more than 30% of the annual electricity consumption of the peak summer electricity demand in major and medium-sized cities [10]. Therefore, it would be significant to control the energy use of residential air conditioners in China to help mitigate the overall trend of global warming.

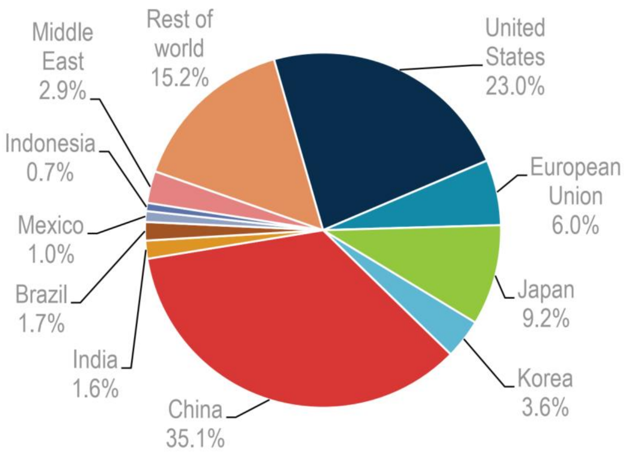

Figure 1-5. Stock of ACs by country/region and type, end 2016 [9]**.**

(Source: The Future of Cooling. Futur Cool 2018. https://doi.org/10.1787/9789264301993-en.)

1.1.2 Domestic background

Over the past century, China's annual average temperature rise has exceeded the global average, according to the Third National Climate Change Assessment Report [11]. As one of the largest emerging economies in Asia, China faces great pressure to save energy and reduce emissions in the building sector. From 2001 to 2016, the percentage of China's population living in cities increased from 37.7% to 57.3% (793 million), as shown in Figure 1-6. Moreover, it is estimated that the rate of urbanization will reach 70% by 2030 [12].

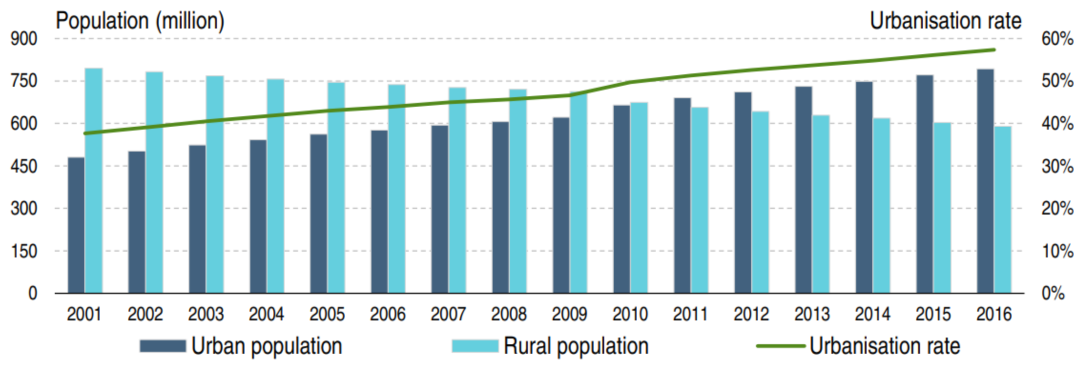

Figure 1-6. Population and urbanisation growth in China (2001-2016) [12]**.**

(Source: Jiang Y, Yan D, Guo S, Hu S. China Building Energy Use 2018. 2018.)

In China, the overall floor area of the existing buildings was already over 56 billion square meters in 2017 [13]. And it is expected to grow dramatically to approximately 78 billion square meters by 2050 [14]. At the same time, there are a large number of low-energy buildings in China's urban housing stock, especially those built before the year 2000 [15]. Of China's urban residential buildings, more than 90% exhibit poor energy performance [16]. Retrofitting existing buildings is an important strategy to improve energy efficiency and significantly reduce energy consumption in the building sector [17].

1.1.3 Regional background

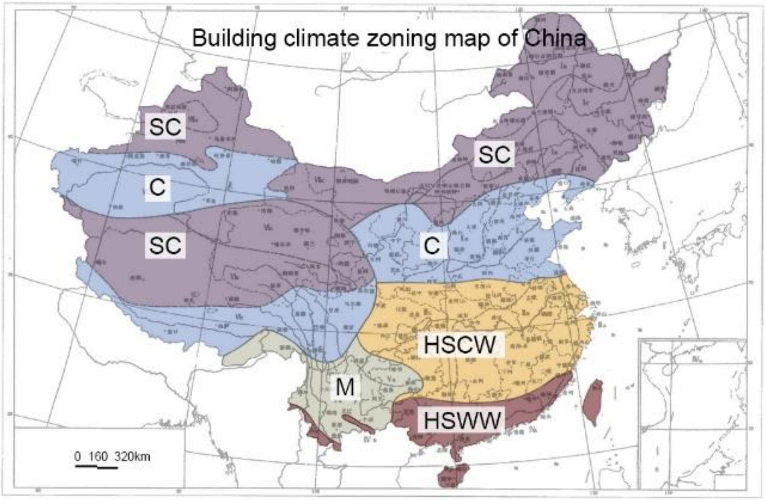

Figure 1-7. Building climate zoning map of China.

(Source: MOHURD. Thermal design code for civil building (GB 50176-2016). Beijing: China Architecture & Building Press; 2016)

If the region in which the building is located is not taken into consideration, all discussion on building energy efficiency is meaningless. For a country as large as China, it is hardly surprising that there are distinct differences between regions in various aspects: such as climate characteristics, degree of economic growth, population density, resource availability, and energy consumption, etc. [18]. To make better use of and adapt buildings to the varying climate situations in China, the whole country is divided into five climatic zones, namely "the severe cold (SC) zone", "the cold (C) zone", "the hot summer and cold winter (HSCW) zone", "the hot summer and warm winter (HSWW) zone" and "the mild (M) zone" [19], as shown in Figure 1-7. According to Thermal Design Code for Civil Building GB50176-2016, the main and auxiliary indicators and design criteria on which the zoning of each climate zone are shown in Table 1-1.

Table 1-1. Building thermal design first-class zoning index and design principles.

(Source: Ministry of Housing and Urban-Rural Development of the People's Republic of China, Thermal design Code for Civil Building GB50176-2016, China Architecture and Building Press, Beijing, 2016 (In Chinese))

First-class zoning name	Zoning Indicators		Design Principles
	Main indicators	Auxiliary indicators	
The severe cold zone (1)	$t_{min \cdot m} \leq -10$ ℃	$145 \leq d_{\leq 5}$	Must fully meet the winter insulation requirements, generally could not consider the summer heat protection
The cold zone (2)	-10℃ $< t_{min \cdot m} \leq 0$ ℃	$90 \leq d_{\leq 5} < 145$	Should meet the winter insulation requirements, part of the region should consider the summer heat protection
The hot summer and cold winter zone (3)	0 ℃ $< t_{min \cdot m} \leq 10$ ℃ 25 ℃ $< t_{max \cdot m} \leq 30$ ℃	$0 \leq d_{\leq 5} < 90$ $40 \leq d_{\geq 25} < 110$	Must meet the summer heat protection requirements, appropriately consider the winter insulation
The hot summer and warm winter zone (4)	10 ℃ $< t_{min \cdot m}$ 25 ℃ $< t_{max \cdot m} \leq 29$ ℃	$100 \leq d_{\geq 25} < 200$	Must fully meet the summer heat protection requirements, generally could not consider the winter insulation
The mild zone (5)	0 ℃ $< t_{min \cdot m} \leq 13$ ℃ 18 ℃ $< t_{max \cdot m} \leq 25$ ℃	$0 \leq d_{\leq 5} < 90$	Some areas should consider winter insulation, generally could not consider the summer heat protection

In Table 1-1, $t_{min \cdot m}$ represents the average temperature of the coldest month, $t_{max \cdot m}$ represents the average temperature of the hottest month, $d_{\leq 5}$ represents the number of days with an average daily temperature ≤5 ℃, $d_{\geq 25}$ represents the number of days with average daily temperature ≥ 25 ℃.

Among these five climate zones in China, the HSCW zone is very special for the following reasons. More than 40% of the country's population lives in this region, but it occupies less than 20% of the country's total area [20]. Figure 1-8 provides strong evidential support for population density, it shows the population density of each province in China of 2015. The darker the color of the map, the higher the population density. It can be observed that the provinces in the HSCW zone are generally darker than other zones, such as Sichuan, Anhui, Hunan, and Zhejiang, which implies a higher population density in the region. In addition, the region's economy is growing faster than other regions, accounting for approximately 48% of the country's GDP [21].

Figure 1-8. China's provinces by population density and main regions in 2015 [18]**.**

(Source: Agency IE. World Energy Outlook-2017 2017.)

However, in such a densely populated and economically developed region, the indoor environment is the worst of the five climate zones in China [22]. People's demand for an indoor environment has increased with the economic level. This has led directly to a rapid increase in energy consumption for cooling and heating in this region. Due to strong dependence on air conditioning under such high population density, the HSCW region has the highest number of air conditioners in urban households of China, as shown in Figure 1-9. Take Chengdu city as an example, the number of air conditioners owned per 100 households in 2015 ranged from 100 to 150 [8]. This means that each household has an average of 1 to 1.5 air conditioners.

Figure 1-9. Regional AC units owned per 100 urban households (2015) [8]**.**

(Source: Hu, S., Yan, D., & Qian, M. (2019). Using bottom-up model to analyze cooling energy consumption in China's urban residential building. Energy and Buildings, 202, 109352.)

There is no doubt that the HSCW region will face enormous challenges based on the high population density and harsh climatic conditions. The energy demand is also increasing during rapid urbanization, which is contrary to China's current energy saving policy. Therefore, how to improve the indoor comfort of homes in the HSCW region with limited energy consumption becomes a key issue for this country.

1.2 Relative Definition

1.2.1 Interior insulation

In the existing studies on building envelope optimization, most of them focus on the insulation of the building envelope/wall, such as outside insulation or inside insulation. As these insulation methods do not take into account the insulation of the internal envelope, they are not optimal in Chengdu's intermittent, part-room air-conditioning patterns. Based on our previous simulation studies, interior insulation proved to be a better option for this region [23]. To avoid confusion with the conventional exterior wall insulation methods, the definition of it needs to be explained. In this research, interior insulation means to place insulation on all the opaque structural surfaces inside a building or space [23].

To make it clearer, the comparison of these three insulation methods mentioned above are compared in Table 1-2.

Table 1-2. Comparison of the three insulation types.

Location of Insulation	Outside Insulation	Inside Insulation	Interior Insulation
Exterior surface of the outside wall	√	×	√
Interior surface of the outside wall	×	√	√
Surface of interior wall	×	×	√
Ceilings	×	×	√
Floors	×	×	√

1.3 Present research situation on building retrofit worldwide

Retrofitting existing buildings was demonstrated to be an effective way to reduce worldwide greenhouse gas emissions and energy consumption. The International Energy Agency reports that approximately 30% of global carbon emissions are contributed by the building sector. In addition, the building sector consumes over 30% of total global energy consumption [24]. Compared to existing buildings, new construction makes up only a small amount of the sum of the buildings built each year. Improving the energy efficiency of existing buildings is therefore essential to achieving sustainable development goals [25].

Sustainable retrofitting of residential buildings has attracted a considerable amount of attention in the field of architectural research. This is because residential buildings are responsible for 60% of carbon emissions and 70% of energy consumption, respectively, in the global scope of construction [26]. Retrofitting is an important means of improving indoor comfort when the building is in use and effectively reducing energy consumption. Also, it is a very effective way to achieve a country's energy saving and emission reduction goals.

1.3.1 Foreign research situation

In the European Union (EU), buildings take up 40% of final energy and 36% of CO2 emissions respectively, showing a huge energy saving potential [27]. Since the energy crisis of the 1970s, promoting the efficient use of energy in the building sector has received widespread attention and is an important policy objective for EU member states. The European commission has enacted several energy-efficiency standards. Of these, the Energy Performance of Buildings Directive (EPBD) is of great importance, as is the Energy Efficiency Directive (EDD) [28]. According to the European Commission, by implementing these directives, the heating and cooling energy demand of buildings are to be reduced by approximately 17% from 2005 levels by 2050 [29]. Meanwhile, upgrading existing buildings to meet the minimum energy performance required in each Member State is also advocated by the EPBD [30]. The EBPD considers that opportunities to reduce energy consumption arise when buildings require major renovation [31].

Besides, the United States (US) has also supported the renovation of existing buildings with considerable financial assistance. Also, in order to achieve commercial near-zero energy buildings by 2050, the US adopted the Energy Independence and Security Act in the year of 2007 [32]. In the case of the Kingdom of Saudi Arabia, more than two-thirds of the total electricity consumption is consumed by the building sector. As a result, the Kingdom government has been focusing on the residential sector as the main target of its energy efficiency efforts. Since 2009, the Saudi Energy Conservation Law has been a mandatory code for government buildings. The following year, insulation standards were required in all new-built buildings [33].

In addition to mandatory regulations and incentives at the government level, many other factors need to be considered for the energy efficiency optimization of existing buildings. For example, the public's willingness to pay for retrofits and the alignment of tenant and landlord interests. In the research by Agnieszka Zalejska-Jonsson (2014) [34], people in Sweden are more willing to pay for very low-energy buildings than for buildings with environmental credentials. Furthermore, the results of the study show that people's willingness to pay is also influenced by their perception of the importance of energy and environmental factors. Landlord/tenant dilemmas that result from the misalignment of landlord and tenant interests often occur in the retrofitting of European residential buildings. The research by Björn Ástmarsson et al. (2013), based on the actual situation in Denmark, shows that although there are many ways to overcome the landlord/tenant dilemma, the principal/agent problem can only be conquered through a package solution. This includes a combination of legislative reform, financial incentives, and better information dissemination.

1.3.2 Chinese domestic research situation

Unlike Europe and North America, where energy-efficient design was mandated in the 1970s, many other countries started late and began to paying attention to the energy efficiency of buildings since the 1990s [35]. In the development of China's building energy efficiency standards, the first landmark occurred in 1987 when the Energy Conservation Design Standard for Residential Buildings in Severe Cold and Cold Areas (JGJ26) was first issued. For other climate areas without central heating, the energy-saving standards were released later. The energy-saving design standard for residential buildings in the HSCW zone (JGJ 134) was first launched in 2001. Attention to rural residential buildings came even later, with the first energy efficiency design standards for rural residential buildings only available in 2013 [36].

As mentioned above, the development of energy efficiency in residential buildings in China started very late (from 1995) and only for the severe cold and cold regions. Consequently, a large number of existing buildings in China were built with poor energy performance. Up to 2016, the country's total floor area was nearly 58.1 billion m^2, of which residential floor area accounted for 46.4 billion m^2 [12]. Most of the existing buildings are energy inefficient and have low comfort levels. According to the protocol negotiated in the Paris Agreement in 2016, the Chinese government set a reduction target of 65% of total carbon emissions [37]. The current energy efficiency situation in the building sector in China is not promising due to the rapid growth of urbanization rates, the continued increase in population, and the increasing demand for better indoor environmental quality. There are two regions of the building sector in China where the indoor thermal environment remains very poor, namely rural area and the HSCW zone [38]. With the increase in economic income and quality of life requirements of people in these two regions, China has a very large potential for future energy consumption.

1.4 Research purpose and significance

1.4.1 Research purpose

This study was conducted in a residence community in urban area of Chengdu, China. The high-rise residential buildings in this residence community were already outside-insulated when they were designed and built. The bedroom area of a residential unit on the 5th floor of one building was selected for interior insulation retrofit. Another residential unit of the same floor and layout in the adjacent building was selected as a comparison unit. From 2019 to 2020, comparative measurements were conducted in the experimental and comparison residential units mainly for the following research objectives：

1. To study the energy-saving effect of adding interior insulation to the bedrooms of existing external-insulated building in Chengdu, China, under the typical intermittent cooling and heating air conditioning modes.

2. To investigate the improvement of the indoor thermal environment in the retrofitted bedroom compared to the un-retrofitted one, under the typical intermittent cooling and heating air conditioning modes.

1.4.2 Research significance

Although there are many studies on retrofitting existing buildings in China, there are still limited studies on retrofitting insulation for the special climate and usage patterns in the HSCW region. Interior insulation has very good application prospects and value in the renovation of existing buildings. The significance of this paper mainly includes the following aspects:

1. Interior insulation is less expensive to install than outside insulation. Case studies for central-heating regions in northern China show that outside wall insulation has the most energy-saving potential but is the least cost-effective among various retrofitting measures [39].
2. For existing high-rise residential buildings, interior insulation retrofitting is a more feasible and flexible approach. Unlike detached houses, external insulation retrofitting is relatively easy to implement. The largest proportion of urban dwellings in the HSCW region are high-rise residential buildings. For those high-rise residential buildings that have already been sold and in use for several years, the renovation of outside insulation also involves the renovation of the entire facade of the building, which is very expensive and takes a long time. But interior insulation retrofits can be done flexibly [40], regardless of the scope. It can be applied to a residential unit or just a single room.

3. Moreover, such a complete renovation cannot be carried out without the permission of the whole building's occupants. Under such circumstances, interior insulation retrofitting is easier to achieve, as it usually requires only the consent of the owner of the dwelling unit.
4. Through evidence of actual measurements, this case study can be a reference to insulation retrofit of existing residential buildings in the HSCW region or similar climate zones, and it also can be an inspiration for the optimized design of insulation systems in new residential buildings under a similar climate.

1.5 Research structure

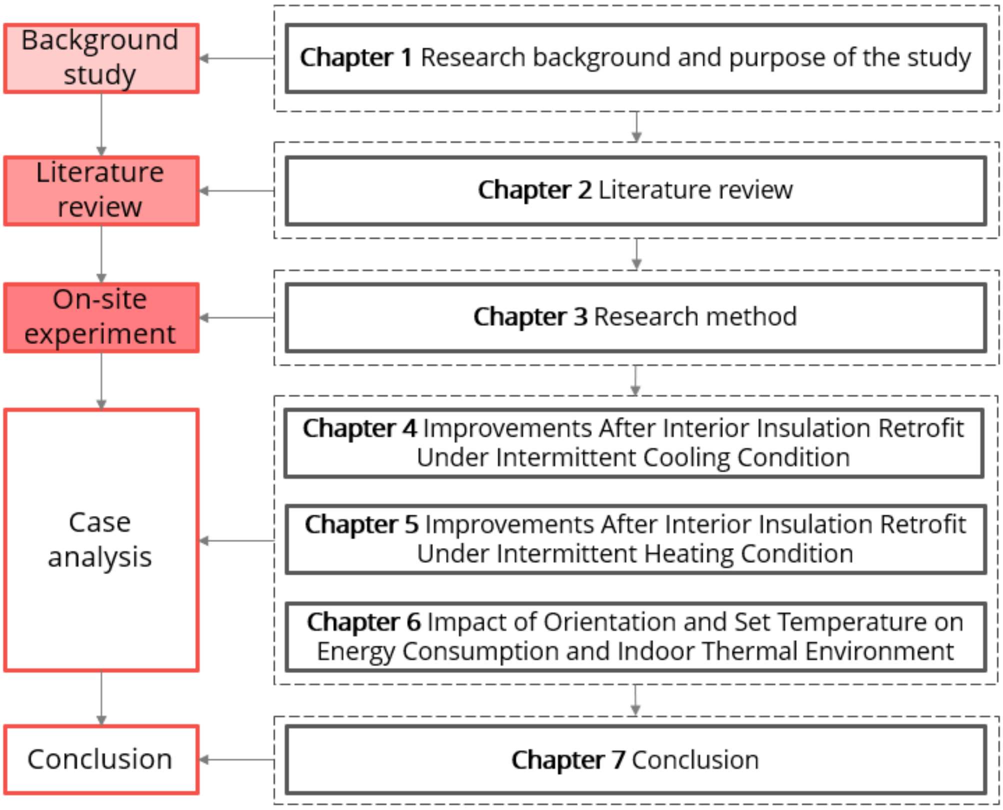

Figure 1-10. Research framework.

This research was conducted to quantify the improvement of cooling load and indoor thermal environment after adding interior insulation to a typical outside-insulated residence under the summer condition of Chengdu, China. The bedrooms in the selected residence were retrofitted in the summer of 2017 by adding insulation panels to all the interior surfaces of the opaque envelope. From 2019 to 2020, a series of comparative on-site measurements were done to investigate the effect of the retrofit work under three typical intermittent air conditioning patterns in a real-life scenario. The experimental result shows that interior insulation exhibits a significant improvement in energy-saving and the indoor thermal environment.

Figure 1-10 shows the research framework of this study. This research includes seven chapters and can be divided into five sections. The first section is the research background and research purpose. The second section is the literature review of the climate, current status of existing residential buildings in the HSCW zone, and occupants' behaviors in the HSCW zone and review of insulation retrofit measures of building envelope. The third section is the research method and experiment design. The fourth section is the analysis of the on-site experiments, including the situation under intermittent cooling and intermittent heating condition, and the comparison of orientation and set temperature. And the last section provides the conclusion of this thesis.

Chapter 1, Research Background and Purpose of The Study. International, domestic, and regional background research was conducted to clarify the research background. After that, the definition of interior insulation, the purpose and framework of this study, and its innovation were presented.

Chapter 2, Literature Review. Firstly, the climate and energy use characteristics of the HSCW region (including Chengdu), the physical and indoor environment characteristics of existing residential buildings, and the air-conditioning usage patterns were summarized and presented. Secondly, the building energy codes for residential buildings in this region were collated and shown. Finally, common measures to improve the insulation performance of the existing building envelope were summarized and analyzed. The above literature review showed that interior insulation is a more appropriate approach under the climatic and air-conditioning usage patterns of the HSCW region.

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Chapter 5, Improvements After Interior Insulation Retrofit Under Intermittent Heating Condition. Under three typical local intermittent heating models were measured in the winter of 2020 in experimental and comparison homes. The intermittent heating comparison experiment was carried out on 10 of the coldest days and the main findings are as follows. Firstly, the retrofitted room showed a good energy-saving effect. The average daily energy-saving ratio was 41.58%, with a maximum energy savings of 55.53%. Secondly, compared to the original south bedroom, the renovated one exhibited the following characteristics of the indoor thermal environment when heating the space. When the heating temperature was 24 °C, the overall average indoor temperature was 0.7 °C higher after the retrofit. The indoor temperature was well controlled at 1.1 m and 2.7 m but showed a greater range of fluctuations. Besides, indoor relative humidity was lower and fluctuated more after the retrofit.

Chapter 6, Impact of Orientation and Set Temperature on Energy Consumption and Indoor Thermal Environment. In the first part, intermittent cooling experiments in 2019 were carried out in both the north and south bedrooms and the results of the comparison experiments were shown below. The retrofitted south bedroom outperformed the north bedroom in terms of both energy-saving rate and indoor thermal environment, with the average daily energy-saving rate was 28% in the retrofitted north bedroom compared to 41% in the south bedroom. In terms of the temperature difference between the inner surface of the external walls and the indoor temperature, the vertical indoor temperature difference, and the range of temperature fluctuations, the south bedroom was significantly smaller than the north one. In the second part, in the intermittent heating experiment of 2020, three days with the same operating mode were selected to compare the impact of setpoint temperature on the retrofit effect. The results showed that a 2 °C difference in set temperature had a less noticeable effect on energy consumption and indoor temperature.

Chapter 7, Conclusion. The results of every chapter were summarized, and the contribution of this research was presented.

1.6 Innovation of this study

The innovation of this paper is mainly reflected in the following three aspects:

1. First, differing from the calculation and simulation studies we discussed in the literature review, this case study is based on the actual interior insulation retrofit in a residence in the HSCW area. Therefore, the data obtained through the actual measurement is more convincing than the calculation and simulation.
2. Secondly, the weather data during the experiment was also measured in real time, which can reflect the real climate condition of the area where this building is located.
3. Thirdly, the experiments in this paper were conducted in actual life scenarios, it can reflect more realistically the changes in energy use and indoor thermal environment after the addition of interior insulation in partial rooms of the residence.

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Chapter 2

LITERATURE REVIEW

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

Without a comprehensive understanding of residential buildings in the HSCW area, it is almost impossible to select the right envelope improvements. Residential buildings' energy consumption is influenced by a range of elements, as listed in Figure 2-1. On the one hand, there are technical and physical related influences, including the climatic environment in which the building is located, the characteristics of the building envelope, the equipment employed in the building, etc. On the other hand, there are user-related influences, such as the influence of occupant behavior, the operation of equipment and indoor environmental conditions, etc. [1]. In fact, in the HSCW area, the climate condition, the current status of existing buildings, occupants' cooling and heating patterns have their unique characteristics. Therefore, this chapter adopts a literature review approach to study these basic and important factors in the HSCW region. By analyzing research papers in recent years for various parts of the HSCW region, the purpose of this chapter is to provide a categorized review of the climatic conditions in the HSCW region, the current status of residential buildings and energy use, heating-related codes, and common ways of retrofitting existing buildings in this area.

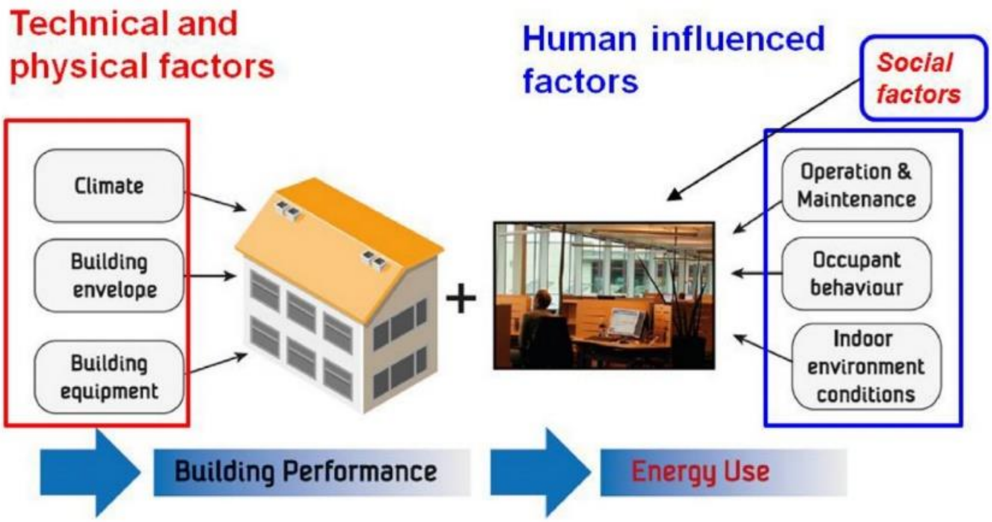

Figure 2-1. Six influencing factors on building energy use [1]**.**

(Source: Yoshino, H., Hong, T., & Nord, N. (2017). IEA EBC annex 53: Total energy use in buildings—Analysis and evaluation methods. Energy and Buildings, 152, 124-136.)

The rest of the chapter will be developed in the following way. 2.2 is an introduction to the climate conditions, and energy use in the HSCW region and Chengdu city. 2.3 is a summary and analysis of the current situation of existing residential buildings in the HSCW region. 2.4 is a summary and analysis of the energy use habits of households in the HSCW region. 2.5 is a summary of common insulation optimization methods for existing buildings. 2.6 is a summary of all the sections.

2.2 Description of the HSCW zone and Chengdu city

2.2.1 Description of the HSCW zone

2.2.2.1 Geography features of the HSCW zone

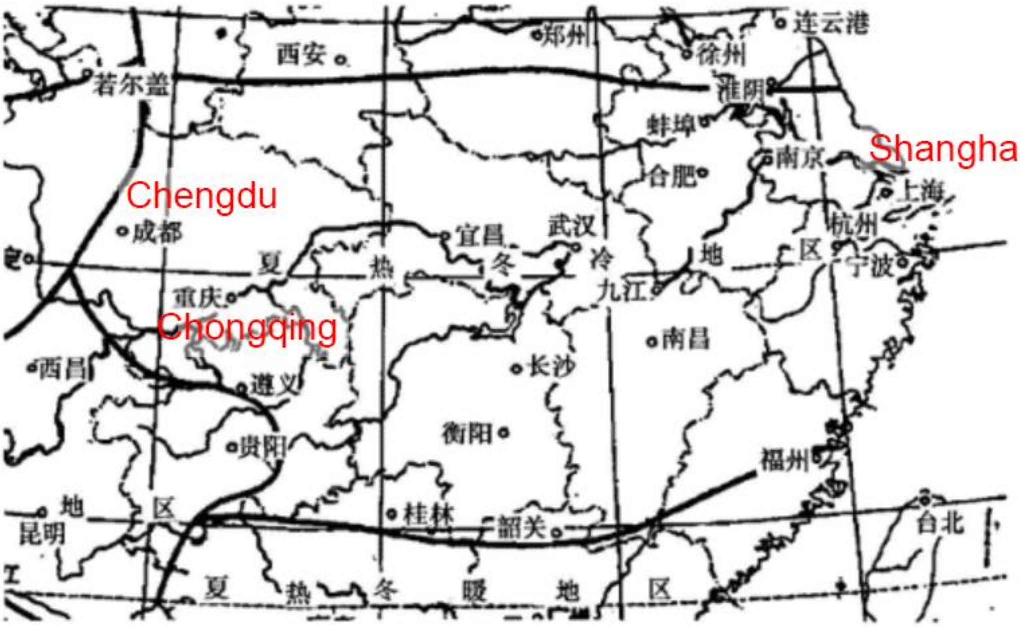

Figure 2-2. Regional coverage of the hot summer and cold winter area [2]**.**

(Source: (2010). JGJ 134-2010. Domestic - Industry Standard - Industry Standard - Construction industry CN-JG.)

Owing to the vast geographical area, climatic conditions vary greatly from one region of China to another. In 1993, China's thermal design code for civil buildings was promulgated, dividing China into five major climatic zones. According to the characteristics of each climate zone, the corresponding design principles are developed. Overall, for severe cold and cold regions, the design principles focus on winter insulation, while for hot summer and warm winter regions, the main design principles focus on summer heat protection. Compared with them, the HSCW zone appears to be special, because it is characterized by both hot summers and cold winters, it is, therefore, a necessity to meet the requirements of summer heat protection along with proper winter insulation.

According to the code for thermal design of civil building (GB 50176-2016) [2] in China, the HSCW region refers to the mid-to-lower reaches of the Yangtze River and its adjacent regions, as shown in Figure 2-2. The region involves 16 provinces, municipalities, and autonomous regions, nearly halves of all Chinese provinces. At around 1.8 million square kilometers in area, it is populated by roughly 550 million people. At the same time, its gross domestic product (GDP) amounts to nearly 48% of the country's total. To sum up, it is characterized as a densely populated and economically developed area.

2.2.2.2 Climate features of the HSCW zone

Exactly as its name implies, the climate in the HSCW area is characterized by hot and humid in the summer months. The specific climatic characteristics of summer can be summarized as follows. Firstly, in comparison to other regions of the world at the same latitude, the average temperature in July in this region is usually 2-3 °C hotter. In some cities of the HSCW zone, the maximum temperature can be higher than 40 ℃ (Table 2-1). Secondly, heavy annual precipitation leads to a high mean relative humidity of 70%. Besides, a tiny temperature difference between day and night, accompanied by gentle wind speed at night, making the indoor environment in summer stuffier. The average indoor temperature is 29 ℃, the highest even up to 39 ℃.

Table 2-1. Summary of thermal environmental parameters in summer in China's HSCW zone [3]**.**

(Source: Liu H, Wu Y, Li B, Cheng Y, Yao R. Seasonal variation of thermal sensations in residential buildings in the Hot Summer and Cold Winter zone of China. Energy Build 2017;140:9–18. https://doi.org/10.1016/j.enbuild.2017.01.066.)

Parameters		**T_{out} (◦C)**	**T_a (◦C)**	**RH_{out} (%)**	**RH_a (%)**	**V_{out} (m/s)**	**V_a (m/s)**
Summer (N = 2521)	Mean	29.57	28.98	70.35	70.79	0.97	0.28
	Min.	18.20	15.90	38.00	41.60	0.00	0.00
	Max.	41.50	38.70	98.40	98.00	5.56	4.42
	SD	3.58	2.86	11.31	9.90	1.03	0.41

In Table 2-1, T_{out} represents outdoor air temperature, T_a represents indoor air temperature, RH_a represents indoor relative humidity, RH_{out} represents outdoor relative humidity, V_{out} represents Outdoor air velocity and V_a represents Indoor air velocity.

In winter, on the other hand, it is cold and wet with low sunshine rates. Table 2-2 shows the winter climate data from a field measurement done in cities such as Wuhan [4], it shows the actual indoor and outdoor climate data. The average outdoor temperature in urban areas is 9.9 °C and the average outdoor relative humidity is 59.2%. The climate indoors differs very little from that outdoors, both in terms of temperature and relative humidity. Compared to rural areas, the survey showed that the average outdoor temperature in urban areas was 2.0 °C lower and the average outdoor relative humidity was 10.5% higher.

Table 2-2. Measured indoor and outdoor environmental parameters in winter in Wuhan [4].

(Source: Xiong Y, Liu J, Kim J. Understanding differences in thermal comfort between urban and rural residents in hot summer and cold winter climate. Build Environ 2019;165:106393. https://doi.org/10.1016/j.buildenv.2019.106393.)

Parameters	Region	Min	Max	Mean
T_{in} (°C)	Urban	6.6	16.0	11.1
	Rural	5.4	16.7	11.1
T_{out}(°C)	Urban	2.9	16.2	9.9
	Rural	3.8	23.0	11.9
RH_{in} (%)	Urban	23.6	87.9	60.6
	Rural	30.3	85.9	52.3
RH_{out} (%)	Urban	25.4	89.0	59.2
	Rural	14.9	90.6	48.7

2.2.2.3 Energy consumption situation in the HSCW zone

The HSCW region has a vital role to play in the process of building energy efficiency in China. This is because energy consumption in the region is high and growing dramatically in recent years due to climatic and social reasons. Since the 1950s, the Chinese government has drawn the Qinling-Huaihe line to define the central heating zones in the country. Areas located north of this line (which mainly includes the severe cold and cold regions) have access to central heating, while areas to the south have no such privileges. The HSCW region discussed in this study belongs to the non-centralised heating area, where the wet and cold winters combined with poor envelope performance result in an indoor thermal environment that is even worse than in the north [5]. It is also for this reason that there is a strong public appeal for central heating in this region every winter.

As living standards improve, people's reliance on air conditioning becomes higher. Air conditioning systems now account for 50-60% of annual residential energy consumption [6]. It is predicted from relevant studies that to maintain thermal comfort indoors, this region would require a heating load of 20 million kilowatts in winter and a cooling load of four times that in summer [7].

In 2016, China's total building energy consumption was 899 million tons of standard coal, taking up 20.6% of the country's overall energy consumption, as reported in the China Building Energy Efficiency Research Report (2018). Of this, residential buildings in urban areas consume 38% (339 million tons of standard coal) of the energy used in buildings.

2.2.2 Description of Chengdu city

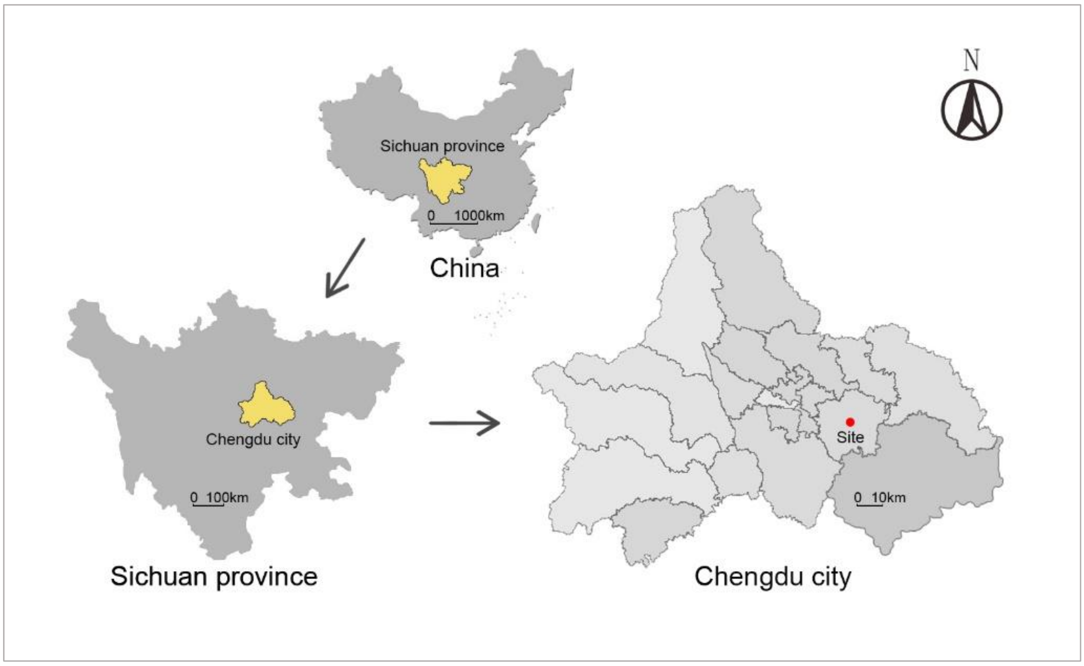

Figure 2-3. Location of Chengdu city.

In this research, Chengdu city was selected as the study area. As shown in Figure 2-3, it is in the central part of Sichuan Province. It’s the capital of Sichuan province and a representative area of the HSCW region. It is located between latitude 30◦05′N ~ 31◦26′N and longitude102◦54′E ~ 104◦53′E [8]. It is the scientific, cultural, and financial center and transportation center of southwest China. Chengdu's urbanization process has experienced rapid growth, from 34.1% in 2000 to 70.4% in 2014, which is 15.6% higher than the national average level [9].

Figure 2-4, Figure 2-5, and Figure 2-6 show the temperature, humidity, and solar radiation for the whole year based on the climatic data of a typical meteorological year in Chengdu. Chengdu city owns the typical climatic characteristics of the HSCW region. In summer, the temperature is generally high, and in winter the average temperature remains below 10 °C. In general, there are not enough solar resources in winter and relatively more in summer, so the building design needs to pay attention to insulation in winter and heat prevention in summer.

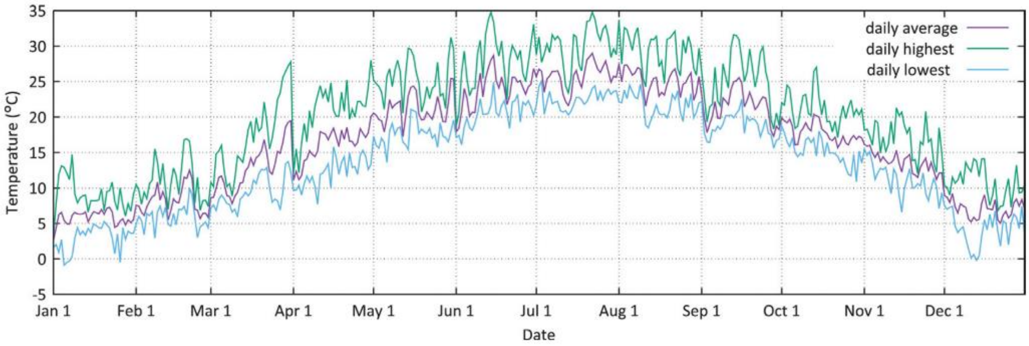

Figure 2-4. Daily outdoor temperature of the typical meteorological year in Chengdu [10]**.**

(Source: Feng X, Yan D, Wang C, Sun H. A preliminary research on the derivation of typical occupant behavior based on large-scale questionnaire surveys. Energy Build 2016;117: 332–40. https://doi.org/10.1016/j.enbuild.2015.09.055.)

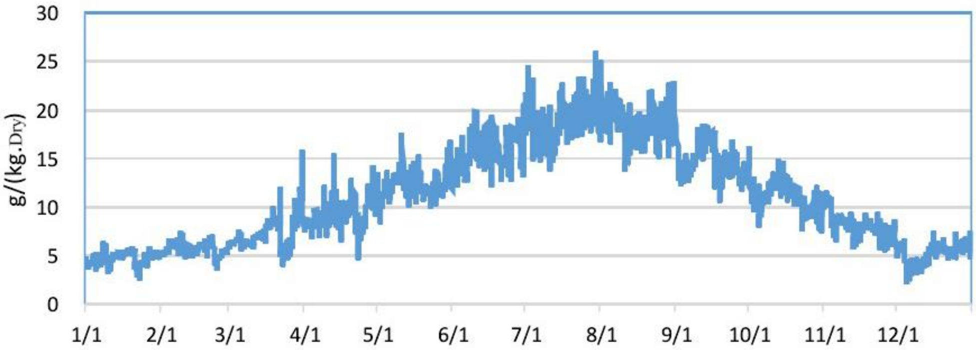

Figure 2-5. Statistics of hourly Humidity in Chengdu [11]**.**

(Source: Gu Shunqin. Study on energy consumption of residential buildings in Chengdu, Sichuan. (Doctoral dissertation, Chongqing University)

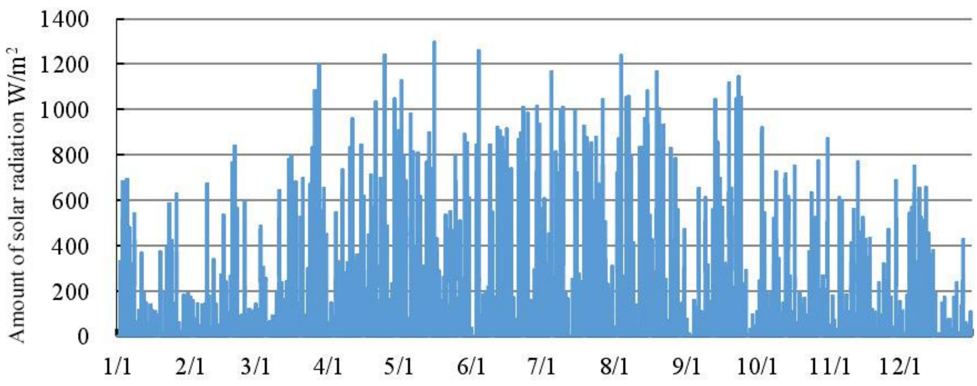

Figure 2-6. Statistics of hourly Solar radiation in Chengdu [11]**.**

(Source: Gu Shunqin. Study on energy consumption of residential buildings in Chengdu, Sichuan. (Doctoral dissertation, Chongqing University)

2.3 Previous studies on existing residential buildings in the HSCW zone

To get a clearer picture of existing residential buildings in the HSCW zone, studies from existing research on residential buildings in the HSCW zone, especially in urban areas, have been reviewed and presented in this part.

2.3.1 Physical characteristics of existing residential buildings

Much previous research has been done to investigate the building characteristics of existing residential buildings in different cities of the HSCW zone. The main physical properties that affect the energy consumption of a building include the year of construction, the structure of the building, the insulation design, the construction of the windows, etc.

Take a large-scale field study of residential buildings, for example, which was conducted nationwide from 2008 to 2011 [12]. The results show that the main characteristics of residential buildings in the HSCW region are as follows. First, in terms of the age of construction, 15.3% were built prior to the 1990s, 35.8% in the 1990s, and 37.8% after the 1990s (Figure 2-7). This is also confirmed by the results of another face-to-face survey [13]. This survey was conducted in 2017 in five major cities in the HSCW region, it shows in Table 2-3 that only 18.9% of buildings were built in 2009 and later. This is in line with the 19.6% rate in the census data.

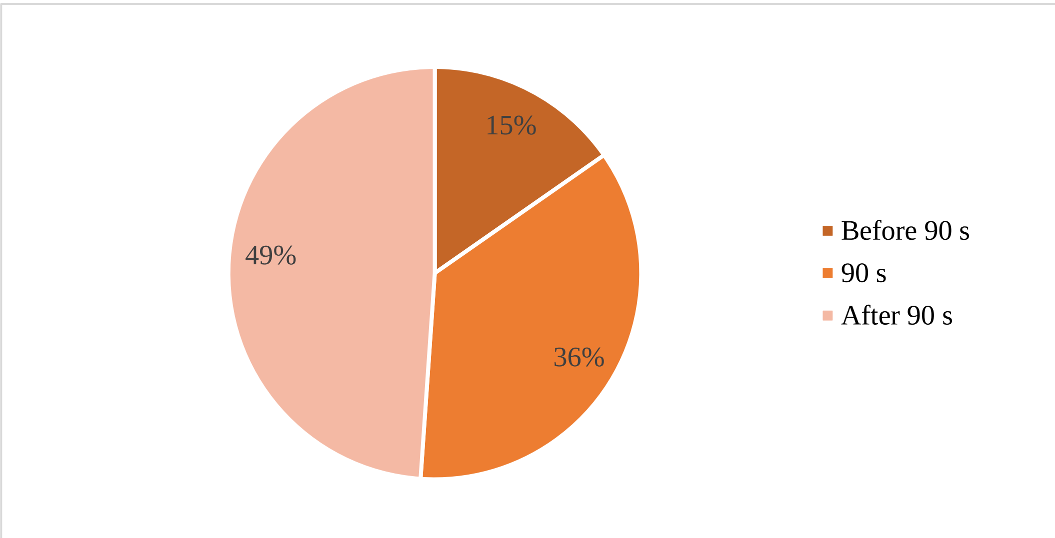

Figure 2-7. Construction ages (%) [12].

(Source: Li B, Du C, Yao R, Yu W, Costanzo V. Indoor thermal environments in Chinese residential buildings responding to the diversity of climates. Appl Therm Eng 2018;129:693–708. https://doi.org/10.1016/j.applthermaleng.2017.10.072.)

Table 2-3. Proportion of building age of this survey and the census data [13]**.**

(Source: Jiang H, Yao R, Han S, Du C, Yu W, Chen S, et al. How do urban residents use energy for winter heating at home? A large-scale survey in the hot summer and cold winter climate zone in the Yangtze River region. Energy Build 2020;223:110131. https://doi.org/10.1016/j.enbuild.2020.110131.)

Location of Insulation	Before 2001	2001-2009	After 2009
Census data	35.5%	44.9%	19.6%
Surveyed buildings	36.1%	45.0%	18.9%

Secondly, in terms of construction type, 37.8% of residential buildings are constructed of brick and concrete, 61.9% are made of reinforced concrete, and 0.3% are made of others (Figure 2-8). Thirdly, in terms of window types, single frame single glazing accounts for 81.2%, single frame double glazing accounts for 10.2%, and double frame double glazing accounts for 8.6% (Figure 2-9).

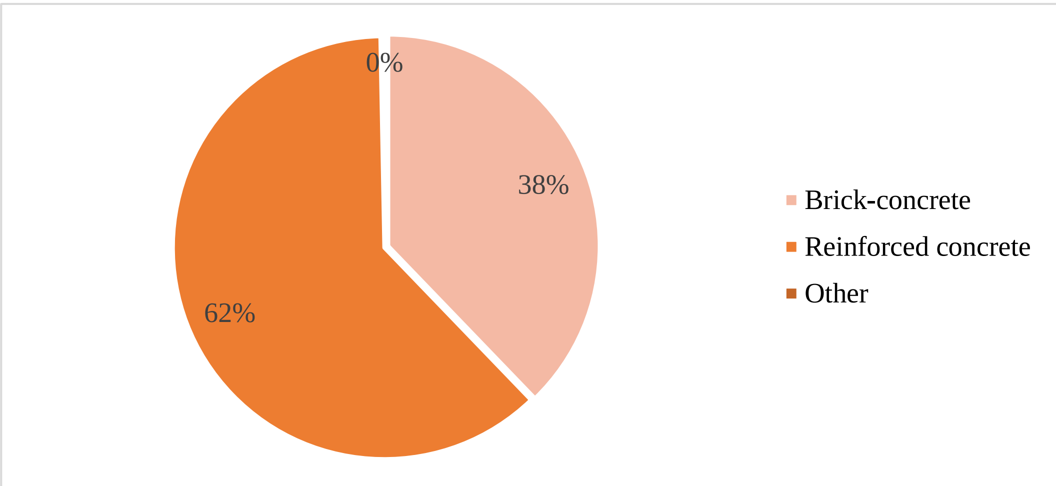

Figure 2-8. Construction type (%) [12]**.**

(Source: Li B, Du C, Yao R, Yu W, Costanzo V. Indoor thermal environments in Chinese residential buildings responding to the diversity of climates. Appl Therm Eng 2018;129:693–708. https://doi.org/10.1016/j.applthermaleng.2017.10.072.)

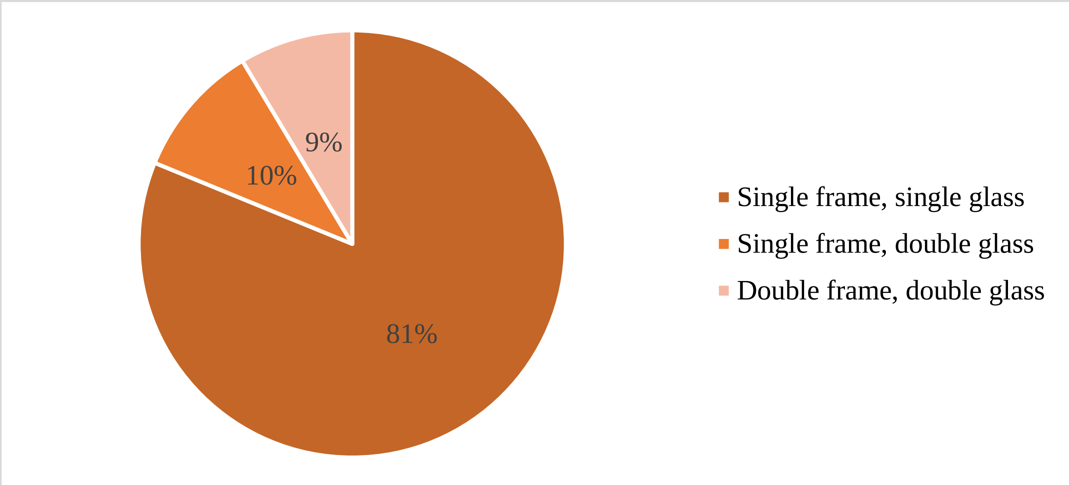

Figure 2-9. Windows type (%) [12]**.**

(Source: Li B, Du C, Yao R, Yu W, Costanzo V. Indoor thermal environments in Chinese residential buildings responding to the diversity of climates. Appl Therm Eng 2018;129:693–708. https://doi.org/10.1016/j.applthermaleng.2017.10.072.)

In addition, the prevailing insulation method in existing buildings is external wall insulation, as insulation in the HSCW zone follows the practice of the central heating area in the north.

2.3.2 Indoor thermal environment in existing residential buildings

Many researchers have also investigated the indoor environment in this area, some of them are the comparison of the region with other climate regions and countries. Bin Cao et al. (2016) carried out a comparative field study in the Severe Cold zone (Harbin), Cold zone (Beijing), and Hot Summer & Cold Winter zone (Shanghai) respectively. During the study period, the outdoor climate in these three cities was the lowest in Harbin and the highest in Shanghai. When comparing the average daily outdoor temperature, Harbin is nearly 17 °C colder than Shanghai. However, in Harbin and Beijing, where central heating is available, the average indoor temperatures are 23.9 °C and 21.3 °C respectively, much higher than the 16.4 °C in Shanghai, where central heating is not available [14]. In addition, when compared to the UK, which has similar winter conditions, the mean indoor temperature of residences in the HSCW climate zone is 6 °C colder. More seriously, such a terrible indoor environment has been maintained in the HSCW area for 15 years without noticeable improvement [15].

In Chengdu, rough outdoor conditions combined with poor local building insulation design and construction directly contribute to the poor indoor thermal environment of local residential buildings. In summer, indoor temperatures in residential buildings in Chengdu can be as high as 38 °C, showing very small temperature differences from outdoor temperatures [12].

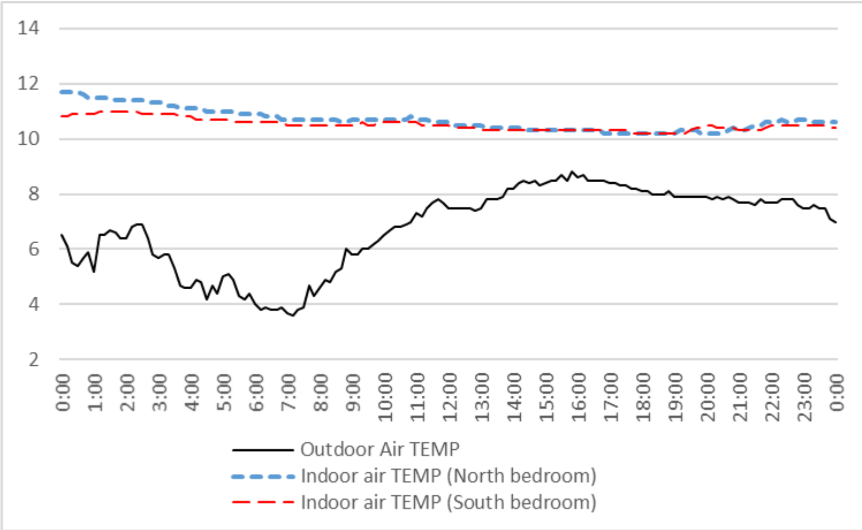

Figure 2-10. Measured indoor and outdoor temperature (°C) in the winter of Chengdu.

Our group conducted on-site measurement in Chengdu city in January 2019. Data from January 31th (Figure 2-10) shows that the average indoor temperature is 10.7 °C for the north bedroom and 10.5 °C for the south bedroom, while the mean outdoor temperature is only 6.8 °C. And Figure 2-11 shows an average outdoor relative humidity of 84.5% and an average indoor relative humidity of 72.5% and 81.1% for the north and south-facing bedrooms respectively.

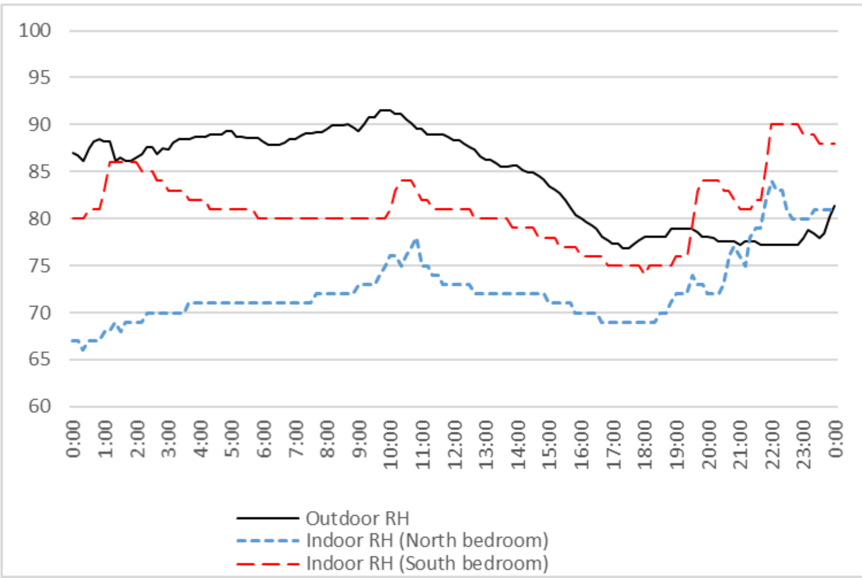

Figure 2-11. Measured indoor and outdoor relative humidity (%) in winter in Chengdu.

2.4 Previous studies on residential occupants' behaviors in the HSCW zone

In addition to the building envelope's thermal performance, the energy consumption of residential buildings is strongly influenced by the behaviour of the occupants. In recent years, research and studies on the energy consumption of air conditioning in residential buildings have raised awareness of the significant impact of occupant behaviour on energy consumption. The findings of research conducted by Nan Li in August 2007 for a residential house in Sichuan show that there is a large impact of personnel behaviour on energy consumption in residential buildings. Three groups of households in the same unit, on nearby floors, with a similar composition and economic level were selected for comparison, and the maximum difference in energy consumption for air conditioning and cooling within the group was 815 kWh, a difference of 468.3% [16]. Therefore, this section will sort out and summarise the cooling and heating usage habits of households in the HSCW area to lay the groundwork for the design and conduct of the experiment.

2.4.1 Cooling and heating equipment in the HSCW zone

With the increasingly demanding comfort of the indoor thermal environment, the per-capita of cooling equipment has increased rapidly in cities of the HSCW zone. And the cooling equipment is mainly split air conditioners and electric fans. According to a questionnaire investigation in Hangzhou, each household has an average of 2.2 air conditioners and 1.9 electric fans [17]. Similarly, in the summer of Chongqing, residents have a strong dependence on air conditioning. Air conditioning is the main mode of residential indoor cooling and heating in Chongqing. The number of air conditioners in each residential house in Chongqing is about 3.09 [18]. At the same time, they account for most of the annual energy consumption. About 35% of the residents in Chongqing only use air-conditioners to cool down, and about 55% of residents use fans and air conditioning alternately [18].

In addition, in terms of heating equipment, the most common heating devices are split air conditioners and electrical heaters [19], which account for approximately two-thirds of the total heating consumption (Figure 2-12).

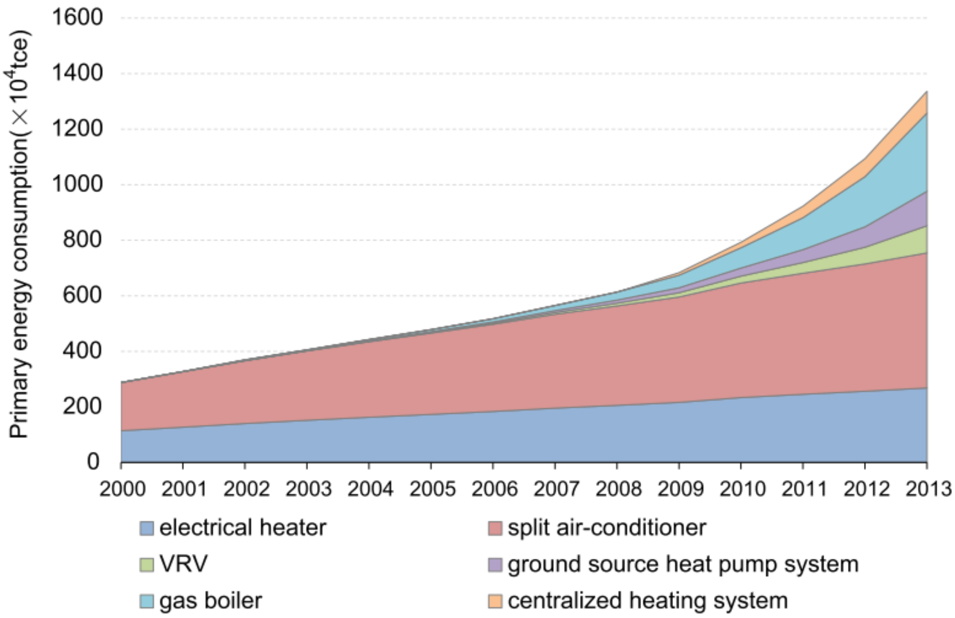

Figure 2-12. Heating consumption of HSCW-UR (urban residential areas) by equipment type [19]**.**

(Source: Hu S, Yan D, Cui Y, Guo S. Urban residential heating in hot summer and cold winter zones of China-Status, modeling, and scenarios to 2030. Energy Policy 2016;92:158–70. https://doi.org/10.1016/j.enpol.2016.01.032.)

2.4.2 Cooling and heating behaviours of occupants in the HSCW zone

Occupant behaviour is an important factor affecting the energy consumption of residential buildings. The rapid growth of the Chinese economy has led to an increase in the demand for housing thermal comfort. More and more residents in this area take measures to solve the problem of indoor thermal environment in winter and summer. It has been demonstrated that the behaviour of occupants results in up to 71% of changes in building energy consumption [20].

In fact, the frequency of air conditioning use is not evenly distributed throughout the year. The frequency of residential air conditioning use is directly related to the year-round climate, and Figure 2-13 shows the month-by-month frequency of air conditioning opening rate in Chongqing in 2016 based on big data. It is apparent that the demand for air conditioning is much stronger in summer than in winter. Especially since the beginning of June, the use of air conditioning has increased exponentially. During July and August, outdoor temperatures peak in Chongqing, so the average air conditioning usage rate is over 50%. During the winter and transitional seasons, on the other hand, air conditioning usage is lower, with less than 20% of the air conditioners being utilised on a daily basis [18]. Overall, air conditioning is used three times more frequently in the summer than in the winter in the Chongqing area.

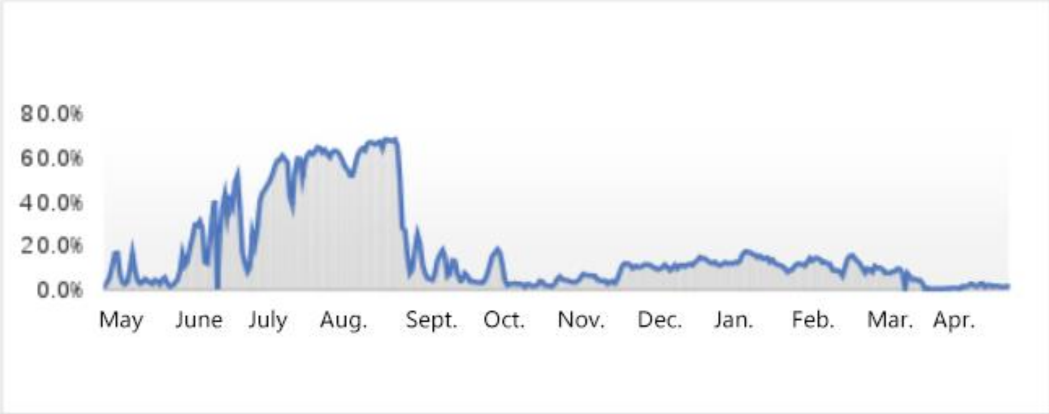

Figure 2-13. Distribution of air conditioning opening rate throughout the year of 2016 [18]**.**

(Source: Tan Jing Yue. A study on the characteristics of room air conditioner usage in residential buildings in Chongqing based on big data. (Doctoral dissertation, Chongqing University).)

2.4.2.1 Cooling behaviours of occupants

More than 97% of the households turn on or turn off the air conditioners according to their thermal comfort at that moment. A survey of air conditioning usage in Hangzhou shows that the bedroom's air conditioner is often turned on when the occupants feel hot, and turned off when they feel cold or after they getting up. Evidence from Chongqing reveals similar results, the most frequent way of using the air conditioner in the bedroom is to switch it on or off at any time, according to the residents' needs. While the fixed mode, which means to operate the air conditioner in a fixed time, gains the minimum number of votes in the questionnaire survey [21]. In summary, no matter it is air conditioning in the living room or bedroom, residents in the HSCW zone tend to use air conditioners in an individual room in an intermittent way. This is completely different from the "all time, all space" energy consumption mode in the north region.

Residents generally use the air conditioner in the afternoon and evening, mostly for 4 to 12 hours, and a high proportion of them do not leave it on overnight. Data from a field study in Sichuan [16] showed that among the households surveyed, 41.6% use air conditioning for 4 to 8 hours a day, 31.3% for 8 to 12 hours, leaving 20.5% using it for less than 4 hours a day. In terms of the period used, 42.3% of households turned on their air conditioners in the evening, while 27.7% and 18.4% used them in the afternoon and midday respectively. In addition, 11.7% of users choose to turn on their air conditioner in the morning or late at night.

The energy saving code for the HSCW region states that the cooling temperature for air conditioning in summer is 26°C. However, in actual use, a large number of residents prefer to set their air conditioners at a much lower temperature. The results of a questionnaire survey in Chengdu showed that 81% of households set their air conditioning temperature below 26 °C, and 7% of users even used to set their air conditioning temperature below 20 °C. Previous studies have confirmed that for every 1 °C increase in the set temperature of an ordinary household air conditioner, between 8% and 12% of electricity can be saved. Therefore, with the current air conditioning usage habits of Chengdu residents, the potential for energy savings in residential buildings is huge [11].

In summary, the cooling behaviour of air conditioning in the HSCW area can be summarised as intermittent use in part of the space. Moreover, the air conditioning is usually set at a lower temperature.

2.4.2.2 Heating behaviours of occupants

Firstly, similar to the cooling behaviour of air conditioning, the heating use pattern in the HSCW area shows a "part space, part time" feature, which is totally different from the centrally heated northern areas. Although almost all families have separate air conditioners, they don’t use it all the time. Take an on-site measurement of a residence in Wuchang city as an example, it is found that most of the time in the daytime the residents are in the living room, so only the living room is heated. At night the household rests in the bedroom, so only bedroom air conditioning is turned on [22]. When the air conditioning is switched on, the average heating time in the living room and bedroom is 2.3 hours and 2.8 hours respectively [15]. Additionally, when occupants are asked whether air conditioning is on while sleeping on a winter night, only 27% of residents in the HSCW area choose to sleep with their air conditioning on to keep them warm [23].

Secondly, with regard to the critical interior temperature that triggers the use of air conditioning, a temperature range between 10 and 14 °C is the one in which most occupants choose to switch on their heating equipment. This means that in the absence of heating, the lowest acceptable internal temperature for residents in the area is around 10 °C. Actually, this is 2 ℃ lower than the hygienic minimum temperature of the building thermal environment (12 ℃) [16]. This is because people who are exposed to cold environments for a long time are tolerant of a wider range of temperatures.

Thirdly, we want to figure out that under what situation people will switch on or off the air conditioner. In winter, 62.6% of the surveyed households turn on the heating equipment all the time as long as there is someone at home, while 37.4% of the households turn on the heating equipment when they are using a room, turn off the heating equipment when they feel warm, and turn on the heating equipment again when they feel cold [16].

In addition, the setpoint of the air conditioner plays an important role during the heating season. Thermal comfort expected by residents is limited by regional climate and material conditions and gradually becomes a lifestyle. The HSCW zone used to be non-centralized heating areas, so residents' adaptability to cold environments leads to lower indoor temperature requirements than cold and severe cold areas. According to the survey results, 63.1% of the surveyed households in the winter set the air conditioning temperature is higher than 20 ℃, 19.7% of the surveyed households' air conditioning set temperature is 19 ℃ to 20 ℃, 10.1% of the surveyed households' air conditioning set temperature is 17 ℃-18 ℃. More than half of the population's heating temperature is set at 20 ℃ or more, and less than 30% of the population's winter air conditioning design temperature is set at 18 ℃-20 ℃, indicating that most residents' set temperature does not meet the standard residential design temperature (18 ℃-20 ℃). The effect of an appropriate reduction in heating temperature on energy savings is significant. This is because, according to the survey, for the total heat load of the entire heating season, if the interior design temperature of a dwelling is lowered by 1 °C, the cumulative heating season energy consumption will drop about 11% on average [22].

2.4.3 Window opening behaviours of occupants in the HSCW zone

Indeed, in addition to air conditioning habits, the interaction between occupants and windows can exert a very considerable influence on a building's energy consumption, indoor air quality [24], and comfort. Dayi Lai et al. (2018) [25] conducted a year-long measurement of flats in typical cities of each climate zone in China, the results show that climate characteristics directly influence occupants' window opening behaviour, with windows being opened longer in the south than in the north. Research studies have shown that even in winter, long-term residents of the HSCW area are accustomed to opening their windows for fresh air [3]. In the past, as there was no mechanical ventilation in residential buildings, windows often had to be opened to ensure indoor air quality and to avoid the growth of bacteria. Since air conditioning is not widely available, long-established habits still affect people's daily lives. Only 10% of households do not open windows all day, and 90% of residents maintain the habit of opening windows. But considering the energy-saving factor, nearly half of the people only occasionally open windows to meet the indoor environmental quality.

The investigation of the window opening habits needs to be carried out under two different conditions: air-conditioned and non-air-conditioned conditions. Under non-air conditioning conditions, opening the window increases the ventilation rate, effectively increases the indoor wind speed, and improves the indoor thermal environment. However, open the window under air conditioning conditions, and fresh outdoor air enters the room to improve indoor air quality, but increases the air conditioning load at the same time, resulting in increased energy consumption. Under air-conditioning conditions, 61% of the residents always close the windows, 23% keep the small area of the windows open all the time, and 16% intermittently open the windows for ventilation. It has been found that even with the use of air conditioning, 39% of residents still want to improve their indoor environment through natural ventilation [26].

2.4.4 Summary of the occupant's behaviours in the HSCW zone

The impact of household behaviour on buildings is a growing research topic. Household behaviour can lead to significant differences in air conditioning consumption between different households in the same region. Through the analysis of several research studies in the region over the last decade, this section summarises the main characteristics of residents' air conditioning use behaviour. On the one hand, the characteristics of household behaviour related to cooling in the HSCW region can be summarised as follows:

1) From the perspective of a whole year, the frequency of air conditioner usage rate in the HSCW region under summer conditions is three times that of winter.

2) Occupants' air-conditioner usage pattern shows the characteristics of "part-time (4-12 hours per day) and part-space (bedroom or living room only), which is significantly different from the continuous space energy mode specified in the specification.

3) Most of the set temperature values are lower than the 26 ℃ (specified point in the specification), there is great potential for energy saving.

On the other hand, the heating-related occupant behaviour patterns in the HSCW region have the following main characteristics:

1) The indoor thermal environment in the HSCW zone is harsh, humid, and cold. Without air conditioning, the indoor temperature is 10~11℃, lower than the minimum hygienic temperature of the building thermal environment (12 ℃).

2) The heating usage pattern in the HSCW region shows the characteristics of "part-space and part-time".

3) Long periods of cold exposure led to a wider temperature range of people's toleration. The temperature that triggers the residents to turn on the air conditioner can be as low as 10℃, and the duration generally lasts for only 2~3 hours.

4) Residents tend to turn on and off the air conditioner according to their thermal sensation, instead of following fixed routine.

5) The heating temperature set point is often higher than the value specified in the specification.

Besides, the interaction between occupants and windows is a factor that cannot be ignored in the region, as it has a substantial effect on indoor heating energy consumption and thermal comfort.

2.5 Residential building energy efficiency standards in the study area

China has been working on building energy efficiency since the 1980s and has promulgated several design codes and standards at national and regional levels. The Thermal Design Code for Civil Buildings was established in 1993 to tailor the building's thermal design to the regional climate in which it is located, to guarantee the fundamental indoor thermal environment requirements, and to achieve the country's goal of energy saving and emission reduction. A revision of the code was made in 2016.

The thermal design zones in the Code for the Thermal Design of Civil Buildings are climatic zones that are defined from the point of view of the thermal design of buildings and are mainly concerned with the design of thermal insulation and thermal insulation of buildings. The "coldest monthly average temperature" and "hottest monthly average temperature" are used as the main indicators, and the "average daily temperature ≤5 °C days" and "average daily temperature >25 °C days" are used as auxiliary indicators. The average daily temperature >25 ℃ is used as a secondary indicator to divide China into five climate zones, namely, the severe cold region, the cold region, the hot summer and cold winter region, the hot summer and cold winter region and the mild region.

Among these five climate zones, the hot summer and cold winter (HSCW) region have a long duration of hot weather in summer, strong sunshine in the daytime, but a high static wind rate at night, which makes it difficult to take away heat. And although winter temperatures are not as low as in the north, the sunshine rate is very low, humidity is high and the overall character is cold and wet. Therefore, the Code of Thermal Design for Civil Buildings requires that the HSCW area must meet the requirements for heat protection in summer while taking into account winter insulation, which illustrates the complexity and importance of building energy efficiency in the HSCW area.

2.5.1 Design standard for energy efficiency of residential buildings in the HSCW zone

Building energy policy has started late and proceeded slowly in the HSCW region. With the aim of improving and enhancing the quality of the living environment for the inhabitants of the HSCW region in China, and promoting energy efficiency in buildings of the HSCW region, the Ministry of Construction promulgated the design standard for energy efficiency of residential buildings in hot summer and cold winter zone (JGJ134-2001), which provided a corresponding technical standard and basis for energy efficiency of residential buildings in the HSCW region. It was revised in 2010 to a new version (JGJ134-2010). This standard, as a mandatory code for energy efficiency of residential buildings in the HSCW region, firstly establishes the design index for indoor thermal environments. The interior design temperature of bedrooms and living rooms should be 18 °C during the heating period in winter and 26 °C during the air-conditioning period in summer. Also, the frequency of air changes should be 1 time every hour in both seasons. It also sets out requirements for the thermal design of the building and envelope (including envelope layout, orientation, form factor and performance indicators), as well as the energy efficient design of heating, air conditioning and ventilation.

However, there is a significant difference between the air conditioning usage pattern adopted in this building energy efficiency standard and the actual usage pattern. The code employs a continuous mode of operation for heating and cooling 24 hours a day, and the energy savings calculated on the basis of this model are significantly different from those in the actual intermittent air conditioning model.

2.5.2 Design standard for energy efficiency of residential buildings in Sichuan Province

The HSCW region covers 18 provinces, municipalities and autonomous regions, which vary greatly in terms of climate, economic conditions and so on. Each province will therefore set out more specific requirements according to the actual situation of the region in terms of energy efficiency in buildings. In order to promote the strategy of energy conservation and environmental protection in Sichuan Province and to guide the design of energy-efficient residential buildings, the Sichuan Energy Conservation Design Standard for Residential Buildings was released for the first time in 2010. It has played an important role in reducing energy wastage in residential buildings and achieving the target of 50% energy saving in buildings.

As people's living standards improve, various new technologies and materials emerge, and the energy efficiency of heating and air conditioning equipment continues to improve, making it possible to achieve further improvements in energy efficiency in residential buildings. Therefore, in 2019, a new version of this design standard has been published with the aim of reducing the energy consumption of heating and air conditioning in residential buildings by 65% for the whole year.

2.6 Review of insulation retrofit measures of building envelope

The results obtained from 2.3 show that a large part of the poor indoor environment of residential buildings in the HSCW area is due to the low energy efficiency of their envelopes. Therefore, upgrading the envelope of existing buildings is an effective way to improve the energy efficiency of residential buildings. Many scientific studies have been done by scientists around the world for this purpose, focusing on the application of energy conservation measures to minimize the use of air conditioning systems and to stabilize internal temperature control and prevent impulsive changes in external temperatures [27]. By analyzing the existing relevant studies, the energy retrofit measures that have been studied more frequently are summarized in this part.

The climatic conditions in which the building is located are a decisive factor for the building to be upgraded. The results of a review study of the passive thermal retrofit literature for over 100 residential buildings showed that the majority of existing studies were for heating-dominated areas, followed by cooling-dominated and mild areas, as shown in Figure 2-14. However, studies for hot summer and cold winter regions are currently the fewest, accounting for only 10% of them [28].

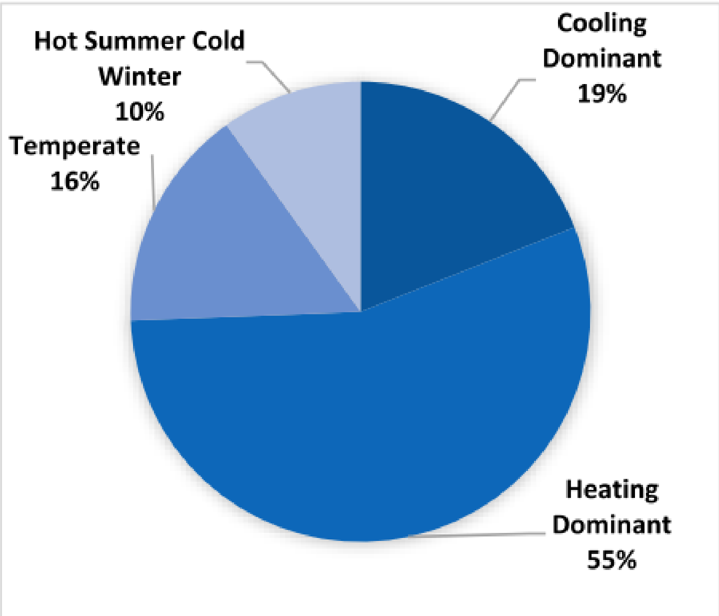

Figure 2-14. Detailed literature set characteristics: dominant climate [28]**.**

(Source: Carratt A, Kokogiannakis G, Daly D. A critical review of methods for the performance evaluation of passive thermal retrofits in residential buildings. J Clean Prod 2020;263:121408. https://doi.org/10.1016/j.jclepro.2020.121408.)

If a building is not insulated, it can lose up to 35% of the total heat from its external walls [29]. According to a recent review by Najme Hashempour et al. (2020) (Figure 2-15) [30] of the energy performance of existing buildings, insulation retrofits were the most selected measure in the studies they analyzed, with a utilization rate of 87%. The review by A. Carratt et al. (2020) [28] shows that wall insulation is the most common building retrofit measure in the literature. A total of 90 separate papers in their review dealt with wall insulation, covering a total of 100 climate zones. In the reduction of heating/cooling energy consumption in existing buildings, upgrading the insulation of buildings is the most affordable way to decrease heating and cooling needs and can largely reduce carbon emissions.

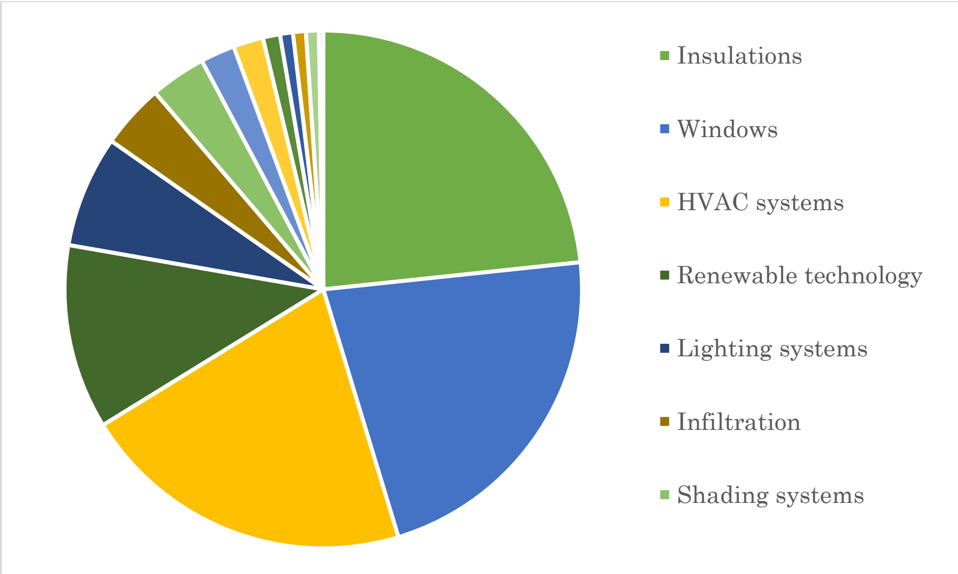

Figure 2-15. Percentage of the use of measures in analyzed studies [30]**.**

(Source: Hashempour N, Taherkhani R, Mahdikhani M. Energy performance optimization of existing buildings: A literature review. Sustain Cities Soc 2020;54:101967. https://doi.org/10.1016/j.scs.2019.101967.)

In the applied research on insulation retrofitting, the areas that are more frequently retrofitted are walls, roofs, ceilings and floors. In addition, the location and thickness of insulation materials, material performance and economic efficiency have also received extensive attention and research. In the subsequent content of this section, studies and results related to building renovation in different building parts are presented in order of type to give a clearer idea of building insulation renovation.

2.6.1 Previous studies on external wall insulation

Building insulation has been widely used for a long time in cold regions due to the need for winter heating, and the research is relatively mature. Bjørn Petter Jelle (2011) [31] provides a systematic summary of the properties and corresponding solutions of existing and future building insulation materials. However, the development of the impact of building insulation on energy consumption in regions where cooling is predominant is relatively late.

Kirsten Engelund Thomsen et al. (2016) [32] presents a comparison of the Danish case apartment building Traneparken before and after it has undergone a complete energy retrofit. The building required a complete retrofit as the facade, roof structure and windows were in disrepair. The combined use of new facades and windows, additional insulation, mechanised ventilation combined with heat recovery and a roof-mounted photovoltaic installation resulted in a 31% reduction in total energy demand and energy costs for heating.

With the rapid urban development and population growth in the United Arab Emirates, Dubai's energy demand is also increasing rapidly. However, since reinforced concrete frames are typically uninsulated, important thermal bridges are introduced in the building envelope. Wilhelm Alexander Friess et al. (2012) [33] investigated the impact of this thermal bridge effect on building energy consumption by modeling it using DesignBuilder and EnergyPlus and performing hourly simulations. The simulation results show that exterior wall insulation strategies can be very helpful in reducing energy consumption, and that energy savings of up to 30% can be achieved simply by using appropriate exterior wall insulation strategies.

In Tunisia, due to the climate, there is both a need for heating and cooling in a year. Buildings in this region are usually insulated with external wall insulation, whose thickness is usually between 4 cm and 5 cm. Naouel Daouas (2011) [34]adopted a complex finite Fourier transform (CFFT) based analysis method, energy savings, optimal insulation thickness and payback periods were calculated for typical wall structures. Calculations show that during the cooling season, walls facing west and east are the least desirable in terms of orientation, while walls facing north are the most desirable in terms of heating. From a cost perspective, south-facing is the most economical. If the optimal insulation thickness of 10.1 cm is used, an energy saving of 71.33% can be achieved, while the payback period is 3.29 years. In addition, the orientation of the wall has a tiny effect on the optimal insulation thickness, but a larger impact on the energy savings.

However, retrofitting existing buildings is not an easy task and needs to be determined on a project-by-project basis and with funding resources. Joohyun Lee et al. (2019) [35] studied a Korean government-initiated retrofit project that examined the process, strategy and implementation of energy retrofits in public buildings through simulations based on a study of green retrofit policies and regulations issued by the government. The simulations plus over showed that improving building envelope components can be effective in reducing the heat transfer coefficient of heat loss. By installing new insulation and efficient windows, heating energy demand can be reduced by about 40%. Also, the study recommends that in order to further improve building energy efficiency, future retrofits are recommended to be planned and designed at a larger level, such as the community or district level.

M. Bojic conducted a series of studies to investigate the thermal insulation of high-rise residential buildings under the hot climate of Hong Kong. Insulation was rarely used in Hong Kong's high-rise residential buildings around 2000. By using the heat transfer simulation software HTB2, M. Bojic et al. (2001) [36] investigated the influence of outside wall insulation upon building loads under cooling conditions in high-rise residential buildings. By comparing three insulation scenarios for the outside, middle and inside of the external walls, the results indicated that annual cooling energy consumption could be saved by 6.8% when the insulation is 5 cm thick and facing the inside of the residence.

In 2002, M. Bojic et al. (2002) [37] further addressed the characteristics of compartmentalized residential use in Hong Kong by investigating the use of insulation in cooling space. Utilizing HTB2 (a heat transfer simulation program for buildings), this study exhibited the effects of adding insulation to the envelope separating the cooled and unconditioned spaces. The results demonstrated that the greatest reductions in both annual cooling load and maximum cooling demand were achieved when 50 mm insulation was placed on the inside of the walls of the enclosed cooling space, with proportions of 9.1% and 10.5% respectively.

In another study that year, M. Bojic et al. (2002) [38] noted that residential buildings in Hong Kong use air conditioning primarily at night, and that insulation of exterior walls in this use pattern does not significantly reduce cooling loads. It is even possible that when the walls are thin, the cooling load becomes higher due to the addition of insulation. Through simulation studies, the authors found that the most efficient way to reduce cooling energy consumption was to insulate the walls of the cooled and uncooled spaces of the dwelling with additional insulation.

To simplify calculations, the continuous operation of air conditioning in the whole building is more commonly used in most insulation related studies. However, in fact, in the HSCW region of China, for example, residents prefer to use air conditioning intermittently. The difference between the air-conditioning operation modes is the reason for the discrepancy between the calculated and actual energy savings. Lili Zhang et al. (2002) [39] compared the differences between continuous and intermittent use of air conditioning in their study. The experimental results indicated that it was the thermal performance of the inner layer of the wall that had the highest thermal response rate to the wall under intermittent operation. The greatest response rates are achieved in internally insulated walls.

Zhaosong Fang et al. (2014) [40] studied the impact of exterior wall insulation on cooling energy consumption and indoor thermal environment in the summer of Chongqing. Cooling energy consumption of an ordinary local laboratory without insulation was compared with an energy-efficient laboratory with an exterior wall insulation system by monitoring data from the laboratory. By analyzing the measured data of the two chambers, the authors found that the exterior wall insulation system can effectively improve the energy efficiency of uninsulated residential buildings in Chongqing. In the cooling case, better air conditioning savings of up to 23.5% can be achieved, as well as a better thermal indoor comfort.

In summary, the external wall insulation model is more suitable for the continuous use of air conditioning, as the thermal mass can be maximised. However, in areas where air conditioning is used intermittently, the internal external wall insulation is a little more suitable because there is a better corresponding speed. At the same time, it is more difficult to retrofit a building with external wall insulation for the following reasons.

2.6.2 Previous studies on internal wall insulation

In fact, the external walls are not the only part of the building envelope that affects air-conditioning energy consumption. If only certain spaces in the building are air-conditioned, internal walls can also be an important influence. For example, when air conditioning is used in just one bedroom of a residential unit, the walls between this bedroom and the living room, as well as the other bedrooms, also absorb and store heat, directly affects the energy consumption of the room as well as the thermal comfort

Li Nan and Chen Qiong (2019) [41] investigated the effect of not heating adjacent rooms when part of the space is heated during the heating season through field trial tests. The results of the study showed that whether or not the adjacent rooms were heated directly influenced the total energy consumption and the surface temperature of the internal walls. A considerable part of the heat is transmitted through the internal walls to the adjacent rooms.

Ge Jian et al. (2021) [42] investigated the improvement effect of different building envelopes for intermittent energy use patterns in residential buildings in the HSCW region through dynamic simulation. The results show that improvements in the performance of internal walls and floor slabs increase the energy savings in cooling and heating, with the overall energy savings in cooling and heating ranging from 6.0% to 7.9%. Furthermore, the poorer the performance of the external envelope, the greater the impact of improving the performance of the internal walls and floors on the energy efficiency of air conditioning.

Ruan Fang (2017) [43]conducted a year-round simulation study for a multi-storey residential unit in Hangzhou, a typical city in the HSCW region. The results show that under the continuous energy use and full space energy use conditions specified in the code, setting insulation in the internal walls instead increases the annual energy consumption by about 1%. This is because, in such a model, internal wall insulation is not beneficial to the thermal storage of the internal walls, thus increasing the instability of the indoor environment. However, in the case of continuous energy use and partial space use, the addition of internal wall insulation significantly reduces annual energy consumption by 13.58% as the internal walls also become an important heat consuming surface in the energy consuming room.

Further, in the case of intermittent energy use, there are two types of energy use: daytime and nighttime. In general, regardless of whether the energy is used in full or partial spaces, internal wall insulation reduces the total annual energy consumption. The total annual energy consumption is reduced by an average of 5.1% in the case of daytime energy use and full space use, and by 8.8% in the case of partial space use. In the case of nighttime energy use, the total annual energy consumption is reduced by an average of 2.75% for full space use and 11.5% for partial space use. Overall, internal wall insulation in residential buildings has a good energy saving effect for both intermittent and partial space energy use buildings.

Wu, Minli (2014) [44] used the software Fluent 12.0 to study the wall performance of a typical residential unit in Hangzhou, a hot summer and cold winter region, in a part-space, part-time energy use model. The simulation results showed that when the bedroom studied had 2 external walls and 2 internal walls, the internal walls consumed about 45% of the total energy consumption, which was only slightly lower than the external walls. In many actual residential buildings, there are many house types where only one wall is even an external wall, so the proportion of energy consumed by internal walls will be even greater.

2.6.3 Previous studies on ceiling and floor insulation

In addition to external and internal walls, the ceilings and floors of residential spaces, as direct contact surfaces for air-conditioned spaces, also affect the air-conditioning energy consumption and the stability of the indoor climate.

Yanna Gao et al. (2020) [45] conducted numerical simulations for intermittent air conditioning operation to optimise the energy performance of the envelope by analysing the energy saving potential of the different components of the non-transparent envelope. The results prove that it is the floor and ceiling that contribute more to the energy saving rate compared to the external and internal walls, reaching up to 35-80%. Moreover, the energy saving contribution increases with the size of the room.

Sam Cohen et al (1991) [46] investigated the energy efficiency and cost effectiveness of individual retrofit options in single-family buildings by analysing both measured energy consumption and actual installation costs. The findings indicated that from a cost-effectiveness point of view, both ceiling and wall insulation are good options. Window replacement, however, is not a suitable retrofit option as it has a very small normal annual energy saving rate of 5% or less.

Based on a statistical analysis of the residential sector in Belgium, G. Verbeeck and H. Hens (2005) discussed economically viable retrofitting methods for existing residential buildings. The roof insulation and better performance of the glass in the envelope seems to be the most effective measure.

F. Al-Ragom (2003) [47] studied energy efficiency retrofitting of old residential buildings under very hot long summer climates in Kuwait. The results demonstrated that in hot and dry climates, it is possible to achieve an annual energy consumption of 293 kWh/m^2 by using both wall and roof insulation together with reflective double glazing with reduced window areas.

2.6.4 Summary of insulation retrofit measures of building envelope

The choice of insulation method for residential buildings is not meaningful if discussed in isolation from energy use habits. The concept of building energy efficiency in China first originated in the severe cold and cold regions. In the case of centralised heating area, external insulation can protect the main structure of the building as a whole from the outside, thus reducing the risk that changes in outdoor climatic conditions will not cause large temperature changes to the main structure inside, and the life of the building is extended, and is therefore chosen. The energy-saving design of buildings in the HSCW region started relatively late and followed the northern way of insulation, that is, external insulation of outside walls. However, the actual usage habits of residents in hot summer and cold winter regions are not continuous, but intermittent. The intermittent mode of energy use, on the other hand, allows for a faster response time with internal insulation. From the above review of the literature on building envelope insulation, it appears that internal insulation of external walls is more appropriate in patterns of intermittent energy use in the HSCW region.

In addition, the typical partial-space energy use pattern in the HSCW region makes internal walls, ceilings and floors an important influence on energy consumption and the indoor thermal environment, compared to the full-space energy use in the north. The insulation of these internal enclosures is important in partial space energy use.

Therefore, the interior insulation proposed in this study is a better insulation style for the air conditioning usage patterns in the HSCW region.

2.7 Summary

Firstly, the climate and energy use characteristics of the HSCW region (including Chengdu), the physical and indoor environment characteristics of existing residential buildings, and the air-conditioning usage patterns were summarised and presented. Secondly, the residential building energy efficiency standards in this region were collated and shown. Finally, common measures to improve the insulation performance of the existing building envelope were analyzed and summarised. The above literature review showed that interior insulation is a more appropriate approach under the climatic and air-conditioning usage patterns of the HSCW region.

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Chapter 3

RESEARCH METHOD

CHAPTER THREE: RESEARCH METHOD

3.1 The framework of empirical experiment

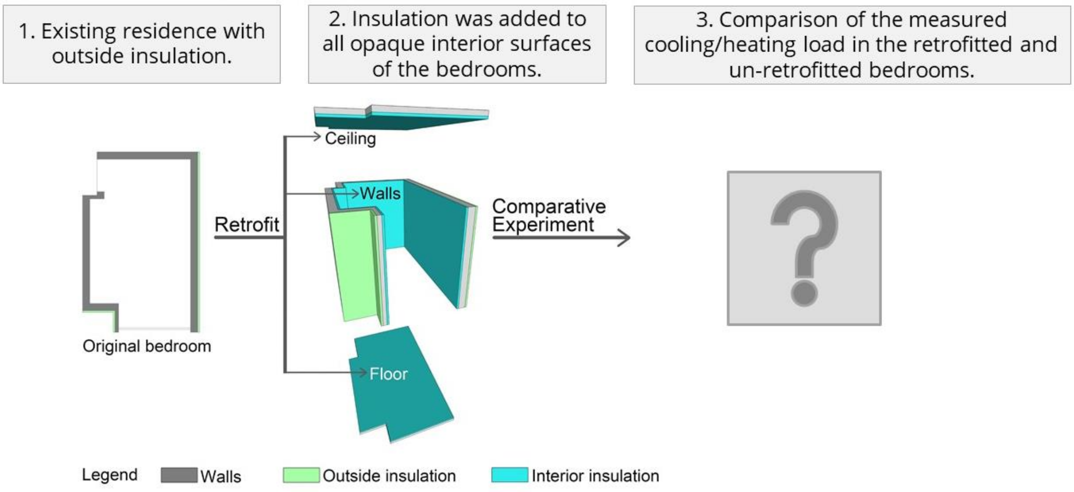

Figure 3-1. The framework of empirical experiment.

The specific methods and steps of the experiments in this study are shown in Figure 3-1. In a residential community in the east of Chengdu, we selected an existing externally insulated high-rise residential building as the case study building. In 2017, the bedroom parts of a residential unit located on the 5th floor of the building were retrofitted with interior insulation, i.e. insulation was added to all opaque interior surfaces of the room. Another residential unit, with the same orientation and layout, located on the 5th floor of an adjacent building in the same residential community, was chosen as the comparison group.

From 2019 to 2020, the households of the experimental and comparison group have been living in the corresponding residential units throughout the cooling and heating seasons. Based on monitoring outdoor weather data in real time, the hottest period of summer 2019 and the coldest period of winter 2020 were chosen for the comparison experiments.

Under the same conditions of the number of occupants, energy usage patterns and energy-using equipment in the building, the three most commonly used intermittent air conditioning methods were set up for comparison experiments in summer and winter respectively. Based on the analysis of the actual measured outdoor weather data, indoor temperature and humidity data and energy consumption data of the air conditioning, the improvement effect of the cooling and heating seasons in a typical residential building in the Chengdu area was obtained after adding interior insulation.

3.2 Description of the case study building

Figure 3-2. Site plan of the selected buildings.

This case study was conducted in Chengdu, the capital city of Sichuan province, located in the southwest region of China. As a representative city in the HSCW region, its climate is characterised by hot and humid summers and cold and wet winters. Figure 3-2 shows the site plan of the chosen residential community. There are seven high-rise residential buildings in the community, built in 2010. These buildings are all 30 stories, with a total height of 99.3 m, and have six apartments on each floor. The main facades of the buildings face north and south. The buildings are constructed of reinforced concrete. And they are already equipped with outside wall insulation, which is the most common insulation practice locally. In terms of window types, they are single-framed and single-glazed, which is prevailing in the HSCW zone.

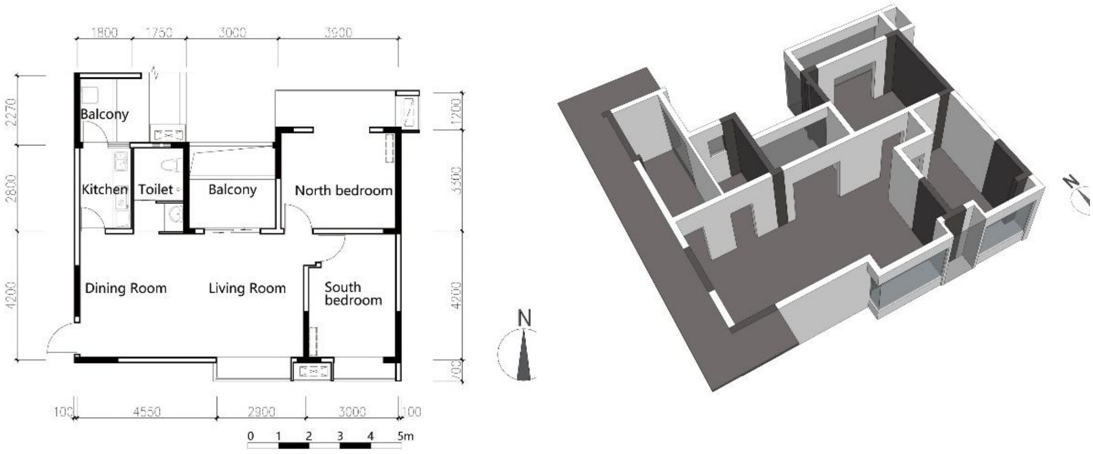

Figure 3-3. Original floor plan (left) and a perspective view (right) of the residence.

To ensure consistent exterior conditions for the experimental and comparison residences, two identical north-south facing residence units on the right side of the 5th floor of residential buildings No. 2 and No. 4 in the community were selected. Among them, the residential unit in Building No. 4 was set as the retrofit group, while the one in building No. 2 was set as the original group for comparison. Figure 3-3 shows the geo-graphical relationship between these two buildings. The original floor plan of the residence is shown in Figure 4, with the original floor plan (left) and a perspective view (right). The unit studied consists of two bedrooms, a living-cum-dining room, a kitchen, and a bathroom.

Figure 3-4. Overview of the selected residences: the original unit.

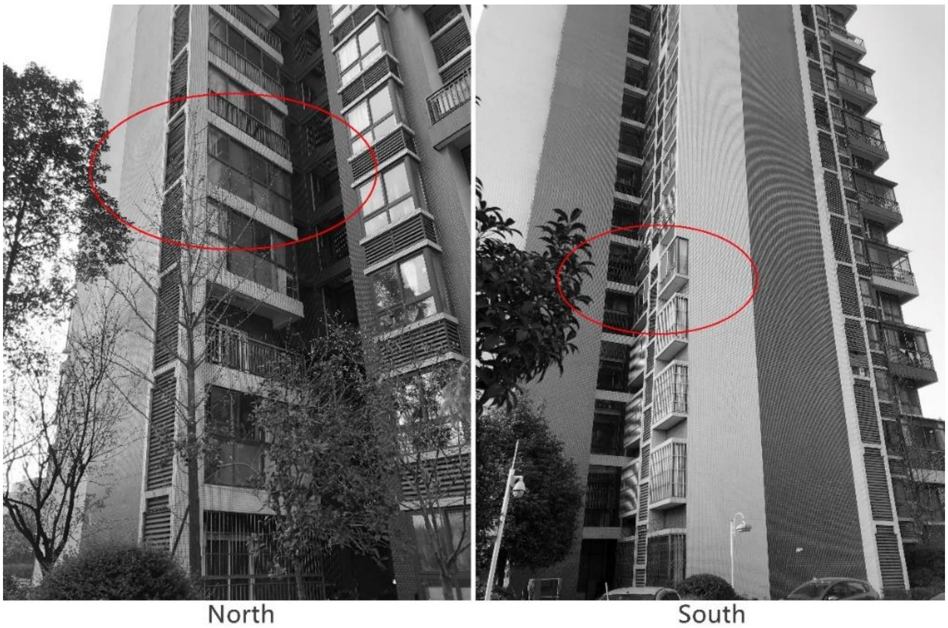

Figure 3-5. Overview of the selected residences: the renovated unit.

A realistic view of the north and south elevations of both units is shown within the red circle in Figure 3-4 and Figure 3-5.

3.3 Description of the retrofit work

3.3.1 Description of the retrofit process

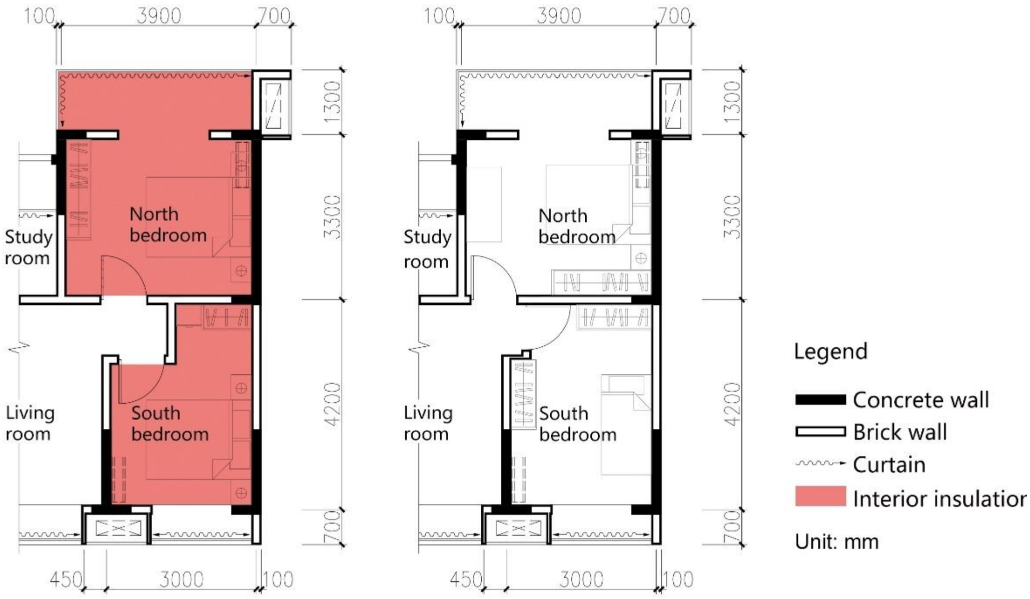

Figure 3-6. Layout plan of the renovation area, renovated unit (left), and original unit (right).

Based on the purpose of this study, the south and north bedrooms of the residence in Building No. 4 was retrofitted with interior insulation during the summer of 2017. That is, insulation was added to all internal opaque structural surfaces of the south bedroom, including walls, ceilings, and floors. Layout plan of the renovation areas of the experimental and comparison units are shown in Figure 3-6.

Figure 3-7. Overall view of the retrofit construction process.

Details of the retrofit are as follows. The insulation panels used in the building were made of extruded polystyrene (XPS) boards, of which 30 mm-thick panels were used for the walls and floors and 20 mm-thick panels for the ceiling areas. Each XPS panels were 300 mm wide, supported by a wooden keel, and then covered with a layer of gypsum plaster-board. The overall retrofit construction process is shown in Figure 3-7. Installation of insulation panels and details are shown in Figure 3-8.

Figure 3-8. Installation process of insulation board.

3.3.2 Comparison of envelope configurations before and after the retrofit

This section shows the specific material composition and parameters of the various parts of the building envelope before and after the renovation. The building parameters are also compared with the specific requirements in the Building Design Code in Sichuan Province.

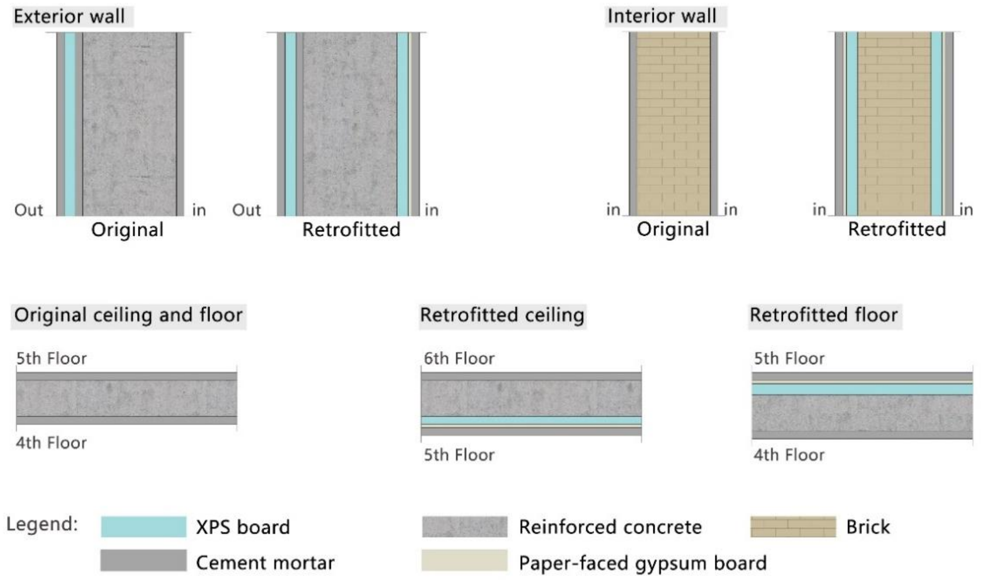

Figure 3-9. Configuration of the building envelope.

The comparison of the configuration of all opaque enclosures (exterior walls, interior walls, ceiling, and floor) in the south bedroom of the original and retrofitted unit is shown in Figure 3-9.

Table 3-1. Material list of outside walls before retrofit (Outside to Inside).

	Cement mortar	**XPS board**	**Cement mortar**	**Reinforced concrete**	**Cement mortar**	R_i	R_e
Thickness (m)	0.02	0.03	0.02	0.2	0.02		
Conductivity W/(m·k)	0.93	0.03	0.93	1.74	0.93		
Thermal resistance R (m^2·K/W)	0.02	1.00	0.02	0.11	0.02	0.11	0.04
Total thermal resistance R (m^2·K/W)	1.33						
Heat transfer coefficient K (W/ m^2·K)	0.75						

The parameters of the material chosen for the original facade of the building and the K value of the facade are calculated in Table 3-1. When the main building material of the facade is reinforced concrete, the K value is 0.75.

Here is the nomenclature list involved in Table 3-1 and Table 3-2:

R - thermal resistance;

R_i - Internal surface heat transfer resistance;

R_e - External surface heat transfer resistance;

K - Heat transfer coefficient.

Table 3-2. Material list of outside walls after retrofit (Outside to Inside).

	Cement mortar	**XPS board**	**Cement mortar**	**Reinforced concrete**	**XPS board**	**Paper-faced plasterboard**	**Cement mortar**	**R_i**	**R_e**
Thickness (m)	0.02	0.03	0.02	0.2	0.03	0.0095	0.02		
Conductivity W/(m·k)	0.93	0.03	0.93	1.74	0.03	0.31	0.93		
Thermal resistance (m^2·K/W)	0.02	1.00		0.11	1.00	0.03	0.02	0.11	0.04
Total thermal resistance (m^2·K/W)	2.34								
Heat transfer coefficient (W/ m^2·K)	0.43								

In Table 3-2, the parameters of the material of the exterior wall and the K-value of the exterior wall are calculated for the selected building after the internal insulation retrofit, and it shows that when the main building material of the exterior wall is reinforced concrete, the K-value decreases to 0.43 after the addition of the interior insulation.

Table 3-3. Shape factor of the selected building.

Parameters	Value
Area of standard floor (㎡)	558.05
Perimeter of standard floor (m)	170.95
Total height (m)	93
External surface area (m^3)	16456.4
Volume (m^3)	51898.65
Shape factor of building	0.32

The shape factor is the ratio of the external surface area of a building in contact with the outdoor atmosphere to the volume it encloses. There is a direct relationship between the building shape factor and the energy efficiency of a building; the larger the shape factor, the larger the external area of the same building volume, the larger the heat dissipation area and the higher the building energy consumption, which is detrimental to building energy efficiency. In Table 3-3, the shape factor is calculated based on the selected high-rise residential building and the result is 0.32.

Table 3-4. Limits on the shape coefficient of residential building [1]**.**

(Source: DB51 /5027, Design standard for energy efficiency of residential buildings in Sichuan Province [S]. Chengdu. Southwest Jiaotong University Press, 2019.)

Climate zone	Number of building floors			
	≤3F	4~6 F	7~11 F	≥12F
The plateau-severe cold climate zone	≤0.50	≤0.30	≤0.28	≤0.25
The plateau-cold climate zone	≤0.52	≤0.33	≤0.30	≤0.26
The hot summer and cold winter zone	≤0.55	≤0.45	≤0.40	≤0.35

According to the design standard for energy efficiency of residential buildings in Sichuan province, the shape factor (S) of the designed building should meet the prescribed limits in Table 3-4. Obviously, the experimental high-rise building selected is in accordance with the design criteria of the table that the bulk factor of residential buildings larger than 12 stories in hot summer and cold winter regions should be less than or equal to 0.35.

Also, the design standard for energy efficiency of residential buildings in Sichuan Province specifies the thermal performance limits for the building envelope in each climate zone involved in Sichuan Province. Table 3-5 shows the thermal performance limits for the building envelope of the experimental building in this study, i.e., the building envelope should satisfy the table if the building shape factor is less than or equal to 0.40. Comparing the actual limit values calculated in Table 3-2 for the buildings after retrofitting, it can be concluded that they are in compliance with the design standards.

Table 3-5. Thermal performance limits for enclosure structures in hot summer and cold winter zone [1].

(Source: DB51 /5027， Design standard for energy efficiency of residential buildings in Sichuan Province [S]. Chengdu. Southwest Jiaotong University Press, 2019.)

Shape factor of building	**Parts of the envelope**	**Conductivity K [W/(m·k)]**	
		D≤2.5	**D＞2.5**
S≤0.40	Roof	≤0.60	≤0.80
	Exterior wall	≤0.80	≤1.20
	Overhead or exposed floor slabs with bottom surface in contact with outdoor air	≤1.20	
	Subdivision Wall	≤1.50	
	Separate floor slabs for living room, bedroom, study room and other functional rooms	≤1.80	
	Door to the outside of the heating and air conditioning room	≤2.50	

3.4 Description of the experimental conditions

3.4.1 Details of the air conditioners

To keep the experimental conditions consistent between the retrofit and non-retrofit groups, the same type of air conditioners was used in both residential units. The brand of air conditioner used in the north bedroom was GREE, while the brand of air conditioner used in the south bedroom was Changhong, and their energy efficiency ratios were 3.53 and 3.25 respectively. Specific information of the air conditioners used in the bedrooms during the experiment is presented in Table 3-6.

Table 3-6. Parameters of the air conditioners in use.

Parameter	North bedroom	South bedroom
Air-conditioner brand	GREE	Chang hong
Type	Variable frequency	Fixed frequency
Cooling power (W)	980 (160-1400)	810
Heating power (W)	1400 (190-1615)	800
COP (Coefficient of Performance)	3.53	3.25

Figure 3-10. Actual photos of the air conditioners (left is the north bedroom, right is the south bedroom).

Figure 3-10 shows the actual photographs of the air conditioners used in the experiment are shown, in which the left is the air conditioner in the north bedroom and the right is the air conditioner in the south bedroom.

3.4.2 Layout and details of the measurement instruments

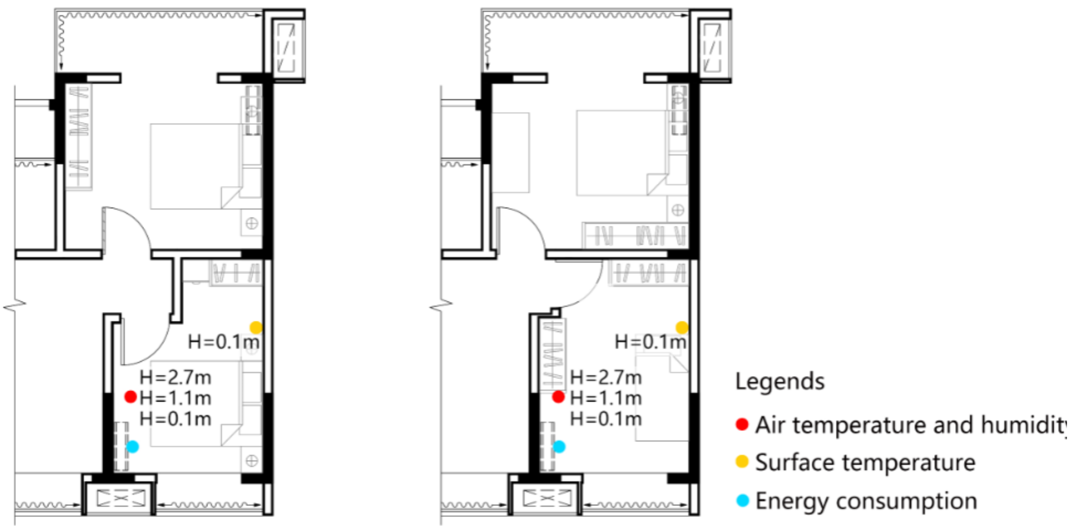

Figure 3-11. Layout of the measuring instruments, renovated unit (left), and original unit (right).

In the main experiment, the measurement area is the south bedroom, and Figure 3-11 shows the layout location map of the indoor experimental equipment. The main parameters measured in the indoor area are indoor temperature and relative humidity, and temperature and humidity meters were arranged at 0.1 m, 1.1 m, and 2.7 m from the position of the red dots in the figure. Also, in order to observe the relationship between the indoor air temperature and the structure surface temperature, the temperature of the inner surface of the external wall was also measured. Finally, in order to accurately obtain the cooling and heating energy consumption of the air conditioners, each air conditioner was equipped with a separate energy measurement device for recording.

The above-mentioned vertical relationship between the thermohydrometer and the air conditioner is shown in Figure 3-12.

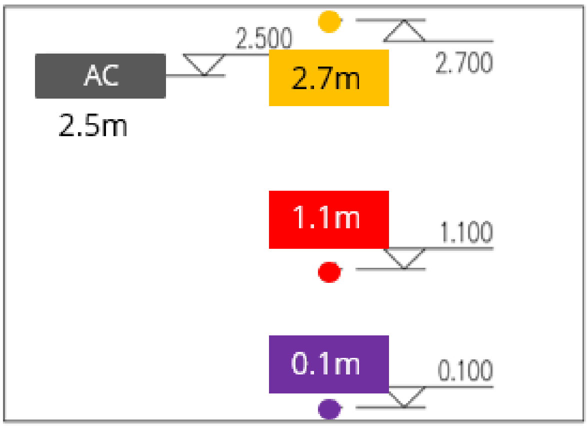

Figure 3-12. Sectional view of the measuring instruments.

To ensure the same experimental conditions, identical air conditioners were installed in the two south bedrooms.

During the experiment, the following parameters were collected:

(1) Outdoor parameters were collected through a weather station on the open roof of a nearby multi-story building, and data were recorded every 10 minutes, including outdoor temperature (°C), outdoor relative humidity (%), solar radiation (W/m^2), wind direction, and wind speed (m/s).

(2) Indoor parameters, including indoor air temperature (°C) and indoor relative humidity (%), were measured every 10 minutes in the retrofitted and original south bedrooms. Among them, the indoor temperature was measured at 0.1 m, 1.1 m, and 2.7 m in the middle of the bedroom.

(3) The power consumption data of each air conditioner was recorded every 2 minutes.

Key parameters of the measuring instruments are shown in Table 3-7.

Table 3-7. Key parameters of the measuring instruments.

Measured Parameter	Instrument	Measuring Range	Accuracy	Recording Interval (Minutes)
Outdoor air	Vantage Pro2	–40– +65 ℃	±0.5 ℃	10
Outdoor relative		1–100%	±3–4%	10
Solar radiation		0–1800 W/m²	±5%	10
Wind speed		1–67m/s	±5%	10
Wind direction		0–360°	±7°	
Indoor air temperature	TR-72UI	0–+50 ℃	±0.3 ℃	10
Indoor relative		10–95%	±5%	10
Surface temperature	TR-71wf	-40~110 ℃	±0.3℃	10
Energy consumption	OriMeter			2

In addition, Figure 3-13, Figure 3-14, and Figure 3-15 show realistic photographs of all the equipment used. They show realistic photos of the small weather station placed outside, the equipment for measuring the electricity of the air conditioner, and the location of each thermo-hygrometer inside the house.

Figure 3-13. Actual layout of the installed measuring instruments.

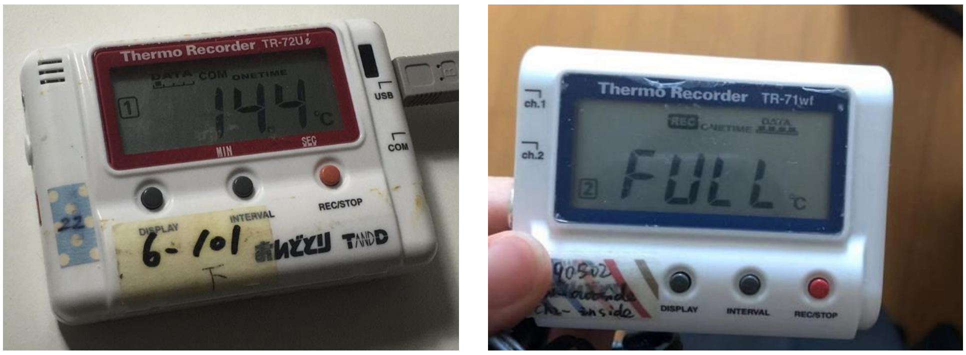

Figure 3-14. Actual photos of TR-72Ui and TR-71wf.

Figure 3-15. Actual view of OriMeter.

Figure 3-16 shows the real photos of the small weather station measuring outdoor weather data, which is placed on the roof of an empty low-rise building about 1 km away from the experimental building in order to ensure that it is not obscured from the surrounding area. Its physical location with respect to the experimental building is also shown in the figure.

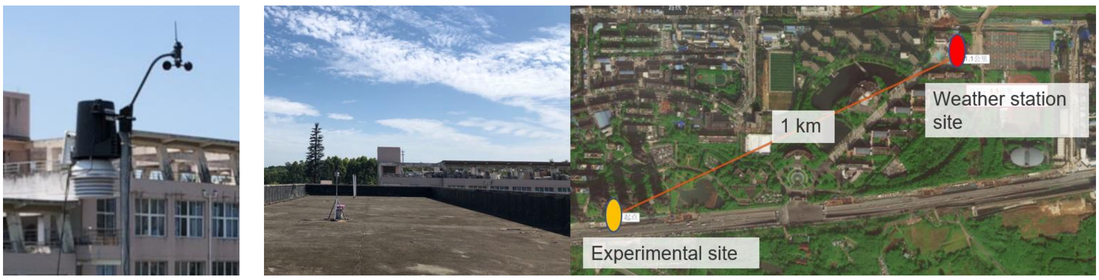

Figure 3-16. Layout of the weather station.

During the summer of 2019, the experimental households lived in the experimental residence and the comparison residence from June onwards, and the indoor and out-door climates were monitored in real time. By tracking real-time measurement data, it was observed that from August 10th, successive hot weather began to appear, reaching almost the hottest levels of previous years. The highest outdoor temperature reached 37 to 38 °C and the fluctuations between indoor and outdoor temperatures were almost the largest among the summer months. Therefore, these typical summer days were selected to conduct the comparison experiment. The actual measurement experiments were conducted over 9 consecutive days from August 10th, 2019, to August 18th, 2019.

During the winter of 2020, the experimental households lived in the experimental residence and the comparison residence from December onwards, and the indoor and outdoor climates were monitored in real time. By tracking real-time measurement data, it was observed that from January 8th, successive cold weather began to appear, reaching almost the coldest levels of previous years. The minimum outdoor temperature reached below 5 °C and the maximum temperature was around 15°C, which was almost the lowest level in previous winters. Therefore, these typical winter days were selected to conduct the comparison experiment. The actual measurement experiments were conducted over 10 consecutive days from January 8th, 2020, to January 17th, 2020.

3.4.3 Summary of experimental conditions

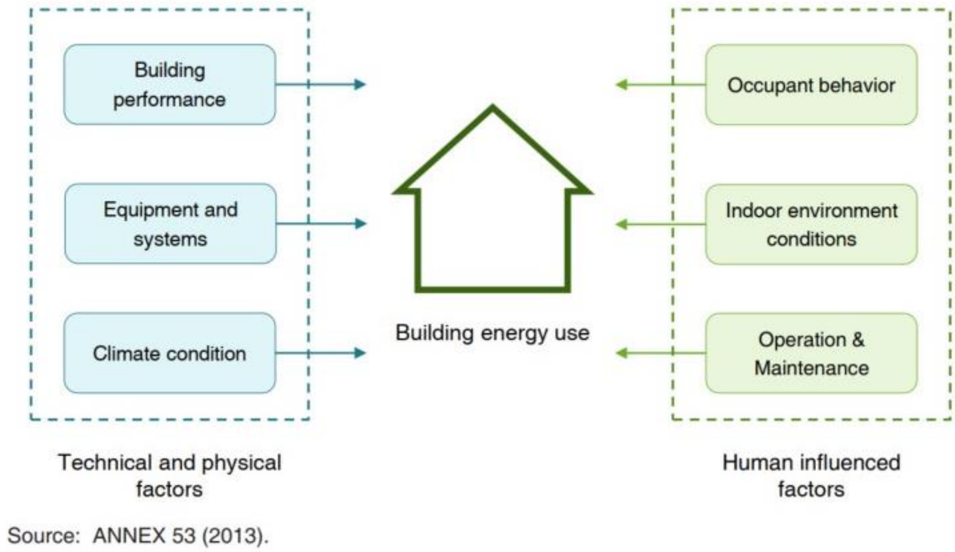

Figure 3-17. Six influencing factors on building energy use [2]**.**

(Source: Jiang Y, Yan D, Guo S, Hu S. China Building Energy Use 2018. 2018.)

In general, in order to limit the study to the insulation of the envelope, all other experimental conditions were made as uniform as possible throughout the experiment. Of the six main factors affecting building energy use shown in Figure 3-17, equipment and systems, climatic conditions, indoor environmental conditions, and the mode of operation of the equipment were all ensured to be consistent between the experimental and control units, and are described in the previous section of this chapter. In addition, the number and behaviour of people in the room were also aligned, with two adults and one pre-school child living in both residential units. They all followed the most common daily behavioural patterns in the area during the day, with the two adults living in the north bedroom and the one child in the south bedroom at night.

3.5 Summary

This chapter includes the framework of the research methodology, the description of the selected case building, the renovation process and the construction of the building envelope, and the description of the experimental conditions. Whether in terms of the structural form of the building, the physical characteristics of the envelope, or the form of insulation, the case building chosen for this study is a typical representative of high-rise urban housing in Chengdu. The actual measurements covered both the cooling and heating seasons. And the consistency of the experimental conditions, apart from the subject (insulation), was ensured during the experiment.

Reference

[1] DB51 /5027， Design standard for energy efficiency of residential buildings in Sichuan Province [S]. Chengdu. Southwest Jiaotong University Press, 2019.

[2] Jiang Y, Yan D, Guo S, Hu S. China Building Energy Use 2018. 2018.

Chapter 4

IMPROVEMENTS AFTER INTERIOR INSULATION RETROFIT UNDER INTERMITTENT COOLING CONDITION

CHAPTER FOUR: IMPROVEMENTS AFTER INTERIOR INSULATION RETROFIT UNDER INTERMITTENT COOLING CONDITION

4.1 Introduction

4.1.1 Background

Cooling is currently one of the most serious threats to human settlement. Air conditioners and electric fans consume nearly 20% of the total electricity used in buildings worldwide today for cooling [1]. Global warming is altering the outdoor climate gradually, and it is predicted that in the future there will be fewer extremely cold days and more extremely hot days [2]. Under this trend, the global demand for air conditioners is growing dramatically, with annual global sales almost quadrupling from 1990 to 2016, reaching 135 million units [3].Wang et al. (2010, 2011) [4,5] quantified the impact of climate change on cooling and heating energy, and their results show that cooling demand will grow by 350% and heating demand will decline by 48% by 2100. Without timely action, the OECD predicts a global temperature rise of 1.7 to 2.4 °C by 2050 [6]. However, the IPCC study shows that global warming of more than 1.5 °C could cause irreversible damage to ecosystems and create a huge crisis for vulnerable people and societies [7]. Limiting global temperature rise to less than 1.5 °C requires an unprecedented global effort and will be more difficult than limiting it to less than 2 °C. Only if we take urgent mitigation action right now, across all sectors, will it be possible to curb such a situation [8].

In fact, global warming does not affect all regions of the world equally [9]. The rate of increase in greenhouse gases varies greatly among countries due to differences in climate, population, and degree of economic development. The OECD's share of global greenhouse gas emissions will decline from 40% to 33% in 2050, while the rate of growth will be faster outside the OECD region [6]. This is because global economic growth is shifting southward; it is projected that nearly 34% and 52% of the new population by 2030 will live in Africa and Asia, respectively [10]. Therefore, as one of the largest emerging economies in Asia, China faces greater pressure to save energy and reduce emissions in the building sector.

Generally, building energy consumption is influenced by both technical and physical factors and human-influenced factors [11]. Chief among the former is the environmental climate in which the building is located. To make better use of and adapt buildings to the different climatic conditions in China, the country is divided into five climatic zones (Figure 1), namely “the severe cold (SC) zone”, “the cold (C) zone”, “the hot summer and cold winter (HSCW) zone”, “the hot summer and warm winter (HSWW) zone” and “the mild (M) zone” [12]. Among these climate zones, the HSCW zone is very special for the following reasons. This region accounts for less than 20% of the country’s total area but is populated by more than 40% of the nationwide population [13]. In the meantime, the region has experienced faster economic growth than other regions, allowing it to contribute close to 48% of the national GDP [14]. However, in such an economically developed and densely populated area, the indoor environment of buildings is the worst of all climatic zones [14]. As its name suggests, the HSCW zone is an area with hot summers and cold winters, with average outdoor temperatures between 0 and 10 °C (the coldest month) and 25 °C and 30 °C [15] (the hottest month). In addition, related studies have also shown that sunshine is in short supply in this region. The percentage of possible sunshine is below 50% in the eastern part of the HSCW region [16]. It is especially low in winter, only 21% in Chengdu [17]. Compared to other parts of the world at the same latitude, the climate in the HSCW region is harsher, with the coldest month about 8 °C lower and the hottest month about 2 °C higher [18]. Chengdu city (Figure 2), where this experiment was conducted, is a representative city of the HSCW region, and the brief situation of climate and buildings are as follows. Rough outdoor conditions combined with poor local building insulation design and construction directly contribute to the poor indoor thermal environment of local residential buildings. In summer, the indoor temperature of residential buildings in Chengdu can be as high as 38 °C, showing a tiny temperature difference between the indoor temperature and the outdoor temperature [19]. As a result, this has led to higher energy consumption per unit of cooling and heating in the HSCW region than in colder regions of China. Related studies have shown that the district requires 80 million kW of cooling load in summer and 20 million kW of heating load in winter if indoor thermal comfort is to be maintained [20].

4.1.2 Literature review

The building envelope acts as a critical element in affecting buildings' thermal performance, because it accounts for about 60–80% of total heat transfer [21]. This means that improving the thermal performance of the building envelope can remarkably enhance the whole building's energy efficiency. The annual building cooling load and peak building cooling demand for buildings located in hot regions can be significantly reduced with insulation [22–27]. When using insulation to improve the building envelope, it is common practice to place insulation on the exterior of the building [28]. In China, outside insulation was first adopted in central heating areas in the north. Centralized heating areas and non-heating areas are defined by set geographical boundaries (the Qinling Mountains-Huaihe River Line) drawn in the 1950s, based mainly on climatic conditions [29]. Take the example of a residential unit in the central heating district, continuous heating is provided for the whole unit by the government throughout the heating season.

Extensive studies have shown that outside insulation is a good choice in the case of continuous energy use over the entire house. Al-Sanea and Zedan (2001) [30] numerically investigated the influence of the insulation layer location on the thermal performance of building walls under steady periodic conditions in Saudi Arabia. Assuming a constant room temperature, the results indicate that better thermal performance can be obtained by placing the insulation on the outer surface of the wall. Kossecka and Kosny (2002) [31] theoretically analyzed the performance of insulation configuration in six different US climates. Energy analysis of six characteristic wall configurations was done based on a continuously used building. The results show that the most energy-efficient configuration was when all insulation was located on the outside of the exterior wall, and the least energy-efficient configuration was where all insulation was located on the inside. The maximum difference in total energy demand may exceed 11%. Another comparative experiment conducted by Fang Zhaosong et al. (2014) [32] in the summer in the HSCW region of China revealed that when exterior wall insulation was used in conjunction with hollow blocks and double-glazed windows, the energy savings in summer air conditioning could reach 23.5%. Sheila et al. (2019) [33] analyzed the façade of a residence that is renovated with external thermal insulation composite systems under a temperate climate in Spain. The results showed that the renovated façades with this insulation system decreased energy loss by 57% and reduced energy gain by 39% compared to the original facade. The above studies prove that when air conditioners are in continuous use, external insulation is the better choice for energy-saving purposes.

However, this continuous usage pattern of air conditioners over the entire residential unit is not common in the HSCW area. In daily life, most occupants use air conditioners according to their real-time thermal feelings—that is, they choose to turn on the air conditioner when they feel hot, and turn it off when they feel comfortable or leave the space. This feature can be summarized as intermittent cooling/heating. Additionally, a large body of studies has shown that in the case of intermittent operation of air conditioners, there is a large difference in building thermal performance compared to a continuous operation mode. Studies by Al-Sanea and Zedan (2001) [34] showed that under the hot and dry climate of Riyadh, placing insulation on the inside of the wall achieves a stable periodic state more quickly than placing it on the outside. The transient load of placing the insulation on the inside during the initial transient process is about 20% of that of the outside insulation. During the first 24 hours of air conditioning operation, the average heat transfer with the inside insulation is around one-third that of the outside insulation. It was recommended that insulation should be placed on the inside of the wall when the air conditioners in the space are used intermittently. The difference between insulation at various locations on the external wall was compared by Ibrahim et al. (2012) [35] under the intermittent and continuous operation of air conditioning. It was found that setting the insulation on the inside of the wall during intermittent operation reduced the energy load by 15% compared to setting it on the outside of the wall in the Mediterranean coastal region and the Lebanese inland highland climate conditions. Energy simulations were conducted by Bojic et al. (2001) [36] to study the installation of thermal insulation in high-rise residential buildings under the hot climate of Hong Kong. The results show that the maximum annual cooling load could be reduced by 6.8% when the insulation is located close to the interior of the apartment when using air conditioning at night in summer. In the HSCW region of China, based on the actual climatic conditions in Shanghai, Liting Yuan (2017) [37] conducted a further study combining mathematical modeling and numerical solution to discuss the effect of insulation characteristics on the building energy consumption of intermittently operating air conditioning systems in office buildings. It was pointed out that the key factor affecting the transmission load of the intermittently operating air conditioning system is the heat dissipation and heat storage of the inner layer of the wall during non-working hours. The energy savings of rooms with internal insulation are at least 18% higher than those with external insulation, while the energy savings of internal insulation are more significant for south-facing office rooms. Some scholars conducted similar studies in religious architecture. A study conducted by Budaiwi and Abdou (2013) [38] was on mosques, which serve as places of worship for Muslims and are usually partially or fully occupied for about one hour several times a day. Without sacrificing thermal comfort, an insulated mosque with oversized HAVC equipment can reduce cooling energy consumption by 23% if operated intermittently (1 h for each prayer), compared to the continuous cooling operation. To achieve the desired thermal comfort conditions with intermittent operation, the HVAC (heating, ventilating, and air conditioning) equipment must be properly oversized or its operation should be performed before occupancy. In addition, the implementation of operational zoning in mosques can additionally significantly reduce the annual cooling energy demand.

Similar to the case of mosques, the use of air conditioning in the HSCW area is also often characterized by zoning, i.e., turning on the air conditioning in a room only when that room is occupied. When the air conditioner is on in only some of the rooms, the interface of heat loss is not only the exterior walls but also the interior walls, ceilings, and floors. In this case, whether the internal envelope is insulated or not can greatly affect the effectiveness of the air conditioning. Field experiments conducted by Li Nan and Chen Qiong (2019) [39] showed that whether an adjacent room is heated or not directly affects the surface temperature and total heat consumption of the interior walls. Compared to the heated neighboring rooms, when the neighboring rooms are not heated, the heat flux density on the surface of the interior walls increases by 29.8–52.2%, resulting in an increase of 5.2–7.2% in the total amount of heat supplied to the room. Yanna Gao et al. (2020) [40] optimized the opaque envelope components of three typical rooms under the intermittent operation of air conditioning in summer by numerical simulation. The results show that the energy-saving contribution of the floor and ceiling reaches 35–80%, which is higher than that of the interior and exterior walls. Moreover, as the room area increases, the energy-saving contribution of the floor and ceiling becomes larger. Therefore, the impact of the internal envelope on the indoor thermal environment and energy consumption cannot be ignored in the actual use situation.

Apart from the location of the insulation, the materials selected in the insulation system and their thickness also have a great impact on the energy efficiency and indoor thermal environment. Energy efficiency and economic efficiency are factors that need to be considered simultaneously when selecting materials. In general, cost-effective materials include glass mineral wool, rock wool, mineral fiber, and flexible wood fiber, XPS, and EPS [41]. Furthermore, the effect of insulation thickness on the effectiveness of energy efficiency retrofits has been widely discussed. It has been found that there is a critical thickness of insulation for exterior wall structures, and when the thickness exceeds the critical value, the insulation effect will be insignificant [42]. The thickness of the insulation also influences the relative humidity. Simulation and empirical studies have shown that reducing the thickness of the insulation and setting up double-layered gypsum boards have a reducing effect on the peak relative humidity in the gap between the internal insulation and the wall when retrofitting the internal insulation of historical buildings [43].

4.1.3 Research gap

Moreover, many of the existing studies are merely simulations and calculations, and the results in actual use cases will be somewhat different from them in many ways. Firstly, many studies use the harmonic response method with periodic changes in climate conditions to calculate the annual heating and cooling load; however, the actual climate conditions change in real-time [44]. Secondly, assuming constant indoor air temperature conditions is also not suitable for the actual use of residences in the HSCW region, since air conditioning tends to be used intermittently [45]. Thirdly, the set-up conditions of simulated buildings are often idealized, while the actual use of the building may have some deviations from the design conditions due to construction processes, material selection, etc. [46]. At last, in the optimization of building energy efficiency, internal and external heat gains are factors that have a great impact on energy consumption, externally, such as solar radiation, and internally, such as heat generated by occupants, air exchange frequency, heat generated by lamps, and appliances, etc. [47]. This part is also more realistic and reliable than simulation studies in real-life scenario-based measurements. All the above may lead to the fact that the results in the actual use scenario are not the same as the simulated ones.

In fact, similar intermittent energy use habits are also very common in Japan. In our previous study, we compared the effects of outside insulation, inside insulation, and interior insulation on energy consumption and indoor thermal environment in Japanese residences by simulation for a whole year situation. Simulation results for seven cities in Japan showed that compared to outside-insulated residential units, the average annual air conditioning energy use was 0.5% lower in the internally insulated unit, and 25.8% lower in the interiorly insulated unit [48]. As a further investigation, this study can provide more persuasive evidence to quantify the improvement of this new insulation system by actual measurement in the operational phase. In addition, interior insulation has very good application prospects and value in the renovation of existing buildings. Case studies for central-heating regions in northern China show that outside wall insulation has the most energy-saving potential but is the least cost-effective among various retrofitting measures [49]. For detached houses, external insulation retrofitting is relatively easy to implement. However, the largest proportion of urban dwellings in the HSCW region are high-rise residential buildings. For those high-rise residential buildings that have already been sold and in use for several years, the renovation of outside insulation also involves the renovation of the entire facade of the building, which is very expensive and takes a long time. Moreover, such a complete renovation cannot be carried out without the permission of the whole building's occupants. Under such circumstances, internal insulation retrofitting is much easier to achieve. The retrofitting work is more flexible [50], regardless of the scope. It can be applied to a residential unit or just a single room. Additionally, interior insulation is less expensive to install than outside insulation. However, at present, there is a lack of research on the optimization of the insulation design of existing buildings in the HSCW region.

4.1.4 Objectives of this study

In building design, the major influence on building energy consumption can be divided into two parts, transparent parts such as windows, window orientation, window-to-wall ratio, and glass type, and opaque parts such as walls, roofing, and insulation [51]. In this case study, the insulation layer is taken as the main object of study while ensuring the consistency of other building components. The south bedroom of a residence in the high-rise case study residential building was retrofitted with interior insulation in Chengdu. The comparative measurements were done in August 2019 for the following research objectives:

1. To study the energy-saving effect of adding interior insulation to the south bedroom of existing external-insulated buildings in the HSCW region of China, under the typical intermittent cooling air conditioning modes in summer.
2. To investigate the improvement of the indoor thermal environment in the retrofitted bedroom compared to the un-retrofitted one.

It should be noted that this study is based on the condition that existing residential buildings already had outside insulation, so the south bedroom of the experimental residence had both outside insulation and interior insulation.

The rest of this article will be developed in this way: the building retrofitting process and the experimental process and conditions will be shown in Section 4.2; the results of comparing the energy consumption and indoor thermal environment measured by experiments under real scenarios will be shown in Section 4.3; Section 4.4 is a discussion of the limitation and future research direction of this paper; and finally, Section 4.5 will be the conclusion of this part.

4.2 Materials and methods

4.2.1 Selection of the experimental time period

During the summer of 2019, the experimental households lived in the experimental residence and the comparison residence from June onwards, and the indoor and outdoor climates were monitored in real time. By tracking real-time measurement data, it was observed that from August 10th, successive hot weather began to appear, reaching almost the hottest levels of previous years. The highest outdoor temperature reached 37 to 38 °C and the fluctuations between indoor and outdoor temperatures were almost the largest among the summer months. Therefore, these typical summer days were selected to conduct the comparison experiment. The actual measurement experiments were conducted over 9 consecutive days from August 10th, 2019, to August 18th, 2019.

4.2.2 Air conditioning operation mode and occupants' behavior pattern

As mentioned earlier, most households in the HSCW region only use an air conditioner for a few hours a day in a separate room, depending on their demand. The air conditioning usage patterns corresponding to the three most typical household compositions were selected. Namely, use the air conditioner from the night to the early morning (case 1: office workers), use the air conditioner during lunch break and from night to the early morning (case 2: elderly people), and use the air conditioner from the morning to late night/next morning (case 3: mixed family). The specific details of the usage model are shown in Table 4-1.

Table 4-1. The operation patterns of the air conditioners.

Operation	Cooling Period	Operation Duration	Operation Temperature	Cooling Area
Intermittent case 1	0:00–2:00; 22:00–24:00	4 h	26 °C	North and south bedroom
Intermittent case 2	0:00–2:00; 12:00–17:00; 19:00–0:00	12 h	26 °C	North and south bedroom
Intermittent case 3	0:00–2:00; 8:00–24:00	18 h	26 °C	North and south bedroom

To minimize the influence of the habits of residents and the time they spend in the building, the following arrangement was made. In both the experimental and comparison residential units, the occupants consisted of a young couple and a preschool child, who live in the north and south bedrooms, respectively. During the experiment, they followed the same routine which is the most common one of the locals. Except for the bedroom area, no cooling equipment such as air conditioners and electric fans were used in any of the rooms. Since the experiment was conducted in a real-life scenario, both bedrooms had the demand to use air conditioners, so residents in both bedrooms followed the same air conditioning usage pattern in Figure 4-1.

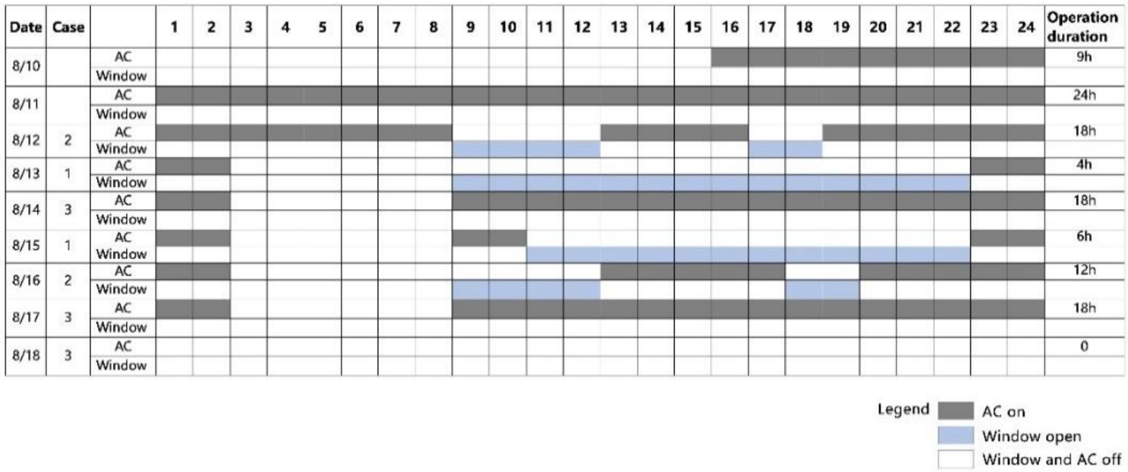

Figure 4-1. The operation schedule of the air conditioner and window.

It should be noted that since the occupants in the experiment were living in the residence, the usage pattern of the air conditioner was inevitably changed due to temporary changes in the occupants' daily plan. Figure 1 shows the actual use of air conditioners and windows during the experiment. During the cooling period of the experiment, the airspeed of the air conditioners was in automatic mode, and windows, doors, and curtains are always closed. While since there is no mechanical ventilation system in local residences, residents are used to opening windows for fresh air every day several times a day. To simplify the operation of the experiment, the windows were opened and ventilated during the daytime hours when the air conditioner was turned off. In the interior of the bedroom, there were no other electrical devices except for an electric light which is the same in both units. During the experiment, the windows were opened and closed according to the schedule in Figure 1, and the open width was 30 cm. The curtains were opened and closed in the same way as the window. During the measurement, the occupant behavior was as follows: during the daytime, nobody stayed in the south bedroom except for the operation point. The main activity in the bedroom was sleeping, and the sleeping time was from 22:00 to 8:00.

4.3 Results

4.3.1 Analysis of outdoor climate

Figure 4-2 shows the outdoor temperature and relative humidity measured every 10 minutes by the weather station in August 2019, which was one of the hottest months of the summer. In this Figure, it can be observed that August 12th to August 18th was an extremely hot period, with maximum outdoor temperature exceeding 37 °C on four days and 32 °C on three other days. The highest temperature was 38.1 °C (between 16:00 and 17:30 on August 12th) and the average temperature was 30.89 °C during the measuring period. Even at night, the temperature remained high, with a minimum temperature of 24.2 °C. Additionally, outdoor relative humidity was at a high level, with an average relative humidity of 61.49% and a maximum of 90% during the test period (between 7:00 and 7:40 on August 14th). The data above demonstrate the typically hot and humid climate characteristics of Chengdu in summer.

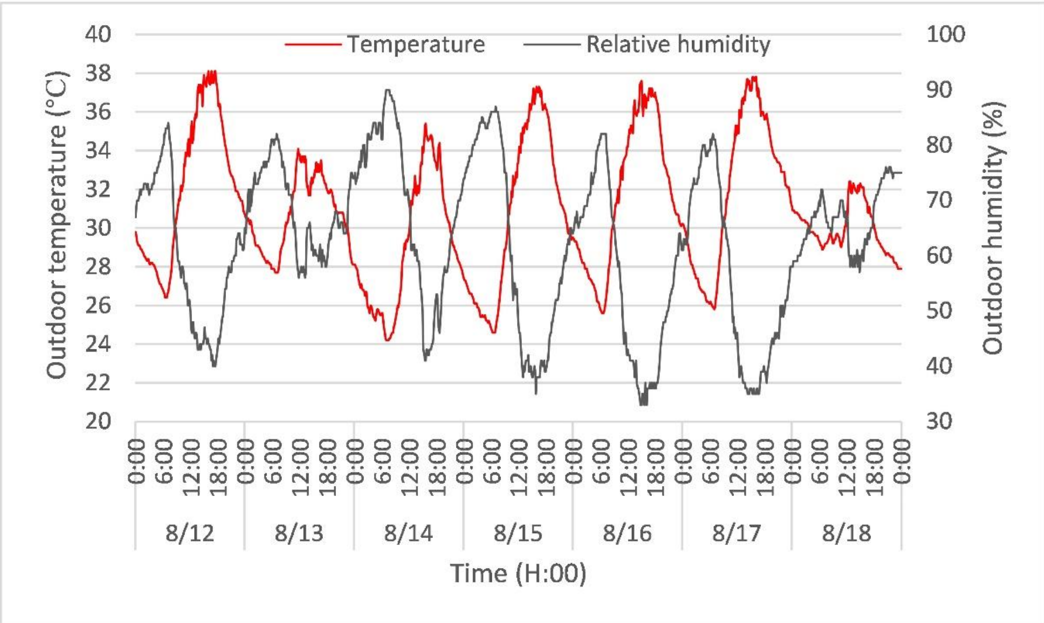

Figure 4-2. Outdoor temperature and relative humidity during the measurement.

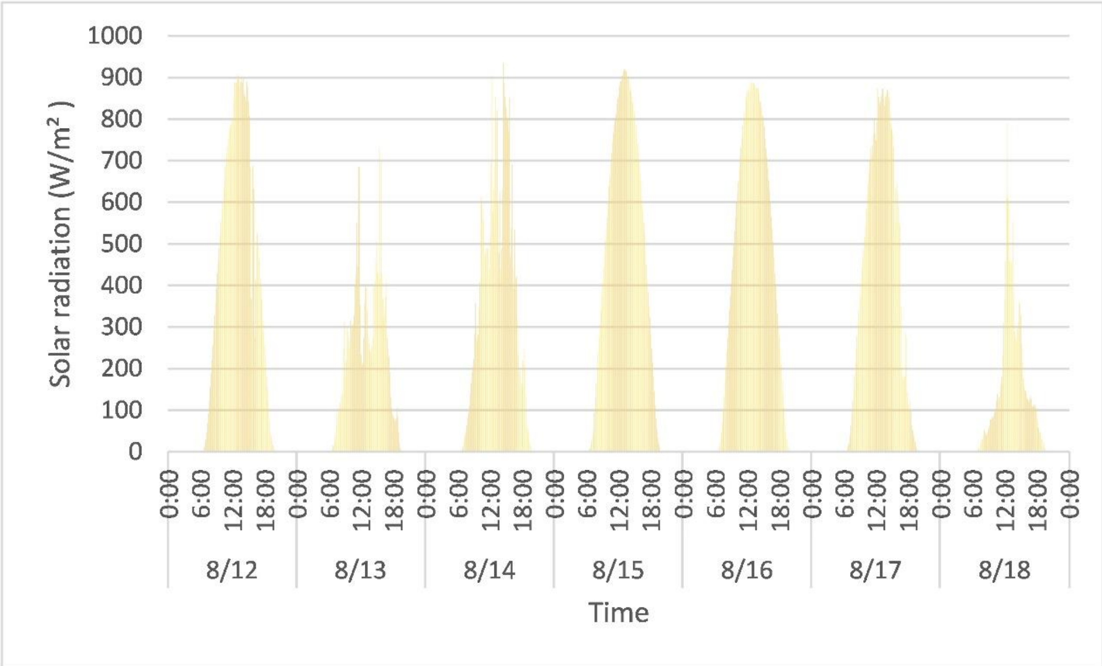

Figure 4-3. Daily solar radiation during the measurement.

It can be seen from Figure 4-3 that the solar radiation during the test period was consistent with the variation of outdoor temperature, and the solar radiation was higher on the 12th, 15th, 16th, and 17th.

4.3.2 Analysis of indoor thermal environment without air conditioning

August 22nd was selected to analyse the comparison of the indoor thermal conditions in the units before and after the retrofit without air-conditioning on. On that day the air conditioning was switched off in the south bedroom of both units from 0:00 to 23:00. Between 23:00 and 00:00, the south bedroom of the homes in the comparison group used the air conditioning for one hour before bedtime. Therefore, only data between 0:00 and 23:00 have been used in the following analysis.

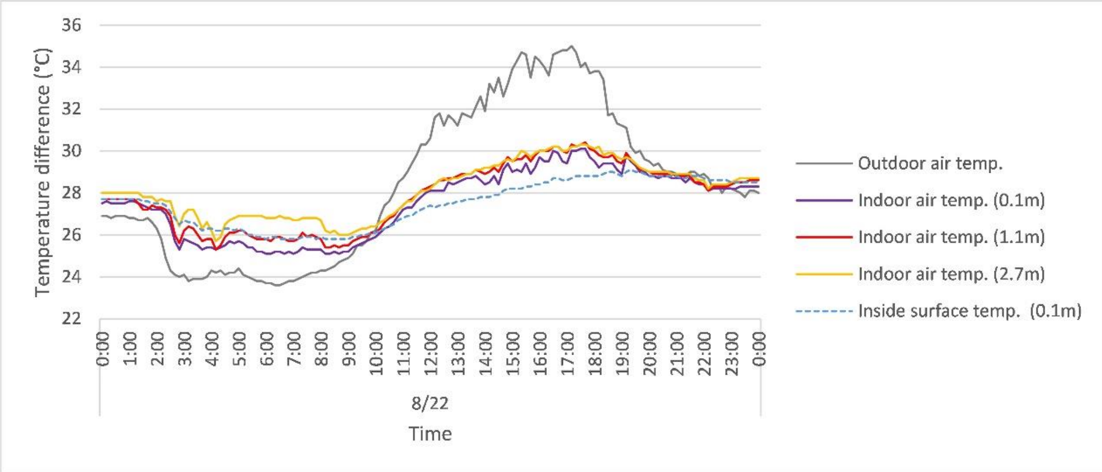

Figure 4-4. Temperature in the retrofitted south bedroom without air conditioning on August 22th.

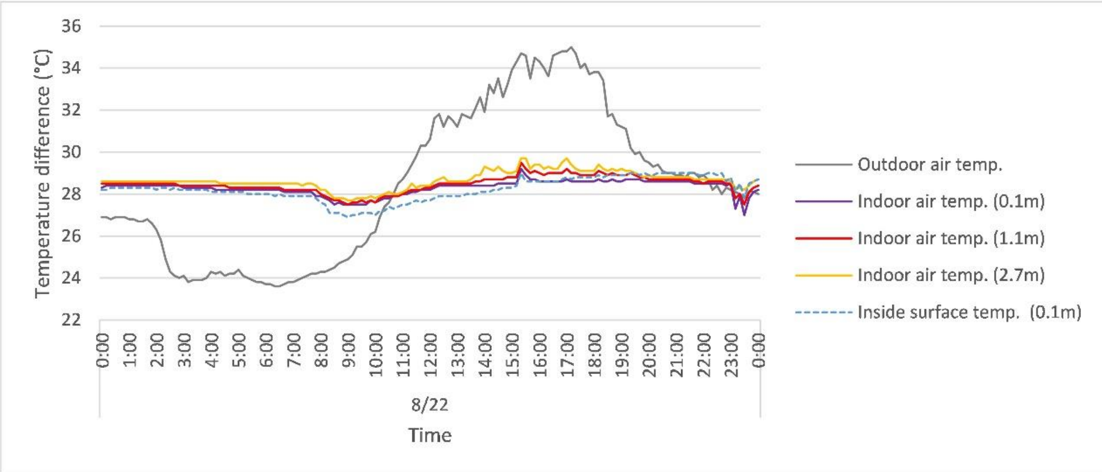

Figure 4-5. Temperature in the un-retrofitted south bedroom without air conditioning on August 22th.

Figure 4-4 shows the temperature in the retrofitted south bedroom on August 22th with no air conditioning on all day. The day's maximum outdoor temperature was 35 °C, with indoor temperatures fluctuating close to those outside and peaking in the afternoon. The indoor temperature ranged from a maximum of 30.4 °C to a minimum of 25.1 °C. The overall average indoor temperature at the three heights was 27.8 °C. There was a more pronounced temperature difference between 3:00 am and 8:00 am for indoor temperatures. During this period, the average temperature was 25.4 °C, 25.9 °C, 26.7 °C for 0.1 m, 1.1 m and 2.7 m respectively. In addition, the inner surface temperature of the external wall (0.1 m, blue dotted line) fluctuates less than the indoor temperature at the same height (0.1 m, purple line), with the peak temperature difference was 1.3 °C in the afternoon.

Figure 4-5 shows the temperature in the un-retrofitted south bedroom without air conditioning on

August 22th. The results show that the unmodified south bedroom has relatively small fluctuations in indoor temperature, with a maximum of 29.7 °C and a minimum of 27.5 °C. The overall average indoor temperature at the three heights was 28.5 °C. The temperature difference between the inner surface of the external walls and the indoor temperature at the same height is small.

Comparing the two bedrooms it can be concluded that the thermal quality of the envelope contributes extremely well to the stability of the indoor temperature in the unmodified unit. However, the average indoor temperature of 28.5 °C is unbearable for living. The use of air conditioning to regulate indoor temperature is essential in the summer months.

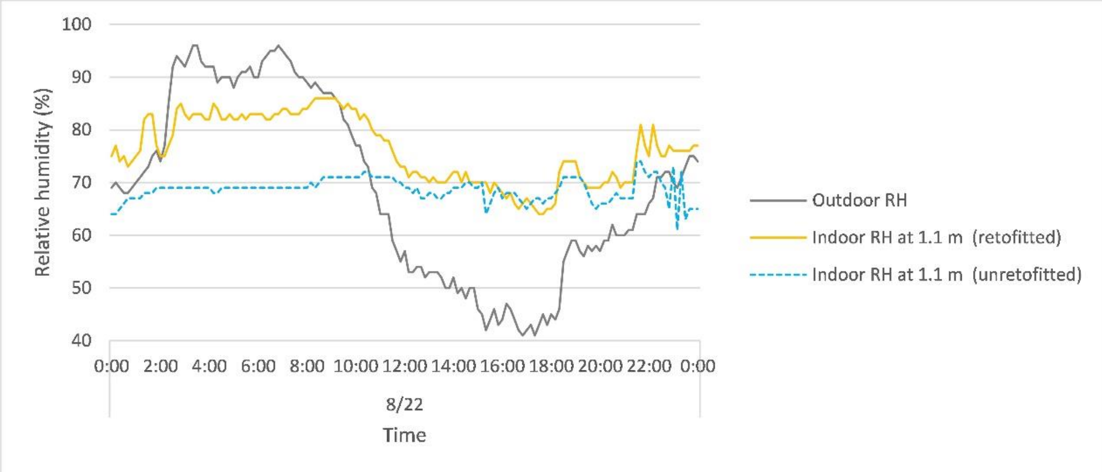

Figure 4-6. Comparison of relative humidity in the retrofit and un-retrofitted south bedroom without air conditioning on August 22th.

Figure 4-6 shows the comparison of relative humidity in the retrofit and un-retrofitted south bedroom without air conditioning on August 22th. The results show that the relative humidity in the retrofitted south bedroom is higher overall than in the un-retrofitted one, and fluctuates more widely. In contrast, the relative humidity values in the unmodified bedrooms were more stable.

4.3.3 Comparison of daily cooling load and cooling load decreases ratios

A fixed cooling operation strategy was used from August 10th to August 17th, and the daily power consumption of the air conditioner during this period is shown in Figure 4-7. August 10th and 11th were set as the preparation period for the experiment, and the air conditioner was used continuously to minimize the effect of thermal mass on the experiment in the unmodified group. In addition, both south bedrooms were not shaded on the outside. The three selected intermittent operation modes were conducted twice during the 6 days from August 12th to August 17th.

Table 4-2. Comparison of daily and total cooling load between the south bedrooms.

	8/10	8/11	8/12	8/13	8/14	8/15	8/16	8/17	Sum
Retrofitted room (kWh)	1.98	4.81	4.86	1.13	4.24	1.69	4.29	4.84	27.83
Un-retrofitted room (kWh)	3.01	8.46	8.48	1.90	7.20	2.77	7.16	9.47	48.46

The energy consumption results in Table 4-2 show that the energy consumption of the south bedroom with interior insulation was significantly lower than that of the original south bedroom under different outdoor weather and different usage patterns. It can be calculated that after 8 days of operation, the total cooling energy consumption of the retrofitted south bedroom was 27.83 kWh, compared to 48.46 kWh for the non-retrofitted one. Therefore, the total cooling energy saving rate over the 8 days was 42.56%.

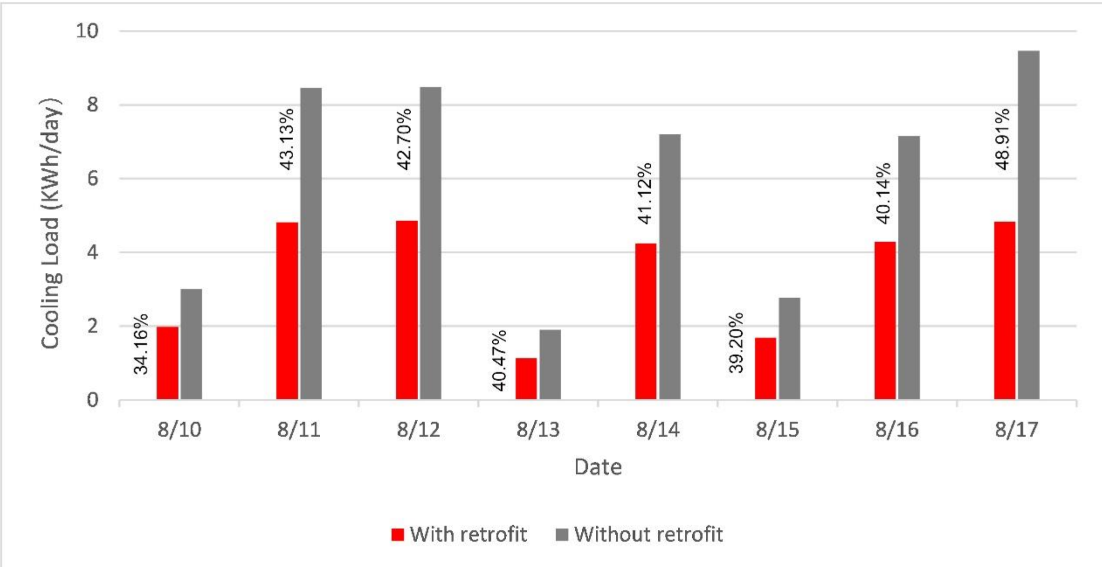

Figure 4-7. Comparison of daily cooling load and cooling load decreases ratios of the south bedroom.

Figure 4-7 shows that during the 6 days of intermittent use, the lowest daily energy savings rate was 34.16% on August 10. The overall trend is that the longer the total time of use, the higher the energy savings rate. The average energy saving rate in the retrofitted south bedroom was 42.09%, and the highest energy saving rate was 48.91% (August 17th).

4.3.4 Comparison of indoor thermal environment

A period of three consecutive days and eight hours (August 15th 0:00 to August 18th 8:00) was selected for further analysis of the indoor thermal environment. This period includes the three typical intermittent cooling patterns selected in this paper. Additionally, these days were extremely hot periods with similar outdoor climates, as shown in Table 4-3. The average ambient temperature was 31.3 °C, and the hottest outdoor period was generally between 15:00 and 16:30, with the highest value of 37.8 °C on August 17th.

4.3.4.1 General comparison of indoor thermal environment

In the evaluation of the indoor environment of a building, the internal air temperature is the dominant variable used to ensure thermal comfort [52]. Therefore, the real-time variation of indoor temperature and energy consumption with weather is further compared in the first place.

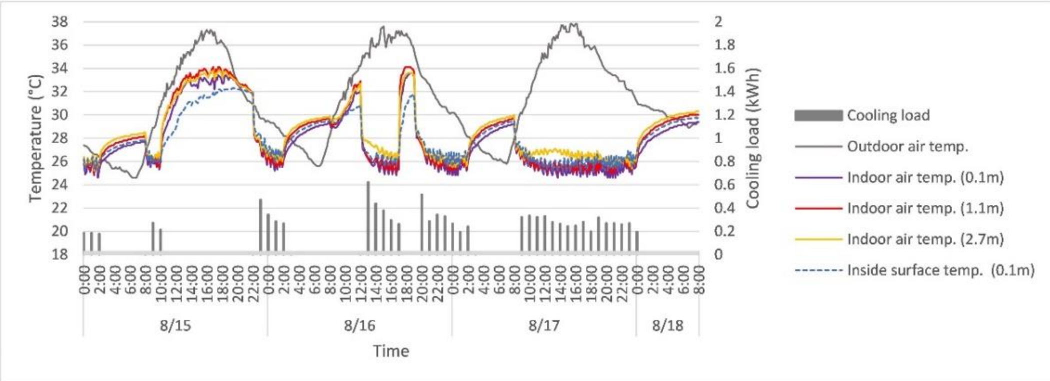

Figure 4-8. Indoor thermal environment and hourly cooling load in the retrofitted south bedroom.

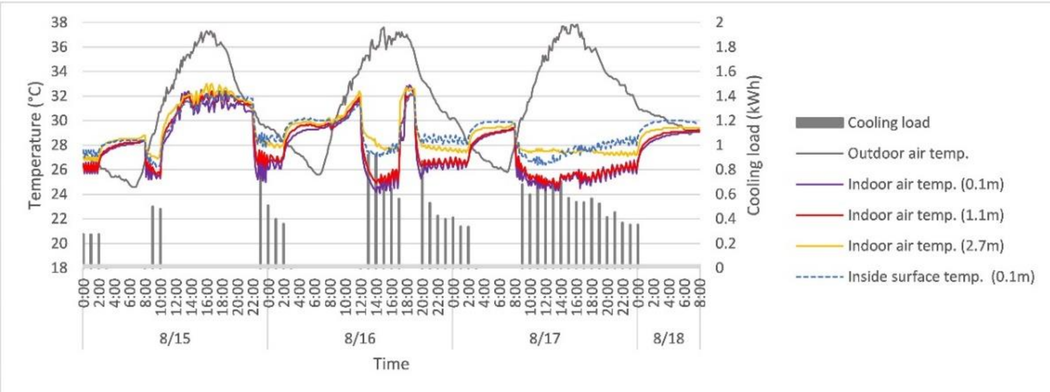

Figure 4-9. Indoor thermal environment and hourly cooling load in the retrofitted south bedroom.

First of all, Figure 4-8 and Figure 4-9 show a comparison of the overall indoor temperature in the south bedroom before and after the renovation from August 15 to 18, and a comparison of the energy consumption per hour. Figure 4-8 shows the room temperature and hourly air conditioning energy consumption in the retrofitted south bedroom. The results show that when the air conditioner is on, the temperature difference between the inner surface of the exterior wall (blue dotted line) and the indoor temperature at the same height (purple line) is relatively small and fluctuates mainly around the set stable 26 °C. And the temperature between different heights also shows that the temperature difference between the interior vertical is relatively small, especially within the area below 1.1 m. The overall trend shows that the temperature is relatively stable in all parts of the room.

Figure 4-9 shows the indoor temperature and hourly air conditioning energy consumption in the unmodified south bedroom. The results show that when the air conditioner is turned on, the temperature of the inner surface of the exterior wall at 0.1 m (blue dotted line) shows a similar trend to the indoor temperature at the same height (purple line), but the temperature of the wall is always higher and the temperature difference is usually greater than 2 °C. The vertical temperatures between different heights also show that the temperature is always higher at 2.7 m. The temperature of the wall is always higher at 2.7 m. Even when the air conditioner was on for several hours, the temperature at that height remained close to 28 °C. The overall trend shows that the temperature in the bedroom before the renovation fluctuates more compared to that after the renovation.

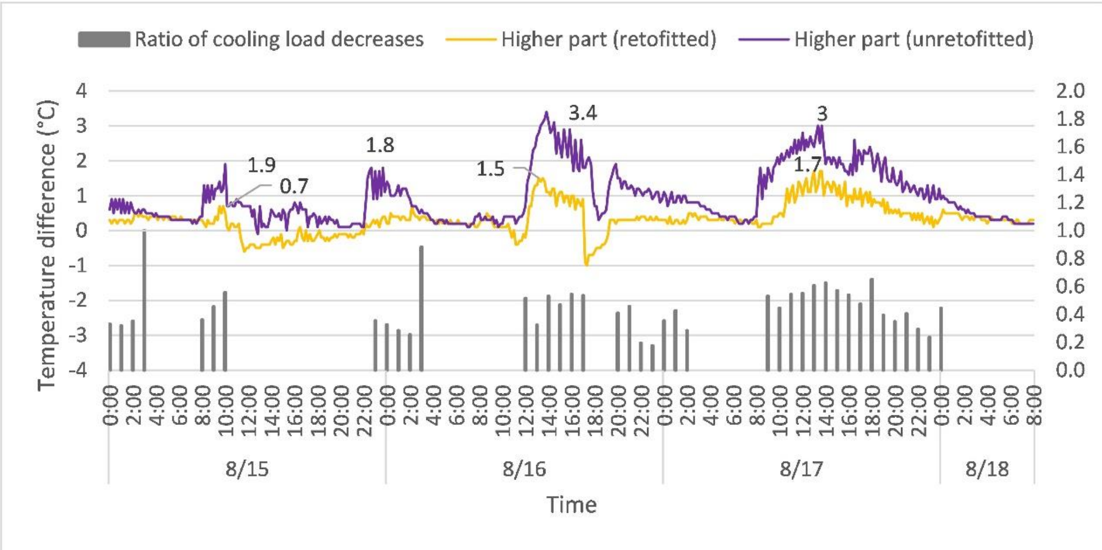

Figure 4-10. Comparison of temperature difference in the higher part (2.7m-1.1m).

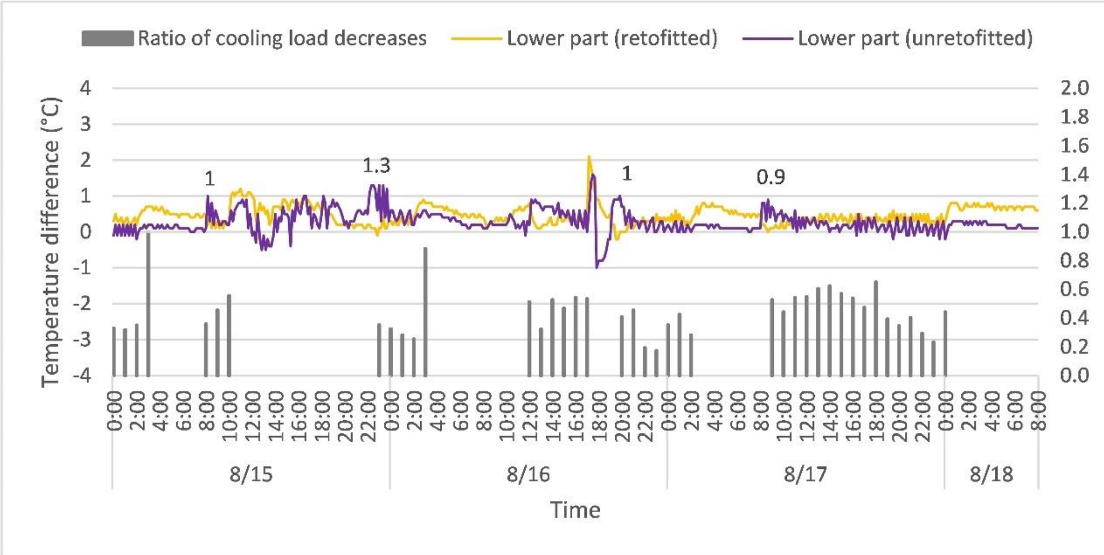

Figure 4-11. Comparison of temperature difference in the lower part (1.1m-0.1m).

Figure 4-10 and Figure 4-11 show the comparison of the temperature difference between the high (between 2.7m and 1.1m) and low (between 1.1m and 0.1m) parts of the room. It can be seen more clearly from the figures that the retrofit improves the temperature difference in the high part of the room very significantly. The temperature difference in the high part of the room without renovation can reach up to 3.4 °C, while in the room after the renovation at the same time, the temperature difference is 1.5 °C.

4.3.4.2 Comparison of indoor temperature during cooling

If we analyze the time period during which the air conditioner was turned on during these 4 days, we can more precisely analyze the changes before and after the retrofit. Table 4-3 shows the overall data-based analysis of the temperature during the cooling time period. It can be observed that the average indoor temperature for the 3 heights (0.1 m, 1.1 m, and 2.7 m) in the retrofitted south bedroom is 26.1 °C, compared to 26.5 °C in the pre-retrofit bedroom. This indicates that the change in outdoor temperature has less effect on the indoor temperature of the retrofitted bedroom.

Comparing only the average temperatures, the temperatures at 1.1 m and 0.1 m are very similar before and after the retrofit. However, the temperature at 2.7 m, after the renovation, was significantly lower than that before the renovation, at 26.6 °C and 27.7 °C, respectively. This means that the average temperature at 2.7 m of the retrofitted south bedroom 26.6 °C was closer to the operating temperature. While in the original bedroom it was 1.7 °C higher than the operating temperature.

Table 4-3. Results of measured temperature data during the cooling period.

Parameters	Height Above Ground (m)	Mean (°C)		Maximum (°C)	Minimum (°C)	S.D.
Outdoor temperature (during the whole period)		31.3		37.8	24.6	3.81
Indoor temperature of retrofitted room during cooling period	2.7	26.6	26.1	28.9	25.2	0.65
	1.1	26.0		28.7	25.0	0.71
	0.1	25.7		28.3	24.6	0.78
Indoor temperature of un-retrofitted room during cooling period	2.7	27.7	26.5	30.0	26.7	0.50
	1.1	26.1		29.0	24.6	0.74
	0.1	25.7		28.3	24.1	0.78

Figure 4-12 to Figure 4-14 present the frequency and cumulative percentage of indoor temperature at 2.7 m, 1.1 m, 0.1 m, respectively in the retrofitted and un-retrofitted south bedroom. They visually show that after the retrofit, the temperature is more concentrated at 1.1 m and 0.1 m, mainly in the range of 25 to 26 °C. In contrast, the temperature in the bedroom without the retrofit was mainly concentrated in a larger range between 25 and 27 °C.

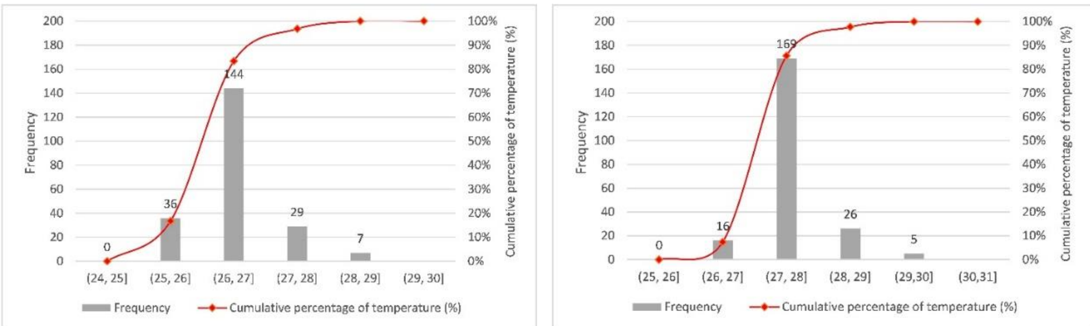

Figure 4-12. Frequency and cumulative percentage of indoor temperature in the retrofitted (left) and un-retrofitted (right) south bedroom at 2.7 m.

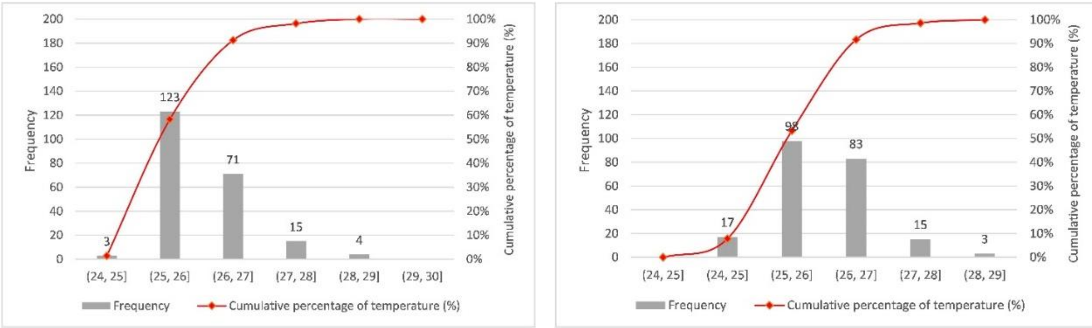

Figure 4-13. Frequency and cumulative percentage of indoor temperature in the retrofitted (left) and un-retrofitted (right) south bedroom at 1.1 m.

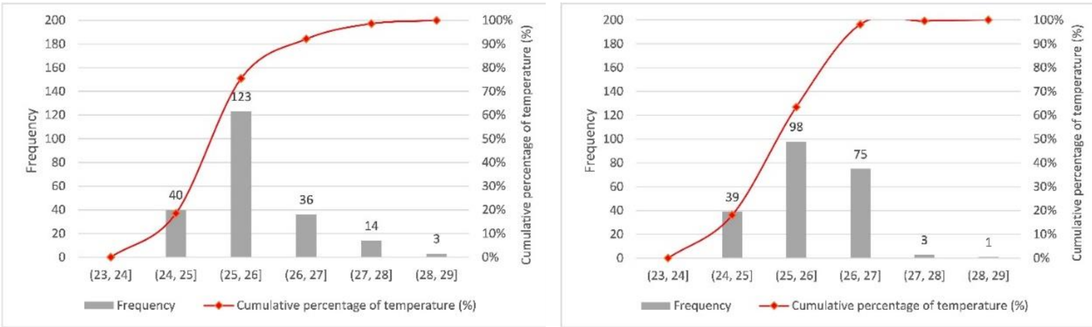

Figure 4-14. Frequency and cumulative percentage of indoor temperature in the retrofitted (left) and un-retrofitted (right) south bedroom at 0.1 m.

Figure 4-15 to Figure 4-17 shows the variation in indoor temperature and hourly energy consumption between 15 and 18 August for three heights.

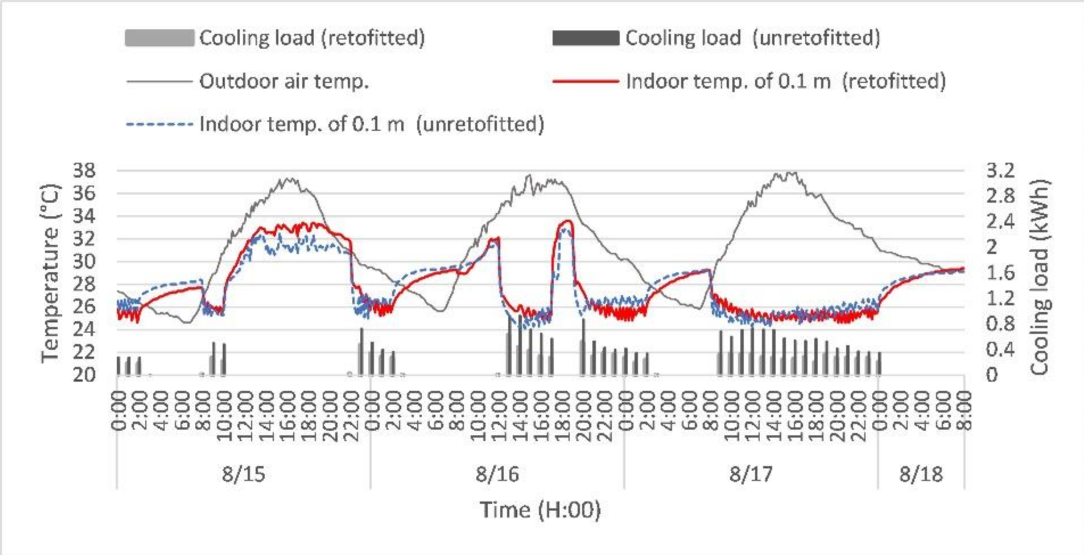

Figure 4-15. Comparison of indoor temperature and hourly cooling load at 0.1 m.

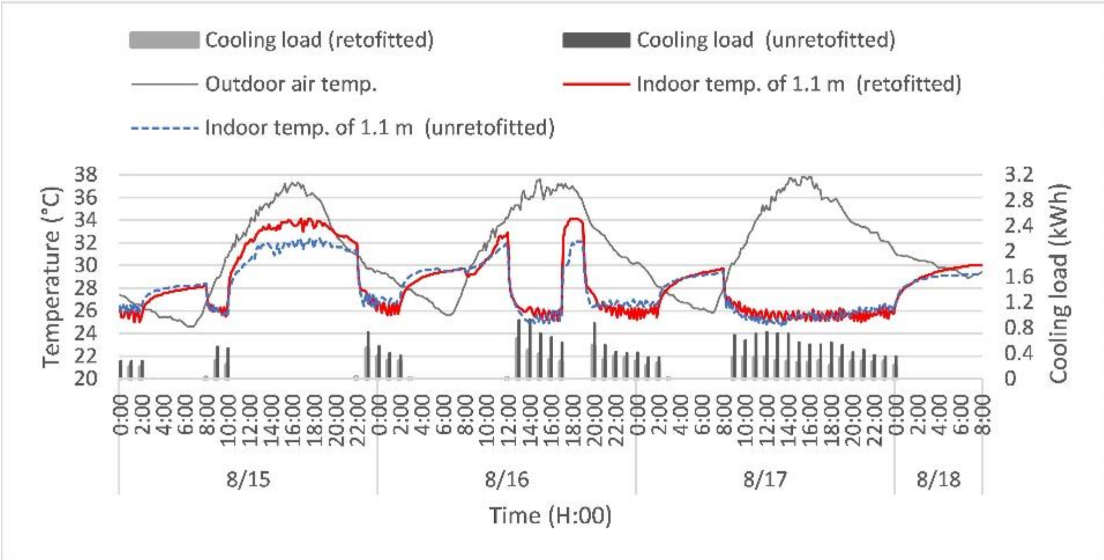

Figure 4-16. Comparison of indoor temperature and hourly cooling load at 1.1 m.

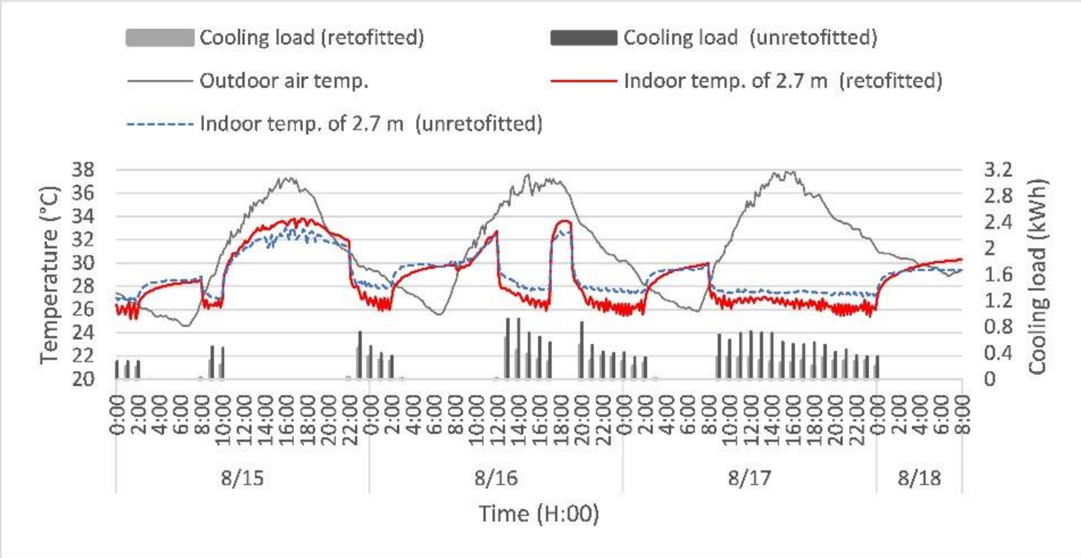

Figure 4-17. Comparison of indoor temperature and hourly cooling load at 2.7 m.

During the various cooling periods, the results show that the indoor temperature in the un-retrofitted bedroom is more affected by the outdoor weather, exhibiting greater fluctuations. Taking the height range which people mainly occupy indoors (0.1 m and 1.1 m) as an example, when the air conditioner started to cool, the temperature in the un-retrofitted bedroom dropped more rapidly, usually below the set temperature of 26 °C for the first few hours, with the lowest temperature at 0.1 m reaching 24.1 °C (August 16th, 14:30). This is mainly because of thermal mass, i.e., the thermal mass of the envelope such as the internal walls in the un-retrofitted bedroom is very large. When the air conditioner released cold air downward, some of it was absorbed by the building envelope, resulting in less cold air reaching the upper part. Therefore, the temperature near the height of the air conditioner's sensor was not cooled in time, so the air conditioner released more cold air, leading to lower indoor temperature, as shown in Figure 4-15 and Figure 4-16. Subsequently, the room temperature usually rose above 26 °C and even reached a maximum of 27 °C (August 16th, 23:40). This is mainly because when the air conditioner was turned on for a period, more cold air from it was used for cooling indoor air after the internal envelope such as the walls of the un-modified bedroom has been cooled enough. Thus, the air temperature in the high places became lower. When the air conditioner sensed the lower temperature, it would release less cold air into the room, resulting in a higher overall temperature in the lower part.

However, in the retrofitted bedroom, the indoor air temperature showed greater stability. It can be observed from Figure 4-15 and Figure 4-16 that after the air conditioner started cooling, the room temperature slowly dropped and fluctuated in a small regular range around the operating temperature. This can be mainly attributed to interior insulation; the envelope, such as the interior walls, were isolated by it, so the indoor air temperature was less negatively affected by the thermal mass. Consequently, the air was cooled more evenly in the retrofitted bedroom. The impact of interior insulation on the indoor environment can be observed more obviously on August 17th. Even when the outdoor temperature fluctuation was close to 10 °C (27.9 to 37.8 °C), the indoor temperature of the remodeled bedroom was still much more stable than the original one.

In addition, Figure 4-17 shows that the overall temperature at 2.7 m of the renovated bedroom was closer to the set temperature 26.0 °C, despite a relatively large fluctuation. In contrast, the temperature at 2.7 m in the un-retrofitted bedroom was higher, even the lowest was 26.7 °C.

Even during the period when the air conditioner was turned off, the retrofitted bedroom had a slightly better indoor environment, i.e., the comfort state was maintained for a longer period. Take the late night to early morning period (0:00 to 8:00) in Figure 4-15 and Figure 4-16 as an example, when the air conditioner is turned off (the windows are still closed), the retrofitted room showed a slight advantage in preventing the indoor temperature from rising. This is mainly because the thermal mass of its envelope is blocked from heat exchanging with the air by the internal insulation.

4.3.4.3 Comparison of indoor relative humidity

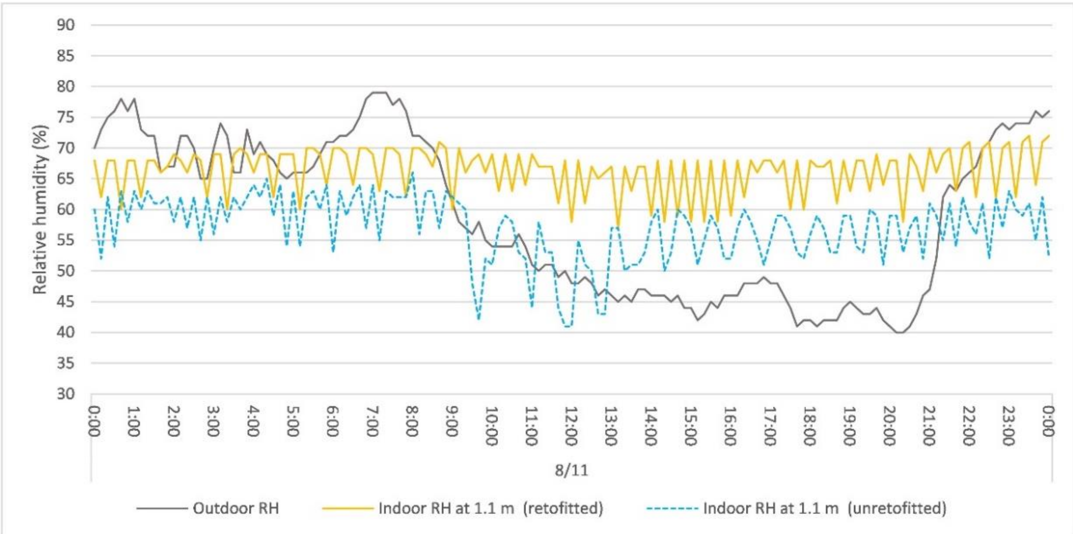

Figure 4-18. Comparison of relative humidity in the south bedroom before and after retrofit on August 11th.

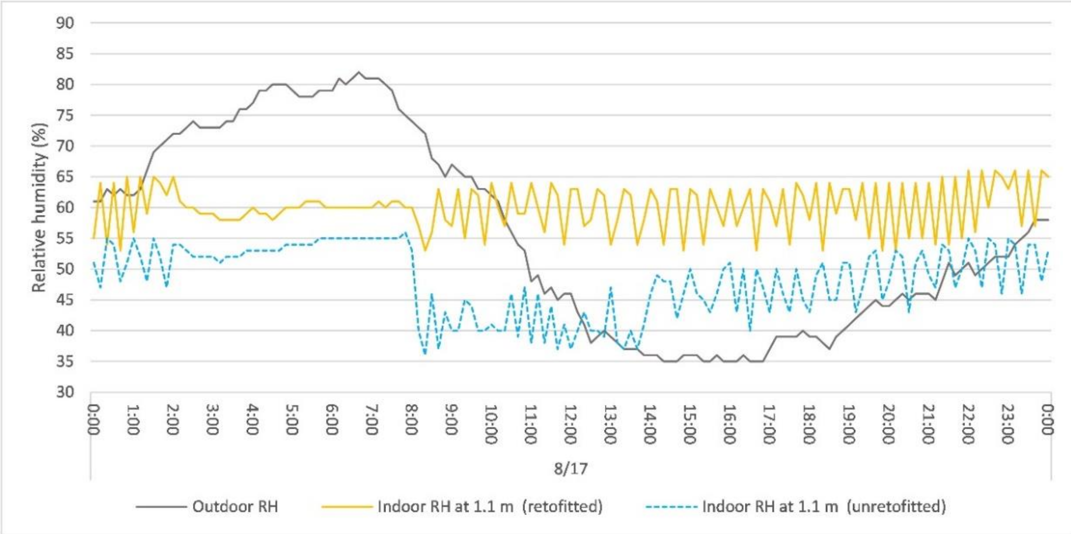

Figure 4-19. Comparison of relative humidity in the south bedroom before and after retrofit on August 17th.

In addition to temperature, the effect of the remodeling work on indoor relative humidity was also studied. Figure 4-18 and Figure 4-19 show the outdoor relative humidity for two days, August 11 and 17, and a comparison of the relative humidity at 1.1 m in the south bedroom with and without the retrofit. The duration of air conditioning cooling in these two days was 24 and 18 hours, respectively, for a longer continuous operation. As can be observed in Figure 4-18, the relative humidity (yellow line) in the retrofitted bedroom fluctuates very steadily in small increments, while the relative humidity (blue dotted line) in the original bedroom is very unstable, with a maximum difference between the highest and lowest points close to 25% (August 11) and 20% (August 12).

Table 4-4. Measured indoor relative humidity during the cooling period of August 11th.

Parameters	Mean (%)	Maximum (%)	Minimum (%)	S.D.
Outdoor relative humidity	59	79	40	12.79
Indoor relative humidity of the retrofitted room	66	72	57	3.69
Indoor relative humidity of un-retrofitted room	57	66	41	5.21

Table 4-5. Measured indoor relative humidity during the cooling period of August 17th.

Parameters	Mean (%)	Maximum (%)	Minimum (%)	S.D.
Outdoor relative humidity	49	74	35	11.60
Indoor relative humidity of the retrofitted room	60	66	53	4.15
Indoor relative humidity of un-retrofitted room	47	55	36	5.35

However, it is also important to note that the results in Table 4-4 and Table 4-5 show relatively high humidity levels in the retrofitted bedrooms. During the cooling time period of August 11 and 17, the average humidity in the retrofitted bedroom was 66% and 60%, respectively, compared to 57% and 47% in the original bedroom. In other words, the difference in relative humidity between the two south bedrooms was around 10%. However, according to the Design code for heating ventilation and air conditioning of civil buildings GB 50736-2012 (Table 4-6), this is still within the range of the secondary comfort level (≤70%).

Table 4-6. Indoor design parameters for air conditioning in areas where people stay for long period.

(Source: Design code for heating ventilation and air conditioning of civil buildings GB 50736-2012)

Type	Thermal comfort level	Temperature (°C)	Relative humidity (%)	Wind speed (m/s)
Cooling condition	I	24~26	40~60	≤0.25
	II	26~28	≤70	≤0.3

4.4 Discussion

A large part of the previous studies discussed the differences in the energy performance of different insulation methods for exterior walls under various climatic conditions. In the case of intermittent energy use, internal insulation can save 15% more energy than external insulation [35] and reduce the annual cooling load by 6.8% [36]. Studies have shown that during intermittent operation of the air conditioner (within 24 hours of operation), the average heat transfer from the indoor insulation is about one third that of the outdoor insulation. Further, in addition to exterior walls, studies have shown that floors and ceilings, etc., contribute more to energy savings than walls, up to 35–80% [40]. The present study is an optimization based on a poorly externally insulated residence, i.e., a new insulation system named interior insulation. In this system, in addition to the internal insulation of external walls, all the internal opaque structures such as the inside wall, floor, and ceiling are insulated. Actual measurements demonstrated that adding interior insulation systems to residences with existing outside insulation had a significant energy saving effect. Compared to the un-retrofitted residence, it can achieve an average energy-saving rate of 42.09% under the mode of intermittent energy use.

This study is based on actual renovations and real measurements, which in turn leads to certain limitations. We needed to ensure consistency in the experimental conditions, i.e., building surroundings, orientation, what floor the residential units are on in a building, and household type. Therefore, there were very few residences that met the conditions in the first place. The occupants were also mostly reluctant to participate in the experiment for privacy and other reasons. All these above factors, coupled with the limited funds available for renovation, resulted in a limited sample size for this experiment. In addition, to keep the air conditioner, windows, doors, and curtains in the same operation mode during the experiment, two to four operations of the equipment were required at defined points in a day. These put a considerable burden and disrupted the daily lives of the occupants, so it was not possible to conduct the test continuously for the entire cooling season, but only for 9 days of the hottest months.

The retrofitted high-rise residence in this study was constructed in 2010, and it conforms to the typical architectural characteristics of residential buildings in the HSCW region according to the survey of Bazhan Li et al. (2018) [19]. In that survey, the most typical local residential characteristics were as follows: buildings built after the 1990s, which have a reinforced concrete structure and a single-frame single-glazed window type. However, it must also be acknowledged that there are differences among buildings in terms of design and construction levels, use of materials, etc. Therefore, the results of this paper are more applicable as a reference for the design and renovation of similar high-rise residences in an area with a hot and humid summer.

In addition, concerns that may result from interior insulation retrofits were also discussed. Firstly, condensation is an issue that should be taken seriously, if it occurs in a building, indoor hygiene problems may occur, as well as the durability and safety of the building structure may be influenced. In general, the probability of condensation in the building structure is relatively high when inside insulation is used in cold regions, because of the large temperature difference between the interior and exterior of the building. This possibility needs to be ruled out by careful calculations or simulations. Meanwhile, in the HSCW region we studied, the temperature difference between the indoor and outdoor is much smaller than in the cold and severe cold regions. In addition, as this research is the optimization of an existing residence, there is both insulation on the outside and inside of all the opaque surfaces of the room, so there is barely any possibility of water vapor condensation. Secondly, the impact of the interior insulation retrofit on the indoor use area was calculated. The specific indoor area occupied by indoor insulation is shown in Table 4-7. It is revealed that when adding interior insulation in a small bedroom, it takes up 3.45% of the total usable area of the room. While when adding interior insulation in the whole dwelling unit, this percentage becomes even smaller, taking up only 1.75% of the total usable area. The results show that the impact of increasing internal insulation on indoor usable area is quite small, and the impact becomes even smaller as the room size grows. This small sacrifice of the area is almost negligible compared to the average 42.09% energy savings it contributes and a faster response rate of room temperature to air conditioning.

Table 4-7. The proportion of interior insulation to the usable area of the residence.

Scope	Usable area before Retrofit (m^2)	Usable Area after Retrofit (m^2)	Area Occupied by Internal Insulation Layer (m^2)	Proportion of Area Occupied by Internal Insulation (%)
Entire residential unit	75.78	74.46	1.33	1.75%
South bedroom	10.94	10.56	0.38	3.45%

It is impossible to explore all possibilities of practical use in the study, and the following studies deserve further investigation in the future.

1. This paper demonstrates the extent of improvement in cooling energy consumption and indoor thermal environment in a residence that was retrofitted with interior insulation. However, how the envelope behaves behind such results needs further analysis, such as the internal and external surface temperatures of its outer walls, the internal temperature of the structure, heat fluxes, etc.

2. In this study, the windows were set to open during the daytime hours when the air conditioner was turned off to minimize operational difficulties. However, in actual use, the window opening pattern is far more complex and flexible than this. Without changing the building layout, the window opening strategy has a very significant impact on the indoor environment and cooling energy consumption of the building [53]. At the same time, climate characteristics, seasons, and the layout of the dwelling all will influence the interaction between occupants and windows [54]. Therefore, it is worth exploring further on what window opening pattern is better in the case of adding interior insulation to buildings in the HSCW region.

3. Based on the relevant survey, it can be found that different set temperatures matter a lot concerning building energy consumption and associated greenhouse gas emissions [55]. The cooling operation temperature set by the households in summer is not fixed, and future studies can be conducted for multiple temperature values for a better set temperature strategy.

4. To obtain a more comprehensive understanding of the effectiveness of the practical application of interior insulation in residence retrofit, other rooms in the residential unit, such as living room and kitchen, will be considered in further research. Orientation and different floors also influence the energy-saving effect of the dwelling, so comparable studies of rooms with different orientations and different floors will be considered in subsequent simulations.

4.5 Summary

Based on the actual use in the building during its operational phase, in situ experiments were done for 9 consecutive days in August 2019, one of the hottest months in the HSCW zone. Three typical intermittent cooling patterns in this area were investigated. The main conclusions were obtained as follows:

During the 6 days of intermittent cooling (August 12th to 17th), the retrofitted south bedroom showed a good energy-saving effect, the average daily energy-saving rate was 42.09% and the highest daily energy-saving rate was 48.91%.

Analysis of the indoor thermal environment during the hottest three days and eight hours of the experimental period (15–18 August) showed that the average indoor temperature of the retrofitted bedroom during the cooling period was 0.4 °C lower than that of the un-retrofitted one. During each cooling period, the indoor temperature at 1.1 m and below was more stable, while the average temperature at 2.7 m was 1.1 °C lower than the original bedroom. Additionally, its value, 26.6 °C, was closer to the operating temperature (26 °C). Besides, indoor relative humidity was higher and much more stable after the retrofit.

It can be concluded from this case study that by adding interior insulation to the south bedroom of an existing outside-insulated residence in a high-rise building in the HSCW region of China, lower and more stable indoor temperature can be achieved accompanied by an energy-saving rate range of 39.20% to 48.91%.

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Chapter 5

IMPROVEMENTS AFTER INTERIOR INSULATION RETROFIT UNDER INTERMITTENT HEATING CONDITION

CHAPTER FIVE: IMPROVEMENTS AFTER INTERIOR INSULATION RETROFIT UNDER INTERMITTENT HEATING CONDITION

5.1 Introduction

5.1.1 Background

A topic that has been widely discussed on social media every winter in recent years is whether the central heating system should be considered for the HSCW region of China. With the improvement of living standards, people's requirements for the indoor environment are getting higher and higher. However, global warming is proceeding at a faster rate than expected. Under this trend, the overall global goal is to limit the rise in temperature to 1.5°C from pre-industrial levels. To achieve global climate goals, significant efforts are needed not only by governments, individual energy-using sectors, and individuals. Every little effort is vital, so it is worth thinking deeply about whether it is necessary to provide central heating in an area as large as the HSCW zone.

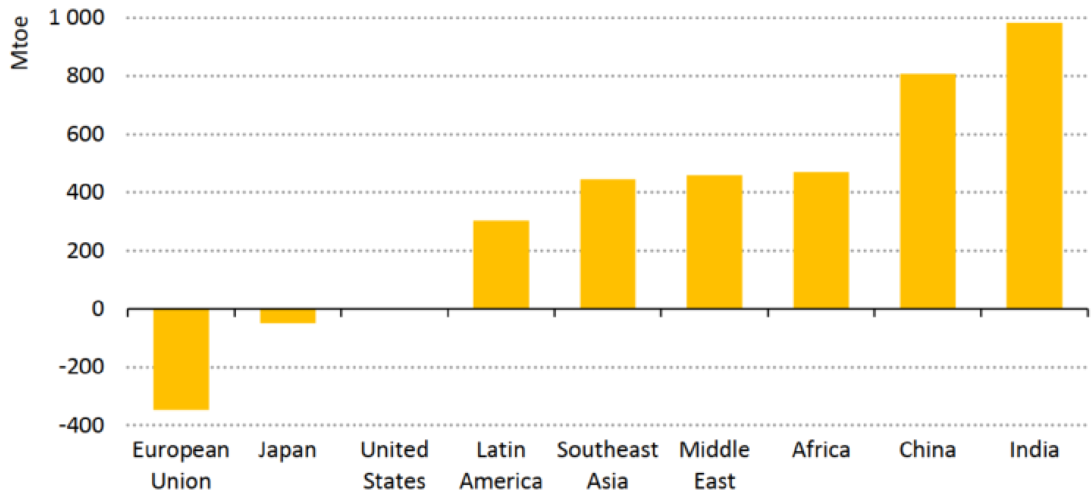

Figure 5-1. Change in total primary energy demand in selected regions in the New Policies Scenario, 2017-2040 [1].

(Source: IEA. World Energy Outlook 2018: Highlights 2018;1:1–661. https://doi.org/10.1787/weo-2018-2-en.)

World energy demand is undergoing a major shift from developed to developing economies, with India and China experiencing the fastest growth in demand [1]. In the two decades between 1990 and 2010, China's building energy consumption increased by about 45% [2]. As the largest consumer of energy in the world, 21% of China's total energy demand is consumed by buildings, and this is estimated to climb to 29% in 2040 (Figure 5-1) [3]. China's urbanization rate is also growing rapidly in line with economic development. 56.1% of China's total population lived in urban areas in 2015, which is nearly 1.5 times the rate in 2001 [4]. It is estimated that China's urbanization rate will increase to 70% by 2030, meaning that the urban population will increase by more than 300 million

[5]. However, there are significant differences between regions and cities in terms of specific buildings and energy use due to differences in their environments.

Due to its vast geographical extent, China is divided into five climatic divisions based on different climatic conditions [6]. They differ greatly from each other due to external climatic conditions, resulting in very different characteristics of building and energy use patterns. The present study focuses on the HSCW zone. When discussing heating there, the Yangtze River Basin is also used, which refers to Hubei, Hunan, Jiangxi, Anhui, Jiangsu, Zhejiang, and Shanghai. The Yangtze River Basin area accounts for 75% of the total residential construction in the city and is the main area of building size in the HSCW area.

As the name implies, this is an area that has both summer cooling and winter heating requirements. These characteristic places great stress on energy consumption for the improvement of the thermal environment in the HSCW area. The demand for increased living standards by local inhabitants has led to a rapid increase in the ownership of heating equipment in the region. As shown in Figure 5-2, the intensity of energy use for heating space in the HSCW region is 1.84 kgce/m^2, which is only one-eighth of that in northern China. In urban households in the region, space heating consumption accounts for 18% of total household energy use. Although this share of end use is not very high at present, it shows great potential for growth and poses a great challenge for energy efficiency in urban buildings. Therefore, in addition to the public appeal for centralized heating, this characteristic of residential energy consumption in the HSCW area has attracted a lot of attention from researchers [7][8].

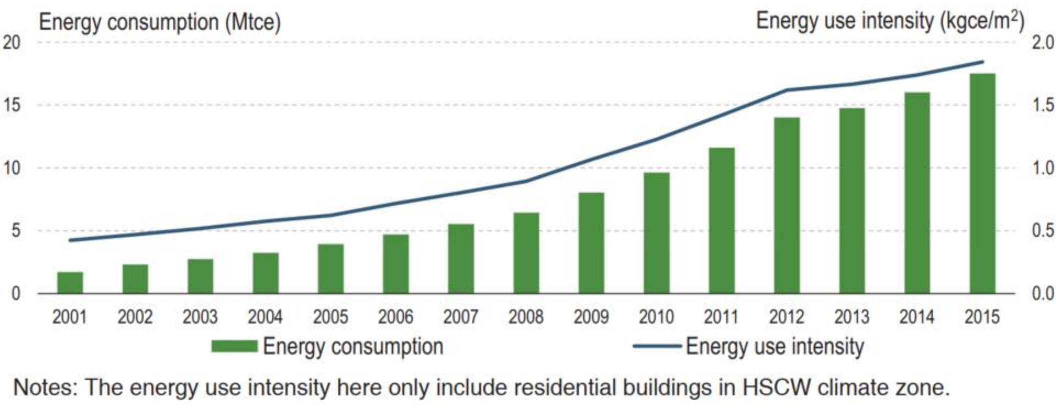

Figure 5-2. Energy consumption of space heating in HSCW climate zone (2001-2015) [4]

(Source: Jiang Y, Yan D, Guo S, Hu S, Zhang Y, Cui Y. China Building Energy Use 2017. 2017.)

5.1.2 Literature review

One of the most basic and important reasons for the widespread appeal for central heating by ordinary households is that the indoor environment in the current HSCW region is the worst of all climatic zones in China. In winter, for example, the lowest average outdoor temperature in January, the coldest month, is about 8.8°C. The average indoor temperature due to the poor performance of the building envelope is about 11.3°C (Table 5-1) [9]. In other words, the difference between indoor and outdoor temperatures is very close. This also leads to uncomfortable indoor conditions that residents have to endure in both summer and winter. For this reason, the residents of the HSCW region are used to wearing heavy clothing indoors in winter [10].

Table 5-1. Monthly air temperature distribution of indoor and outdoor environments in the HSCW climate zone [9].

(Source: Li B, Du C, Yao R, Yu W, Costanzo V. Indoor thermal environments in Chinese residential buildings responding to the diversity of climates. Appl Therm Eng 2018;129:693–708. https://doi.org/10.1016/j.applthermaleng.2017.10.072.)

Month	Outdoor air temperature (°C)				Indoor air temperature (°C)				Cases
	T_{min}	T_{max}	T_{mean}	SD	T_{min}	T_{max}	T_{mean}	SD	
December	−4	20.0	9.3	0.19	3	22.5	12.2	0.14	558
January	−6	14.8	8.8	0.13	2	18	11.3	0.13	548
February	−3.7	18.9	11.2	0.23	3.5	20.2	14.3	0.14	542

However, relevant academic studies have shown that central heating is not necessary for the HSCW area for the following main reasons [11] [12] [13]. Firstly, the heating period is relatively short compared to cold and severe regions, and the benefits from centralized heating will be poor [14]. Secondly, the retrofitting of a large number of existing buildings with central heating would be very expensive [15]. Thirdly, as mentioned earlier, influenced by long-term residence in this region, occupants are more tolerant of cold indoor temperatures than in the north and tolerate inconsistent temperatures, and centralized heating is not conducive to the individual regulation of occupants. For example, rural residents in the HSCW have a higher tolerance to cold temperatures, but a lower tolerance to hot environments than urban residents [16]. Therefore, the implementation of centralized heating in the HSCW area may instead result in greater energy waste, which is contrary to the current energy-saving goals in China and the HSCW area.

Instead, decentralized heating is more appropriate for the HSCW area, but there is currently much room for improvement in the efficiency of this type of heating. In addition to the climate of the micro-environment in which the building is located and the demand for thermal comfort inside the building, an incredibly crucial factor affecting the building's thermal performance is its physical characteristics, particularly the physical features of the envelope [17]. The building envelope is usually classified into non-transparent and transparent parts [18]. Enclosures' main function is to minimize the impact of adverse environmental conditions on the building while ensuring that the indoor environment is within a comfortable range. A proper design of the building envelope allows the building to make better use of natural energy and reduce energy waste.

It was investigated that the building envelope is responsible for 73% of the total heat/gain loss of the building [19]. The proper use of insulation is the most effective way to decrease the heat transfer rate of the building envelope and the cooling and heating energy consumption of the indoor spaces [20]. Many factors can influence the effectiveness of envelope insulation design, such as the location and thickness of the insulation, the materials chosen, and so on. These issues have been extensively and thoroughly researched by various scholars. The research by Dombayci (2007) [21] shows that when the insulation material of choice is expanded polystyrene, emissions of CO_2 and SO_2 based on coal as a fuel energy source may be reduced by 41.53% at optimum insulation thickness. The climate of the building and the habits of the air conditioner are important factors in determining the best location for the insulation. The thermal mass of the building enclosures, such as walls and columns, can well stabilise the indoor thermal environment, so usually in areas where air conditioning is used continuously, insulation for the exterior of the envelope is the better choice. Therefore, in cold and severe cold areas with central heating in China, outside insulation was adopted and showed great advantage. Insulation in the HSCW region also follows the practice in the north, where external insulation is commonly used.

However, in the HSCW region, the main heating usage mode is not to continuously heat the whole building throughout the winter. Instead, people in the area are accustomed to intermittent heating. The massive thermal mass of the envelope serves as a negative factor in such patterns of energy use. A large amount of heat is used to heat the envelope at the initial stage of turning on the air conditioner in winter, which results in the air not being heated to the set temperature in time. Besides, air conditioner is only used in some rooms of the dwelling, such as in the living room or bedroom. In this case, the interior walls and ceiling floors also become somewhat of an exterior wall, which has potentially serious implications for indoor comfort and energy consumption.

From a comprehensive point of view, the energy consumption habits of the HSCW region are characterized by "part time and part space". In order to make the room reach a comfortable temperature quickly in a short period of air conditioning use, it becomes a better choice to use insulation materials on all surfaces inside the energy-using room.

Besides, in areas of high population and rapid urbanization, high-rise residential buildings have inevitably become one of the most prevalent housing solutions. Retrofitting the envelope of a number of existing high-rise buildings with external wall insulation would be difficult to achieve, both in terms of workload and cost. From this perspective, internal insulation is a more suitable retrofit for high-rise residential buildings in the HSCW region.

5.1.3 Research gap

In the current studies related to retrofitting existing buildings, most of them are discussing insulation retrofitting of exterior walls, or comprehensive energy efficiency retrofitting of exterior walls, roofing retrofitting, etc., but there is relatively little discussion on the interior walls and other envelope structures. And research has shown that the impact of these interior envelopes on energy efficiency may be greater in the case of compartmentalized energy use. Therefore, this paper proposes a new type of insulation, internal insulation, which is to insulate all internal surfaces of a home or room.

In addition, most of the current studies have used computational simulations and calculations, and relatively few studies have conducted retrofit experiments for actual buildings. Many studies point out that the data derived from simulations often differ from actual measurements, and those actual measurements provide more convincing data. Therefore, this paper is a practical retrofit of a unit in an existing high-rise residential building in Chengdu, a typical city in the HSCW region, selected for a year with actual measurements during the cooling and heating seasons. This paper mainly shows the data during the winter heating period.

5.1.4 Research objectives

In this case study, insulation was used as the main object of the comparative study, while ensuring the consistency of other building components. In Chengdu, China, the southern bedroom in the selected mid-rise case study residential building was retrofitted with interior insulation. The comparative measurements for intermittent heating were carried out in January 2020 with the following main study objectives:

1. To study the energy-saving effect of adding interior insulation to the south bedroom of existing external-insulated buildings in Chengdu, under the typical intermittent heating air conditioning modes in summer.
2. To investigate the improvement of the indoor thermal environment in the retrofitted bedroom compared to the un-retrofitted one under winter situation.

The rest of the paper will unfold in this way: section 5.2 will show the selection of the experiment time and the determination of the intermittent heating method; section 5.3 will show the comparative results of the experimentally measured energy consumption and indoor thermal environment in a realistic scenario; and finally, section 5.4 will present the main conclusions of the intermittent heating experiment.

5.2 Materials and methods

5.2.1 Selection of the experimental time

During the winter of 2020, the experimental households lived in the experimental residence and the comparison residence from December onwards, and the indoor and outdoor climates were monitored in real time. By tracking real-time measurement data, it was observed that from January 8th, successive cold weather began to appear, reaching almost the coldest levels of previous years. The minimum outdoor temperature reached below 5°C and the maximum temperature was around 15°C, which was almost the lowest level in previous winters. Therefore, these typical winter days were selected to conduct the comparison experiment. The actual measurement experiments were conducted over 10 consecutive days from January 8th, 2020, to January 17th, 2020.

5.2.2 Air conditioning operation mode and occupant behavior pattern

As mentioned earlier, most households in the HSCW region only use an air conditioner for a few hours a day in a separate room, depending on their demand. In order to display this energy use feature, the air conditioning usage patterns corresponding to the three most typical household compositions were selected. Namely, use the air conditioner at night and the early morning (case 1: elderly people), use the air conditioner late at night after work (case 2: office workers) and use the air conditioner from the morning to midnight (case 3: mixed family). The specific details of the usage model are shown in Table 5-2.

Table 5-2. The operation patterns of the air conditioners.

Operation	Heating Period	Operation Duration	Operation Temperature	Heating Area
Case 1	7:30–9:30; 18:00–24:00	8 h	24 °C	North and south bedroom
Case 2	20:00–24:00	4 h	24 °C	North and south bedroom
Case 3	7:30–24:00	16.5 h	24 °C	North and south bedroom

To minimize the influence of the habits of residents and the time they spend in the building, the following arrangement was made. In both the experimental and comparison residential units, the occupants consisted of a young couple and a preschool child, who live in the north and south bedrooms, respectively. During the experiment, they followed the same routine which is the most common one of the locals. There are no heating devices other than air conditioning in the bedroom area such as electric blankets. In addition, none of the other rooms use any heating equipment such as electric heaters. Since the experiment was conducted in a real-life scenario, both bedrooms had the demand to use air conditioners, so residents in both bedrooms followed the same air conditioning usage pattern in Figure 5-3.

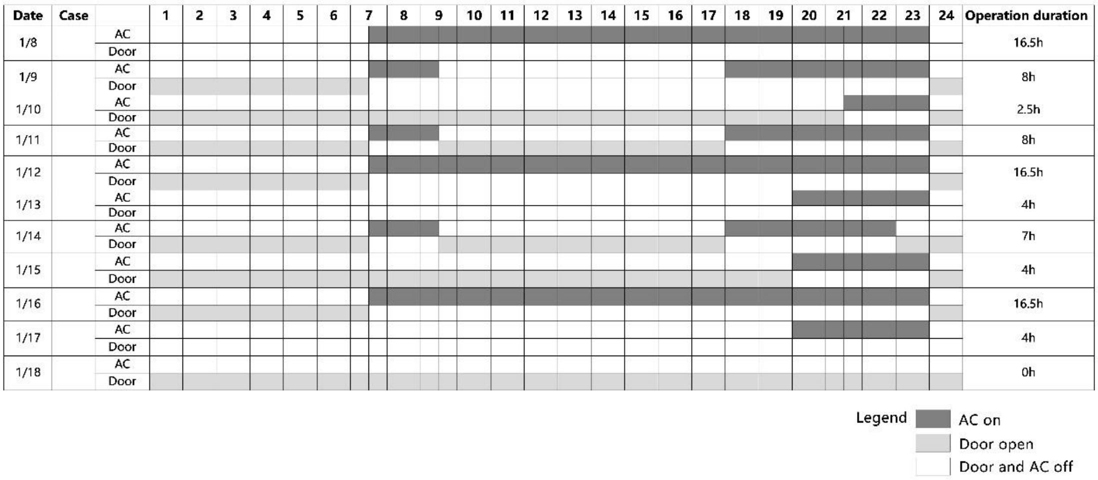

Figure 5-3. The operation schedule of the air conditioner and door.

It is important to clarify that as the occupants in the experiment were living in the residence, the usage patterns of the air conditioner were inevitably changed due to temporary changes in their daily plan. Figure 5-3 shows the actual use of air conditioners during the winter experiment. During the heating period of the experiment, the airspeed of the air conditioners was in automatic mode, and windows, doors, and curtains were kept closed all the time. In the interior of the bedrooms, there were no other electrical devices except for an electric light which is the same in both units. During the measurement, the occupant behavior was as follows: during the daytime, nobody stayed in the south bedroom except for the operation point. The main activity in the bedroom was sleeping, and the sleeping time was from 22:00 to 7:30 every day.

5.3 Results

5.3.1 Analysis of outdoor climate

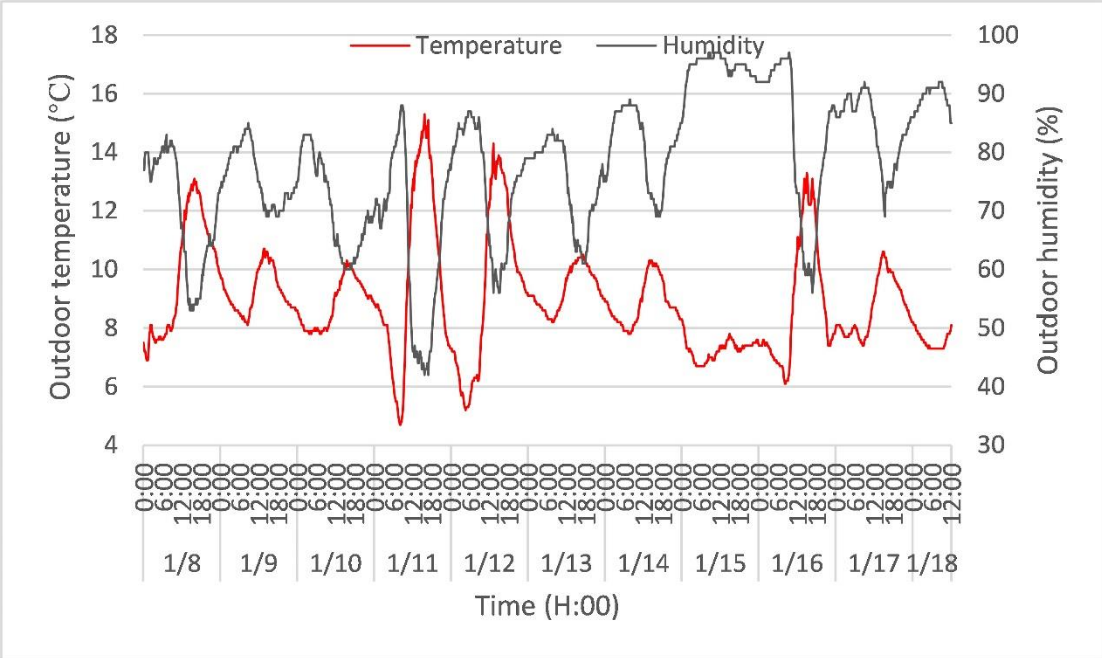

Figure 5-4. Outdoor temperature and relative humidity during the measurement.

Figure 5-4 shows the outdoor temperature and relative humidity measured every 10 minutes at weather stations in January 2020, one of the coldest months of the winter. As can be seen from the graph, January 8 to January 18 was a very cold period, with eight days when the minimum outdoor temperature was below 8°C, and even two of them below 6°C. The lowest temperature was 4.7°C (between 8:00 and 8:10 on January 11) and the average temperature during the measurement period was 8.9°C. In addition, the outdoor relative humidity was also at a high level, with an average relative humidity of 77.8% and a maximum of 97% during the test period (between 10:00 and 12:00 on January 15, and between 9:20 and 9:30 on January 16). The above data show the typical wet and cold climate characteristics of Chengdu in winter.

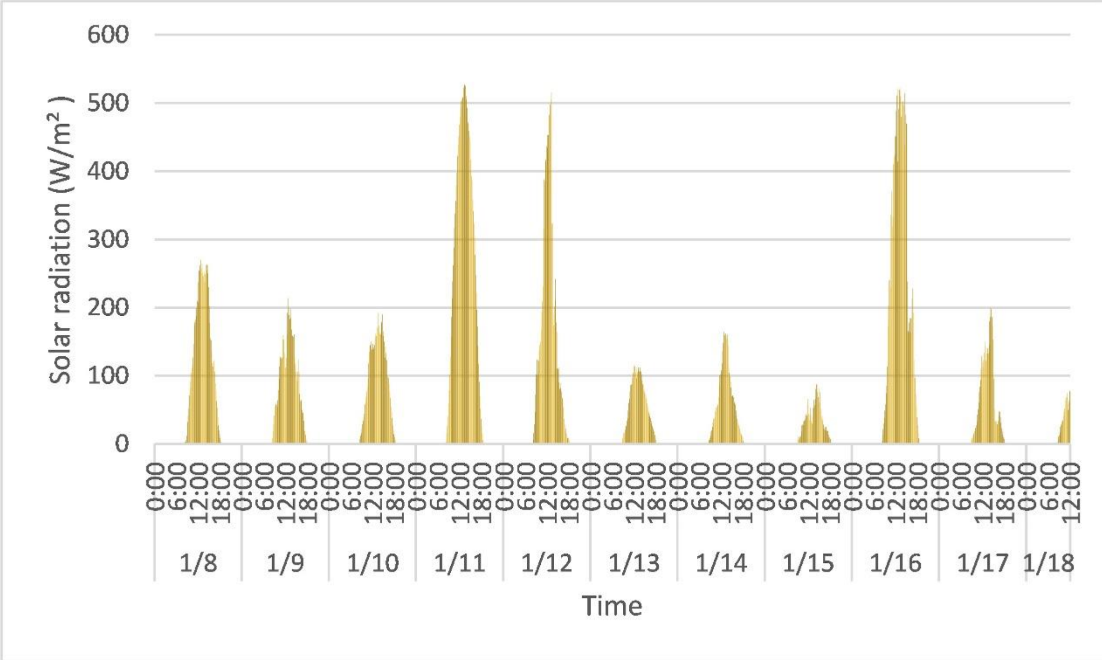

Figure 5-5. Daily solar radiation during the measurement.

Figure 5-5 shows the solar radiation during the measurement period, and from the data of 11 and a half days in the figure, the solar radiation in Chengdu is relatively low. Three of the days had relatively high radiation levels, on January 11, 12, and 16. The maximum daily solar radiation was 527 W/m², which occurred on January 11 at 13:20. The lowest daily maximum solar radiation was 87 W/m², which occurred on January 15 from 14:10 to 14:20.

5.3.2 Analysis of indoor thermal environment without air conditioning

January 19 was chosen to analyse the comparison of indoor thermal conditions in the south bedroom in its natural state (without air conditioning) under winter climate before and after the renovation.

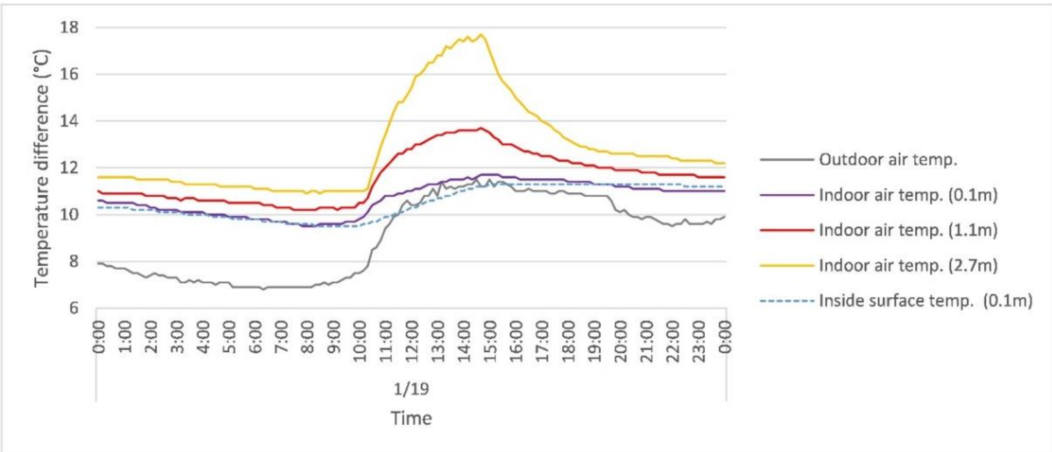

Figure 5-6. Temperature in the retrofitted south bedroom without air conditioning on Jan. 19th.

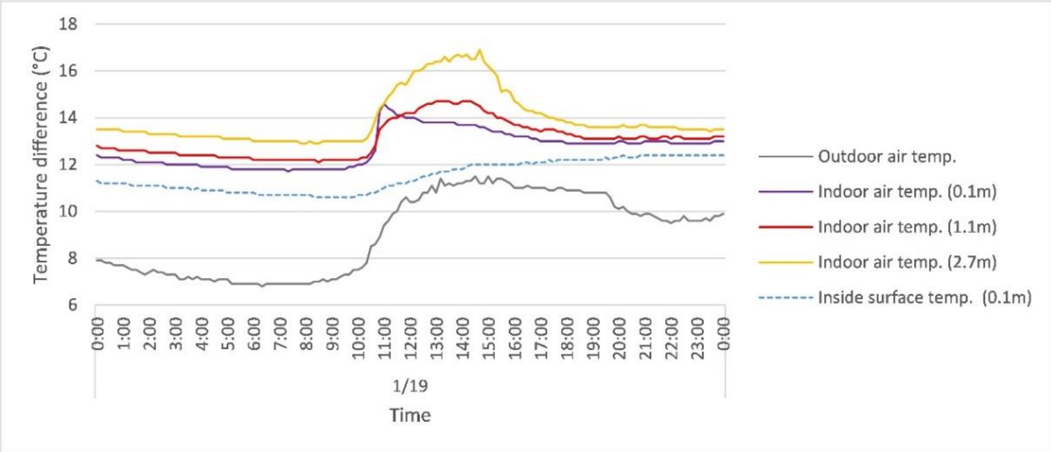

Figure 5-7. Temperature in the un-retrofitted south bedroom without air conditioning on Jan. 19th.

Figure 5-6 show the temperature in the retrofitted south bedroom on 19 January when the air conditioning was not on all day. The lowest outdoor temperature of the day was 6.8 °C and the indoor temperature fluctuated close to the outdoor temperature, both peaking in the afternoon. Indoor temperatures ranged from a high of 17.7 °C to a low of 9.5 °C. The overall average indoor temperature for the three heights was 11.7 °C.

Figure 5-7 show the temperatures in the unmodified south bedroom without air conditioning on 19 January. The results show that the indoor temperature in the unmodified south bedroom fluctuated relatively little with a maximum of 16.9 °C and a minimum of 11.7. The overall average indoor temperature for the three heights was 12.8 °C, 1.1 °C higher than after the retrofit.

Comparing the two bedrooms it can be concluded that the thermal mass of the envelope contributes Comparing indoor and outdoor climate data before and after the retrofit, it can be concluded that the thermal mass of the envelope in the unmodified units contributed to a higher temperature stability in the room, with peak indoor temperatures 0.8°C lower than after the retrofit. However, even the average indoor temperature of 12.8°C is low and very uncomfortable for living. The use of air conditioning to regulate the indoor temperature is therefore a necessary option for everyone during the winter months.

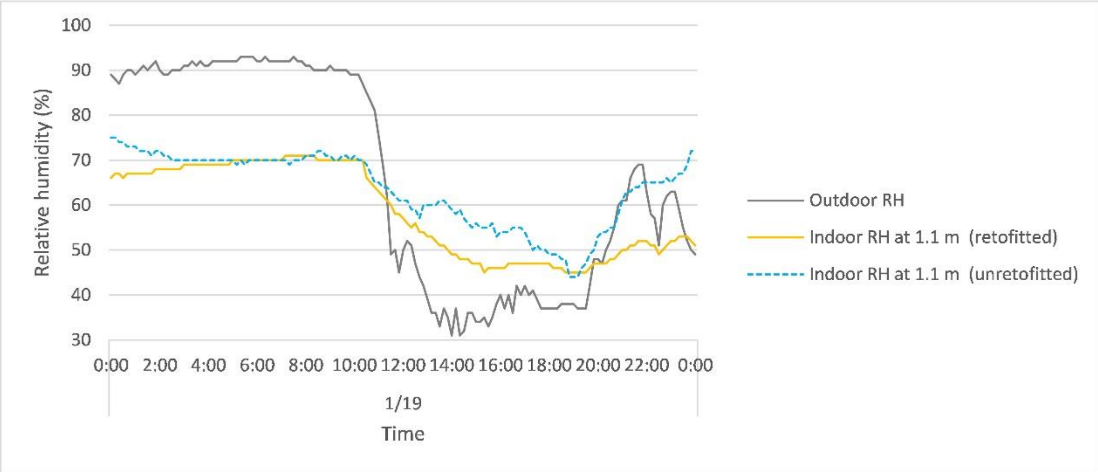

Figure 5-8. Comparison of relative humidity in the retrofit and un-retrofitted south bedroom without air conditioning on Jan. 19th.

Figure 5-8 shows a comparison of the relative humidity in the retrofitted and un-retrofitted south bedrooms on 19 January in the absence of air conditioning. The results show that the relative humidity in the retrofitted south bedroom was slightly lower overall than that in the unmodified bedroom.

5.3.3 Comparison of daily heating load and heating load decreases ratios

From January 8 to January 17, a fixed intermittent heating operation strategy was used, and the daily heating power consumption of the air conditioner during this period is shown in Figure 5-9. Throughout the experimental period, the southern bedrooms of both the experimental and comparison groups did not have any shading measures outside. The three selected intermittent modes of operation were performed twice at an operating temperature of 24 °C during the six days from January 8 to January 13. In addition, the three selected intermittent modes of operation were conducted once at an operating temperature of 22 °C between January 14 and 16.

Table 5-3. Comparison of daily and total heating load in the south bedroom.

Date	Retrofit room (kWh)	Un-retrofit room (kWh)
Jan. 8	4.98	10.93
Jan. 9	3.55	5.20
Jan. 10	1.40	1.88
Jan. 11	3.24	5.62
Jan. 12	4.46	9.01
Jan. 13	1.75	2.58
Jan. 14	2.82	4.49
Jan. 15	1.75	2.62
Jan. 16	3.78	8.49
Jan. 17	1.77	2.92
Sum	29.50	53.74

The energy consumption results in Figure 5-3 show that the heating energy consumption of the south bedroom with indoor insulation is significantly lower than that of the original south bedroom under different outdoor weather and different usage patterns. It can be seen from Table 3 that after 10 days of operation, the total heating energy consumption of the retrofitted south bedroom is 29.50 kWh, while the total heating energy consumption of the non-retrofitted south bedroom is 53.74 kWh. Therefore, the total heating energy savings over 10 days was 45.10%.

Figure 5-9. Comparison of daily heating load and daily heating load decreases ratios in the south bedroom.

Figure 5-9 shows that over the 10 consecutive days of the experiment, with a maximum energy savings of 55.53% (January 16) and a minimum energy savings of 25.55% (January 10). During the measurement, the daily energy savings in the retrofitted south bedroom averaged 41.58%. The results show that the internally insulated retrofitted bedrooms have better energy savings in the winter intermittent operation mode.

5.3.4 Comparison of indoor thermal environment under intermittent heating condition

During the experiment, the outdoor temperature from January 8 to 10 was chosen as the period for detailed analysis because it was relatively close and contained the three set energy use patterns. In this section, the overall indoor thermal environment, the indoor temperature and changes during the heating period, and the comparison of indoor humidity will be analyzed sequentially.

5.3.4.1 General comparison of indoor thermal environment

In the evaluation of the indoor environment of a building, the internal air temperature is the dominant variable used to ensure thermal comfort [22]. Therefore, the real-time variation of indoor temperature and energy consumption with weather is further compared in the first place.

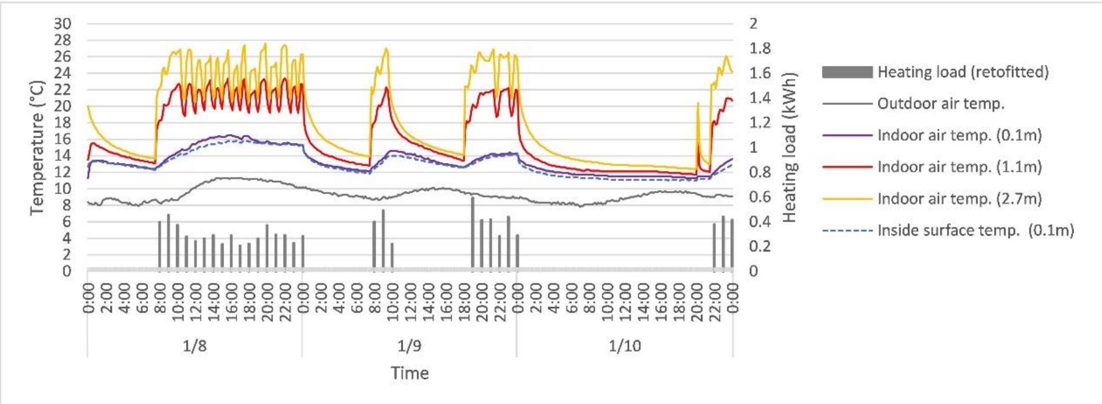

Figure 5-10. Indoor thermal environment and hourly heating load in the retrofitted south bedroom (Jan. 8 to Jan. 10).

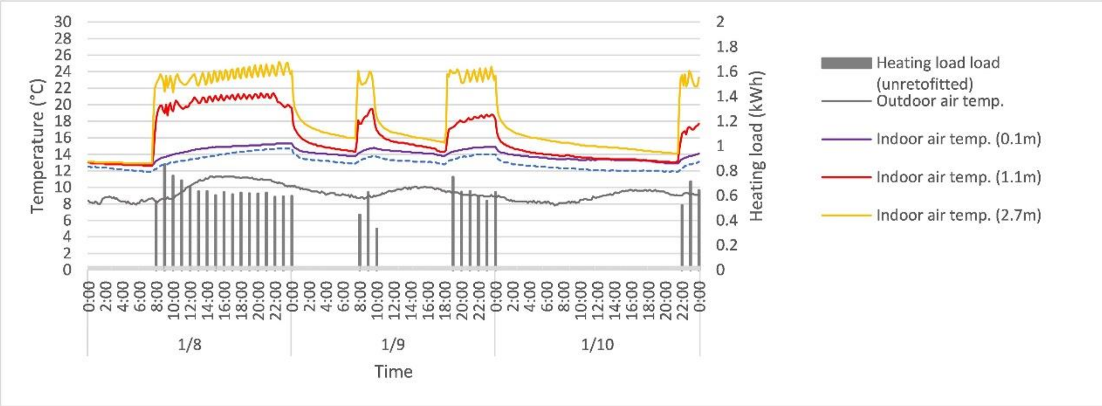

Figure 5-11. Indoor thermal environment and hourly heating load in the un-retrofitted south bedroom (Jan. 8 to Jan. 10).

Figure 5-10 and Figure 5-11 show the overall indoor thermal environment and hourly heating energy consumption in the retrofitted bedroom before and after the retrofit for the three days of January 8 to 10, 2020, respectively. Figure 8 shows the indoor thermal environment and hourly heating load in the retrofitted south bedroom, which shows that when the air-conditioning heating setting is 24 °C, the temperatures at 1.1 m and 2.7 m in the retrofitted bedroom are mostly higher than those in the un-retrofitted bedroom by about 2 °C. The temperatures in the retrofitted bedroom were about 2 °C higher than those in the non-retrofitted bedroom. Also, it was observed that the temperature fluctuations were significantly higher than in the unmodified bedroom. Since hot air always tends to go higher, the indoor temperature measured at 0.1 m, as well as the temperature difference between the indoor temperature and the temperature of the inner surface of the external walls, has only a very slight advantage during the heating period.

And when the air conditioner stopped running, the temperature in the retrofitted bedroom decreased more quickly and eventually stabilized at a much lower temperature.

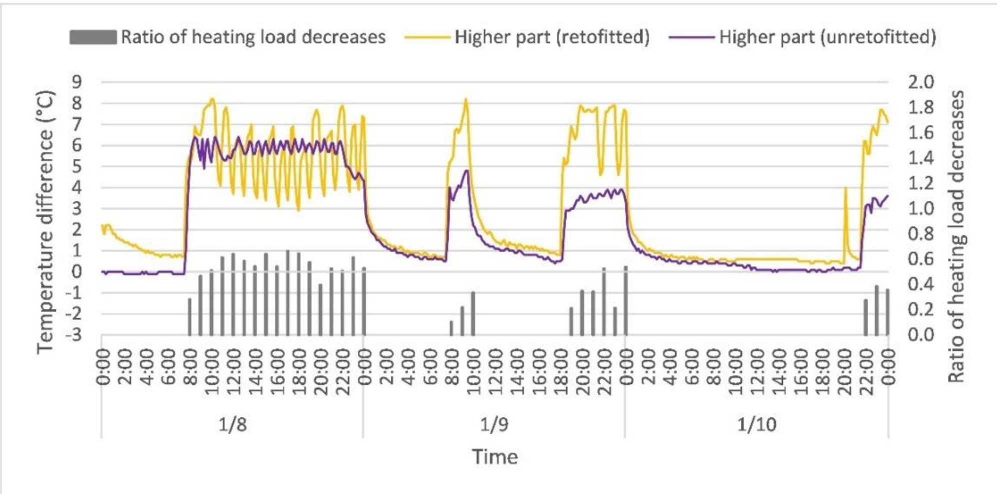

Figure 5-12. Comparison of indoor temperature difference in the higher part (2.7m-1.1m).

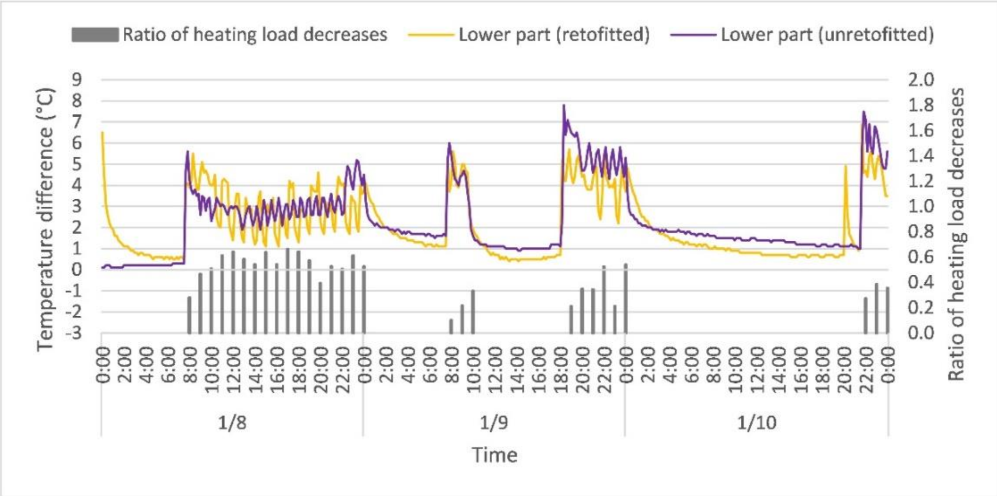

Figure 5-13. Comparison of indoor temperature difference in the lower part (1.1m-0.1m).

Figure 5-12 shows the temperature difference between the modified and unmodified south bedroom at the high point of the room (2.7 m-1.1 m) every ten minutes. It is obvious that during the heating period of the air conditioner, the temperature difference in the high part of the retrofitted bedroom also shows a large temperature fluctuation, with the highest part exceeding 8 °C, while the lowest part is as low as 3 °C. The situation in the un−retrofitted bedroom was that the temperature difference in the high places showed a small and stable fluctuation. And after the air conditioner was turned off, the temperature difference in the remodeled south bedroom was slightly higher than that in the un−retrofitted bedroom.

Figure 5-13 shows the temperature difference at the lower part of the room (1.1m-0.1m) every ten minutes in the retrofitted versus the un-retrofitted south bedroom. It can be very clearly seen that the temperature difference at the lower part of the retrofitted bedroom is close to that in the unmodified bedroom during the heating period of the air conditioner. The difference is that the temperature fluctuation in the retrofitted bedroom is also much larger than that in the un-retrofitted bedroom. After the air conditioning was turned off, the temperature difference in the lower part of the remodeled south bedroom was slightly lower than that in the unmodified bedroom.

5.3.4.2 Comparison of indoor temperature during heating

The overall indoor temperatures for all heating periods between January 8 and January 10 are shown in Table 5-4, where the indoor temperatures of the retrofitted bedrooms fluctuated less and were closer to the operating temperature values than those of the unmodified bedrooms. With an operating temperature of 24 °C, the overall average indoor temperature of the unmodified bedroom at three heights (0.1 m, 1.1 m, and 2.7 m) during the summer experiment was 19.7 °C, which was 0.7 °C higher than that of the modified bedroom. This indicates that the change in outdoor temperature had less effect on the indoor temperature of the remodeled bedrooms. In addition, compared to the unmodified bedrooms, the modified bedrooms showed an advantage in terms of indoor temperature at the same height, being 0.1 °C, 1.4 °C, and 0.9 °C higher than the unmodified bedrooms at three heights of 0.1 m, 1.1 m, and 2.7 m, respectively.

At different heating periods, the results showed that the indoor temperature of the unmodified bedroom was more influenced by the outdoor weather and the overall temperature was smoother but low.

Table 5-4. Results of measured temperature data during the heating period.

Parameters	Height Above Floor (m)	Mean (°C)		Maximum (°C)	Minimum (°C)	S.D.
Outdoor temperature (during the whole period)		8.9		15.3	4.7	1.86
Indoor temperature of retrofitted room during heating period	2.7	24.0	19.7	27.6	13	2.55
	1.1	20.6		23.4	12	1.98
	0.1	14.6		16.5	11.4	1.31
Indoor temperature of un-retrofitted room during heating period	2.7	23.1	19.0	25.2	12.9	1.70
	1.1	19.2		21.4	12.6	1.83
	0.1	14.5		15.3	12.7	0.60

Figure 5-14 to Figure 5-16 show the frequency and cumulative percentage of indoor temperature at 2.7 m, 1.1 m, and 0.1 m for all the heating period from Jan.8 to Jan.10.

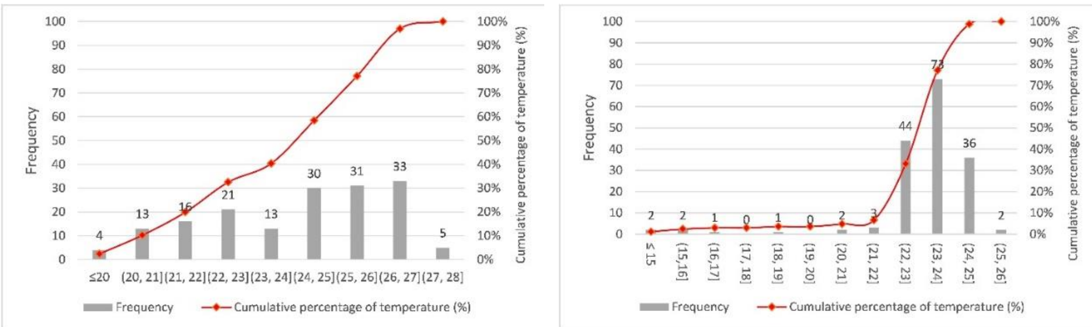

Figure 5-14. Frequency and cumulative percentage of indoor temperature in the retrofitted (left) and un-retrofitted (right) south bedroom at 2.7 m.

It is evident in Figure 5-14 that indoor temperature at 2.7 m in the remodeled bedroom is more dispersed, with a relatively higher concentration between 24 and 27 °C. In contrast, the unmodified bedroom shows a stronger concentration, especially between 23 and 24 °C.

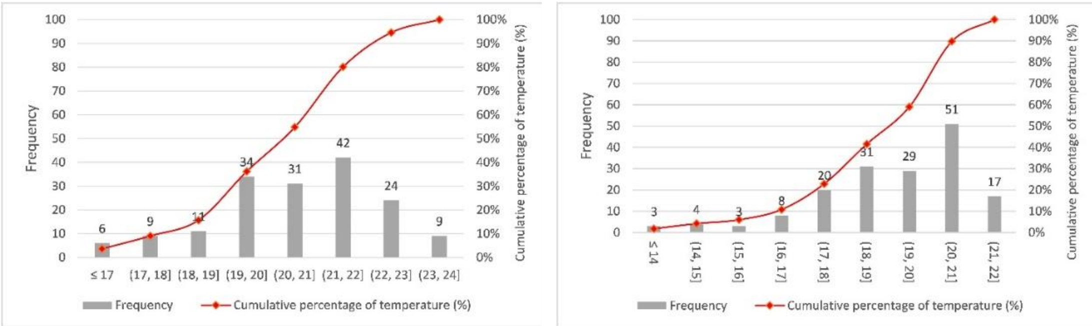

Figure 5-15. Frequency and cumulative percentage of indoor temperature in the retrofitted (left) and un-retrofitted (right) south bedroom at 1.1 m.

The results in Figure 5-15 show that the temperature distribution at 1.1 m is similar to that at 2.7 m. The temperature is a bit more dispersed in the retrofitted units, with a more homogeneous distribution from 19 to 22 °C. In contrast, the highest temperature frequencies were found in the 20 to 21 °C interval in the unmodified bedrooms.

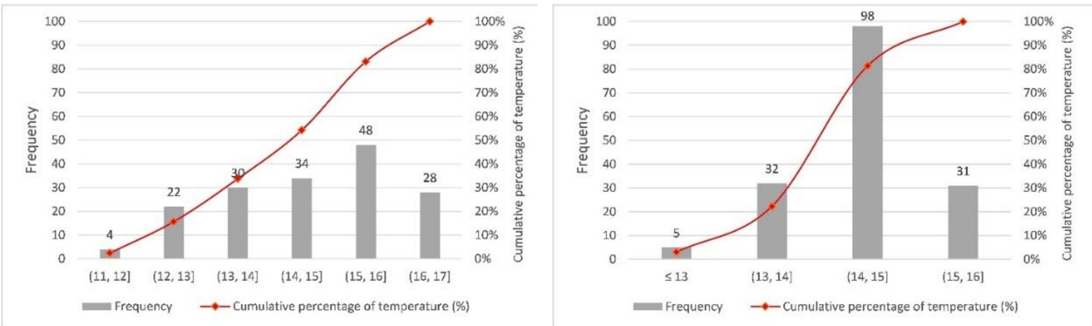

Figure 5-16. Frequency and cumulative percentage of indoor temperature in the retrofitted (left) and un-retrofitted (right) south bedroom at 0.1 m.

The results in Figure 5-16 show that although the temperatures in the bedrooms before and after the retrofit were very low at 0.1 m during the heating period, the retrofitted bedrooms still showed a similar distribution to the higher ones. In contrast, the temperature concentration was higher in the unmodified bedrooms.

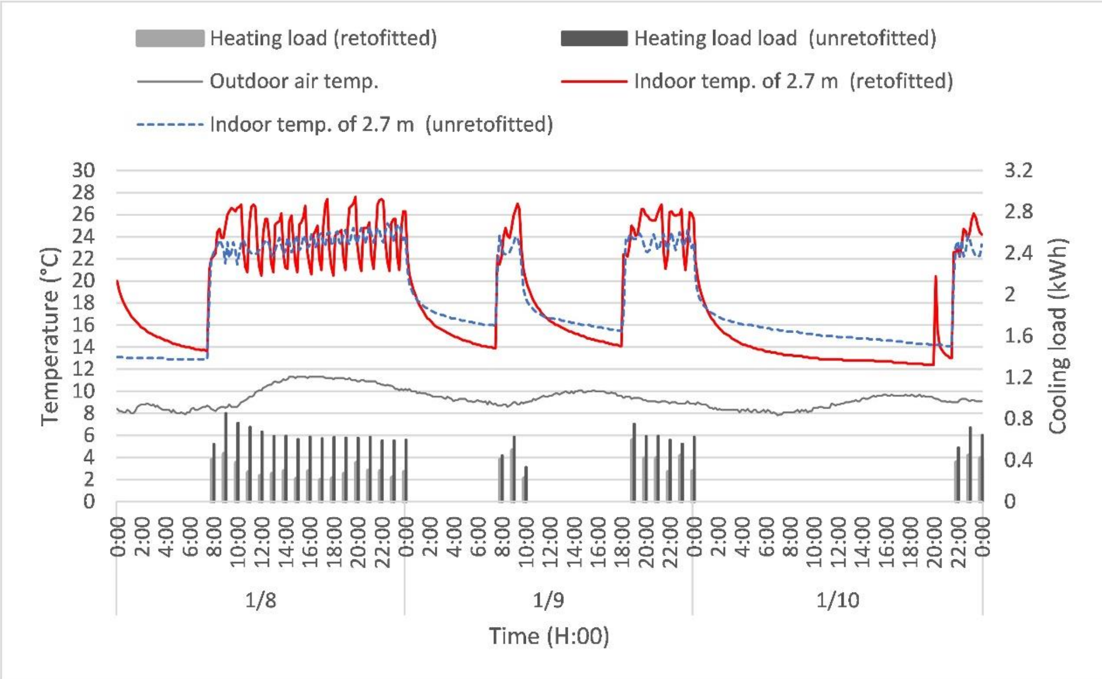

Figure 5-17. Comparison of indoor temperature at 2.7 m and hourly heating load.

Figure 5-17 shows the comparison of indoor temperature at 2.7 m and hourly heating load. The result indicates that the average temperature in the remodeled bedroom was 24 °C, which is exactly the set temperature value. Since this is the closest height to the air conditioner sensor, it can be said that the air conditioner controls the temperature of the whole room well. The average temperature at the same height in the non-remodeled group was 23.1 °C, which was 0.9 °C lower than after the retrofit. In terms of temperature fluctuations, the indoor temperature fluctuations at 2.7 m after the retrofit were very large and frequent, while the temperature in the bedroom of the un−retrofitted group was relatively smooth. This can also be seen from the variance values of the two sets of temperature data, which were 2.55 and 1.70 after and before the renovation, respectively. the main reason for this phenomenon is that the main heat emitted from the bedrooms in the renovated group is used to heat the indoor air when the air conditioner is turned on, so higher temperatures can be achieved. For example, on January 8, when the air conditioner was turned on at 7:30, the highest temperature point of 26.9 °C was reached at 10:20. When the sensor of the air conditioner senses that the nearby indoor temperature has reached the set temperature, it will stop running, so the indoor temperature starts to drop, and at 10:30 the indoor temperature at that height drops to 22.8 °C. The same phenomenon was repeated several times at intervals of about 2 hours, with a maximum fluctuation of 4.6 °C (17:40 on January 8) and a minimum of 1.8 °C (12:40 on January 8).

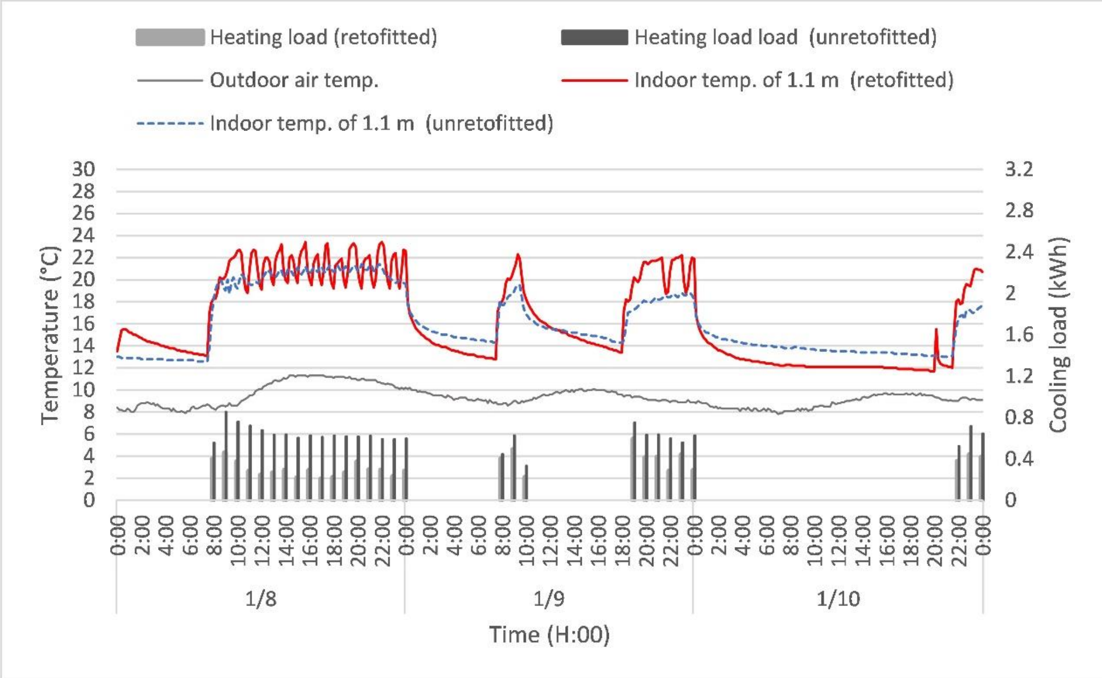

Figure 5-18. Comparison of indoor temperature at 1.1 m and hourly heating load.

At 1.1 meters indoors (Figure 5-18), the temperature showed a similar fluctuation pattern as at 2.7 meters. However, because of the distance between this height and the air conditioning position, its fluctuation is relatively small. The maximum fluctuation is 2.5 °C (15:50 and 17:40 on January 8), and the minimum fluctuation is 0.4 °C (12:40 on January 8).

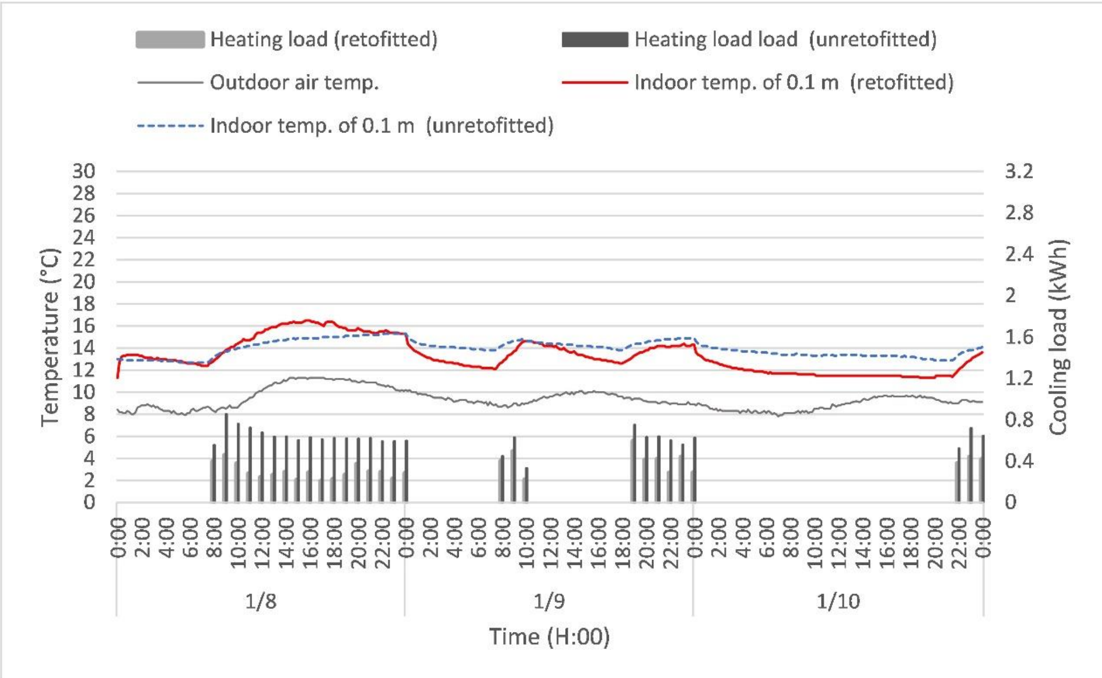

Figure 5-19. Comparison of indoor temperature at 0.1 m and hourly heating load.

As shown in Figure 5-19, the indoor 0.1 meter was too low due to its location, while the air conditioner was located high in the room, and the hot air it released had difficulty reaching the lowest part of the room, resulting in a relatively weak increase in temperature in the room before and after the renovation only on the basis of the unconditioned room. On January 8, for example, when the air conditioner was not turned on at 7:30 a.m., the temperatures in the bedroom before and after the renovation were very close to each other, 12.4 ℃ and 12.7 ℃ respectively. After the air conditioner was turned on for 8 hours, the temperature reached a maximum of 16.5 ℃ at 0.1 meters in the renovated bedroom, and the temperature in the unrenovated bedroom was 14.9 ℃ at that time. In the other periods, instead, the temperature in the unmodified group was slightly higher.

During the time after the air conditioner was turned off, the temperature in the internally insulated unit dropped faster because the insulation isolated the thermal mass of the envelope. In the unmodified rooms, the thermal mass played a certain role in stabilizing the indoor temperature, so the temperature in the original units was generally higher than that in the modified units during the non-heating period, with a temperature difference of about 2 °C.

5.3.4.3 Comparison of indoor relative humidity

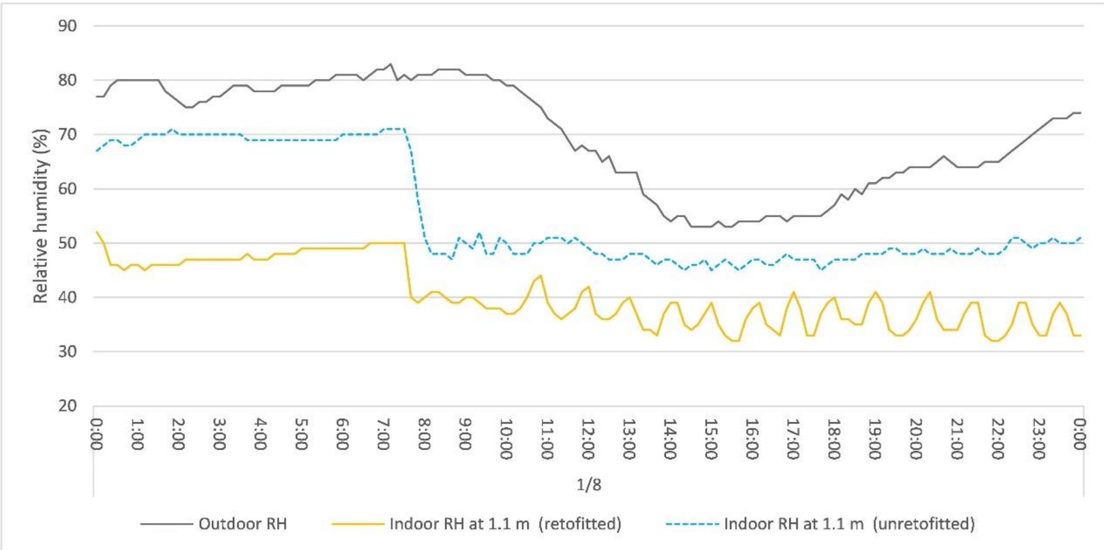

Figure 5-20. Comparison of relative humidity in the south bedroom before and after retrofit on January 8th.

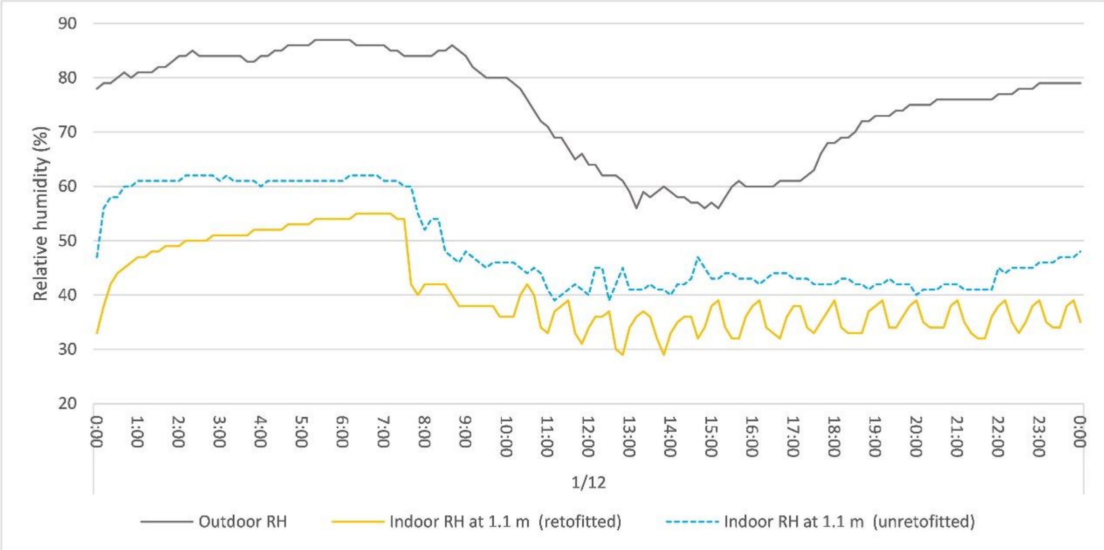

Figure 5-21. Comparison of relative humidity in the south bedroom before and after retrofit on January 12th.

In addition to temperature, the effect of the remodeling project on the indoor relative humidity was also studied. Figure 5-20 and Figure 5-21 show the outdoor relative humidity for two days, January 8 and 12, and the relative humidity at 1.1 m in the south bedroom compared with and without the retrofit. The air conditioner was cooled for 16.5 hours on both days and ran continuously for a longer period. It is obvious that the relative humidity in the retrofitted bedroom (yellow line) is lower and fluctuates in a 5% range. In contrast, the humidity values in the unmodified bedrooms were higher during the heating period.

Table 5-5 andTable 5-6 show measured indoor relative humidity during the heating period of January 8th and 12th, respectively. The data analysis shows that the average relative humidity in the retrofitted bedroom on January 8th was 50% compared to 32% in the un-retrofitted bedroom. However, the S.D. value of relative humidity in the remodeled rooms was 3.10, which is smaller than the 3.48 in the un-retrofitted rooms. This indicates that the overall fluctuation is less.

Similarly, the results in Table 5-6 show that the average relative humidity in the remodeled bedroom on January 12 was 54%, which is 15% higher than the 29% in the un-retrofitted bedroom. The S.D. value was 3.45 in the retrofitted bedrooms and 3.75 before the retrofit, so overall, the average relative humidity in the retrofitted bedrooms was higher in the heating condition, but less fluctuating.

Table 5-5. Measured indoor relative humidity during the heating period of January 8th.

Parameters	Mean (%)	Maximum (%)	Minimum (%)	S.D.
Outdoor relative humidity	66	82	53	9.37
Indoor relative humidity of retrofitted room	37	50	32	3.10
Indoor relative humidity of un-retrofitted room	49	71	45	3.48

Table 5-6. Measured indoor relative humidity during the heating period of January 12th.

Parameters	Mean (%)	Maximum (%)	Minimum (%)	S.D.
Outdoor relative humidity	71	86	56	9.01
Indoor relative humidity of retrofitted room	36	54	29	3.45
Indoor relative humidity of un-retrofitted room	44	60	39	3.75

Meanwhile, according to the design code for heating ventilation and air conditioning of civil buildings GB 50736-2012 (Table 5-7), the lower limit of relative humidity should be stipulated for building areas with high comfort requirements, and it is determined that the relative humidity is not less than 30%. Therefore, the relative humidity in the renovated bedroom is still within the comfort range.

Table 5-7. Indoor design parameters for air conditioning in areas where people stay for long period.

(Source: Design code for heating ventilation and air conditioning of civil buildings GB 50736-2012)

Type	Thermal comfort level	Temperature (°C)	Relative humidity (%)	Wind speed (m/s)
Heating condition	I	22~24	≥30	≤0.20
	II	18~22		≤0.20

5.4 Summary

Based on the actual use of the building in the operational phase, a comparison field experiment was done for 10 consecutive days in January 2020, one of the coldest months in the HSCW region. This field test focused on three typical intermittent heating patterns in the region, and the main conclusions finally obtained were as follows.

During the 10 days of intermittent heating, the retrofitted south bedroom showed good energy savings with an average daily energy savings rate of 41.58% and a maximum daily energy savings rate of 55.53%.

Analysis of the indoor thermal environment during the coldest three days of the experimental period, January 8 to January 10, showed that the average indoor temperature of the retrofitted bedroom was 0.7 °C higher than that of the unmodified bedroom during the heating period. During each heating period, the temperature was well controlled at 1.1 m and 2.7 m. The average temperature in the retrofitted bedroom at 2.7 m was 24 °C, which reached the set temperature value, compared to 0.9 °C lower in the un-retrofitted bedroom. The average temperature in the retrofitted bedroom at 1.1 m was 20.6 °C, compared to 19.2 °C in the un-retrofitted bedroom, which was 1.4 °C lower.

From this case study, it can be concluded that in high-rise buildings in the HSCW region of China, higher and more comfortable indoor temperatures can be achieved in winter by adding interior insulation to the southern bedrooms of existing exterior insulated dwellings, while the energy-saving rate ranges from 25.55% to 55.53%.

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Chapter 6

IMPACT OF ORIENTATION AND SET TEMPERATURE ON ENERGY CONSUMPTION AND INDOOR THERMAL ENVIRONMENT

CHAPTER SIX: IMPACT OF ORIENTATION AND SET TEMPERATURE ON ENERGY CONSUMPTION AND INDOOR THERMAL ENVIRONMENT

6.1 Introduction

6.1.1 Research motivation

The literature review in Chapter 2 focuses on the analysis of the various factors that affect the insulation performance of the building envelope. However, in addition to the envelope, there are also many other factors that influence the energy efficiency of a building. For example, at the level of building and site layout, the orientation of the building as well as the walls, and the shading relationship between buildings. At the level of occupant behavior, differences in income, age, and physical tolerance due to the area where the occupants have lived for a long time can lead to different triggers for turning on and off the air conditioner, as well as significant differences in the operating temperature of the air conditioner. In addition, in addition to the use of air conditioning equipment, the opening behavior of windows by occupants can also have a significant impact on building energy consumption.

In this chapter, based on the actual situation of the experimental building in this study, the orientation and the set temperature of the air conditioner are selected as further analysis targets.

6.1.1.1 Orientation

In the intermittent operation mode of air conditioning in the region, the impact of south-facing inside insulation on energy efficiency is more pronounced. A 2017 study [1] analysed the influence of insulation placement and thermal resistance on the energy transfer and energy consumption of building walls in Shanghai. The results showed that rooms with inside insulation were at least 18% more energy efficient than rooms with outside insulation, and that inside insulation was more effective for south-facing office rooms.

Tunisia also has a climate that requires both winter heating and summer cooling. Naouel Daouas (2011) [2] A rigorous calculation of the annual cooling and heating loads of an exterior wall insulated building was performed based on a complex finite Fourier transform analysis method. The results show that walls facing west and east are the least preferred under cooling conditions, while walls facing north are the most preferred under heating conditions. From an economical point of view, the south-facing is the most economical.

6.1.1.2 Set temperature

In the energy efficiency codes for buildings in hot summer and cold winter regions, the set temperatures for cooling and heating in the region are specified at 26 °C and 18 °C respectively. However, due to the wide geographical area covered in hot summer and cold winter regions and the different levels of tolerance to cold. This results in inconsistencies in the actual set temperatures in heating situations.

In a study of building envelopes in hot-summer and cold-winter regions, Fang Ruan (2017) [3] conducted a study of the behaviour of people living in buildings in Hangzhou, with a total of 934 valid questionnaires. The results showed that people had a relatively wide range of setting temperatures for air conditioning, from 24 °C to 28 °C. Among them, the heating setting temperature was the most frequent at 26 & 28 °C, while the air conditioning setting temperature was the most frequent at 28 °C.

Shunqin Gu (2017) [4] conducted a questionnaire survey lasting six months in 2016 for households in the Chengdu area, with 699 valid questionnaires. The results showed that 81% of the households were used to setting their air conditioners below 26 °C in summer, while the calculated temperature for air conditioners in Chengdu was 26 °C. Therefore, the majority of households set their cooling temperature lower than the calculated value in the code. At the same time, the simulation results of the study show that the air conditioning set temperature has an approximate positive relationship with energy consumption. In summer, each 1 °C reduction in air conditioning temperature will increase the energy saving rate by about 10%.

Masoso and Grobler (2008) used EnergyPlus to carry out a simulation study of office buildings in hot dry climates. The results show that adding wall insulation may not always result in a reduction in annual energy consumption. Taking a 0.08 m extruded polystyrene as an example, the yearly cooling energy savings varied from positive to negative when the set cooling temperature was increased to approximately 26 °C [5].

6.1.2 Research purpose

The purpose of this section of the study is divided into the following two parts.

First, to compare the differences in energy consumption and indoor thermal environment between south-facing and north-facing bedrooms in the experimental dwellings after the internal insulation retrofit.

Second, to compare the differences in the effects of different setting temperatures on air conditioning energy consumption and indoor thermal environment in the dwelling units that underwent internal insulation retrofit.

Besides, the study on orientation was conducted in the summer of 2019 under the experimental pair of intermittent cooling conditions, and the comparison on the set temperature was conducted in the winter of 2020 under the heating conditions.

6.2 Materials and methods

6.2.1 Materials and methods on orientation

The common buildings in most cities in China have two main orientations, namely south and north. Since there is a difference in solar radiation intensity between south and north directions, in order to study the effect of orientation on the internal insulation retrofit, we added north-facing bedrooms to the cooling season in this study to compare with south-facing bedrooms. It should be noted that in the retrofit of the experimental unit, the south-facing room and the north-facing room were both retrofitted with internal insulation.

The south bedroom uses the exact same air conditioning operation mode as the north bedroom, which is the same air conditioning cooling mode for the 3 typical household compositions. As mentioned earlier, most households in the HSCW region only use an air conditioner for a few hours a day in a separate room, depending on their demand. The air conditioning usage patterns corresponding to the three most typical household compositions were selected. Namely, use the air conditioner from the night to the early morning (case 1: office workers), use the air conditioner during lunch break and from night to the early morning (case 2: elderly people), and use the air conditioner from the morning to late night/next morning (case 3: mixed family). The specific details of the usage model are shown in Table 6-1.

Table 6-1. The operation patterns of the air conditioners.

Operation	Cooling Period	Operation Duration	Operation Temperature	Cooling Area
Intermittent case 1	0:00–2:00; 22:00–24:00	4 h	26 °C	North and south bedroom
Intermittent case 2	0:00–2:00; 12:00–17:00; 19:00–0:00	12 h	26 °C	North and south bedroom
Intermittent case 3	0:00–2:00; 8:00–24:00	18 h	26 °C	North and south bedroom

To minimize the influence of the habits of residents and the time they spend in the building, the following arrangement was made. In both the experimental and comparison residential units, the occupants consisted of a young couple and a preschool child, who live in the north and south bedrooms, respectively. During the experiment, they followed the same routine which is the most common one of the locals. Except for the bedroom area, no cooling equipment such as air conditioners and electric fans were used in any of the rooms. Since the experiment was conducted in a real-life scenario, both bedrooms had the demand to use air conditioners, so residents in both bedrooms followed the same air conditioning usage pattern in Figure 6-1.

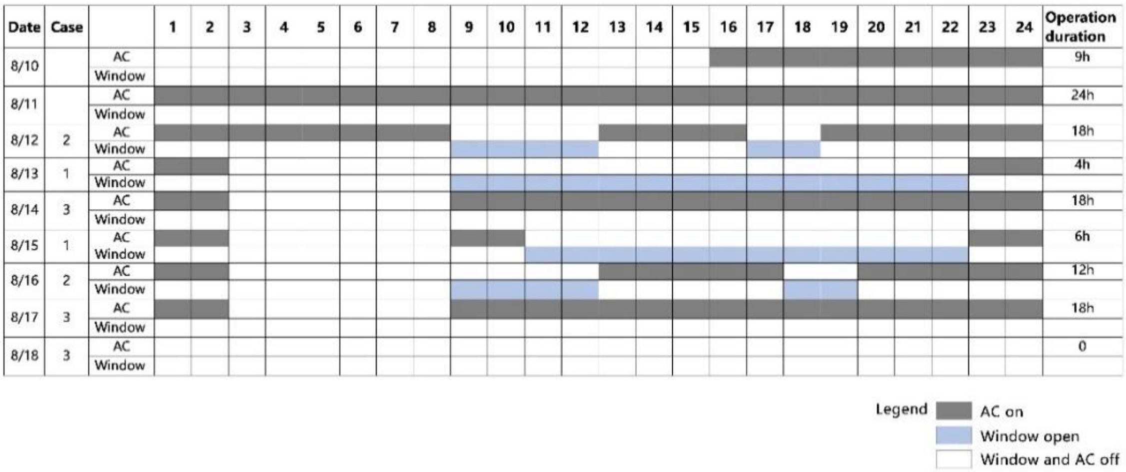

Figure 6-1. The operation schedule of the air conditioner and window.

It should be noted that since the occupants in the experiment were living in the residence, the usage pattern of the air conditioner was inevitably changed due to temporary changes in the occupants' daily plan. Figure 6-1 shows the actual use of air conditioners and windows during the experiment. During the cooling period of the experiment, the airspeed of the air conditioners was in automatic mode, and windows, doors, and curtains are always closed. While since there is no mechanical ventilation system in local residences, residents are used to opening windows for fresh air every day several times a day. To simplify the operation of the experiment, the windows were opened and ventilated during the daytime hours when the air conditioner was turned off. In the interior of the bedroom, there were no other electrical devices except for an electric light which is the same in both units. During the experiment, the windows were opened and closed according to the schedule in Figure 6-1, and the open width was 30 cm. The curtains were opened and closed in the same way as the window. During the measurement, the occupant behavior was as follows: during the daytime, nobody stayed in the south bedroom except for the operation point. The main activity in the bedroom was sleeping, and the sleeping time was from 22:00 to 8:00.

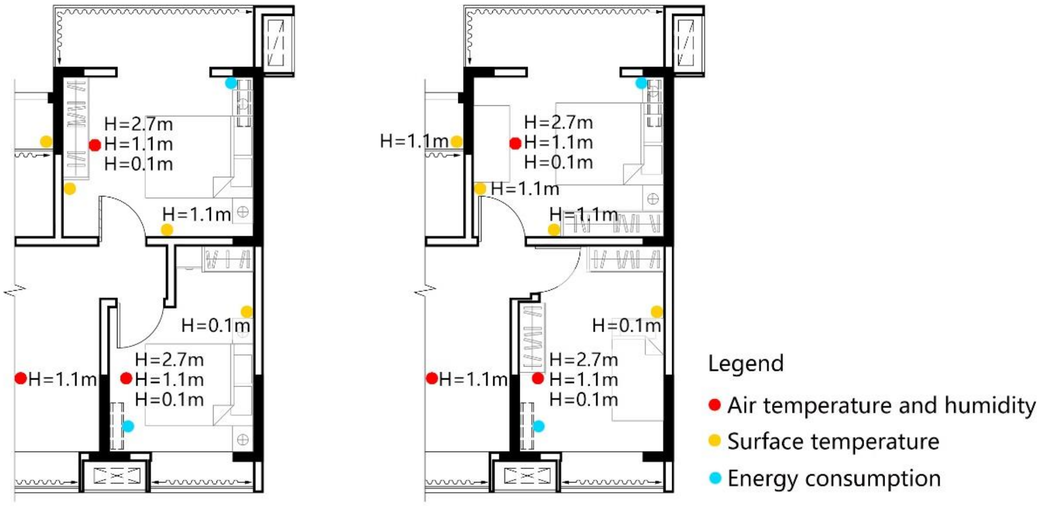

Figure 6-2. Layout of measurement equipment in the summer 2019 experiment (including the south bedroom).

In addition to the equipment in the south bedroom, the distribution of the measurement equipment in the north bedroom is shown in Figure 6-2. The distribution of the indoor measurement equipment is divided into four main sections as follows.

1. Similar to the layout in the south bedroom, devices for measuring indoor temperature and relative humidity were placed in the middle of the north bedroom at 0.1 m, 1.1 m and 2.7 m.

2. In order to better analyze the heat transfer characteristics of the walls, the temperatures of the inner and outer surfaces of the exterior walls were also measured.

3. The surface temperature of the partition wall of the south bedroom near the north bedroom was also measured.

4. The air conditioning energy consumption was recorded in real time during the experiment.

Also, as can be seen in Figure 6−2, the same experimental equipment arrangement was made in the north bedroom of the unmodified unit.

Table 6-2. Parameters of the air conditioners in use.

Parameter	North bedroom	South bedroom
Brand	GREE	Changhong
Type	Variable frequency	Fixed frequency
Cooling power (W)	980 (160-1400)	810
Heating power (W)	1400 (190-1615)	800
Coefficient of performance	3.53	3.25

Table 6-2 shows the information about the air conditioners used in the bedroom part of the retrofitted residential unit and the non-retrofitted unit during the experiment. To make the experimental conditions identical, the same GREE brand air conditioner was used in the north bedroom before and after the renovation, which is an inverter air conditioner with a cooling power of 980, heating power of 1400, and energy efficiency ratio of 3.53, while the same Changhong brand fixed-frequency air conditioner was used in the south bedroom before and after the renovation, with a cooling power of 810, heating power of 800, and energy efficiency ratio of 3.25. Since The north bedroom is the master bedroom, which is larger and occupied by an adult couple, so the cooling and heating power of the air conditioner used in this room is higher.

Figure 6-3. Actual view of the north bedrooms: renovated unit (left), and original unit (right).

Figure 6-3 shows the actual view of the north bedrooms before and after the retrofit, with the retrofitted unit on the left and the unmodified unit on the right.

Figure 6-4. Actual view of the south bedrooms: renovated unit (left), and original unit (right).

Figure 6-4 shows the actual view of the south bedrooms before and after the retrofit, with the retrofitted unit on the left and the unmodified unit on the right.

6.2.2 Method on heating setting temperature

In the January 2020 experiment, two heating temperatures, 24 °C and 22 °C, were used in order to compare the effects of different heating setting temperatures on air conditioning energy consumption and indoor thermal environment. In this case, 24 °C was used as the main heating temperature for a total of 7 days, while 22 °C was used as the comparison setting temperature for a total of 3 days.

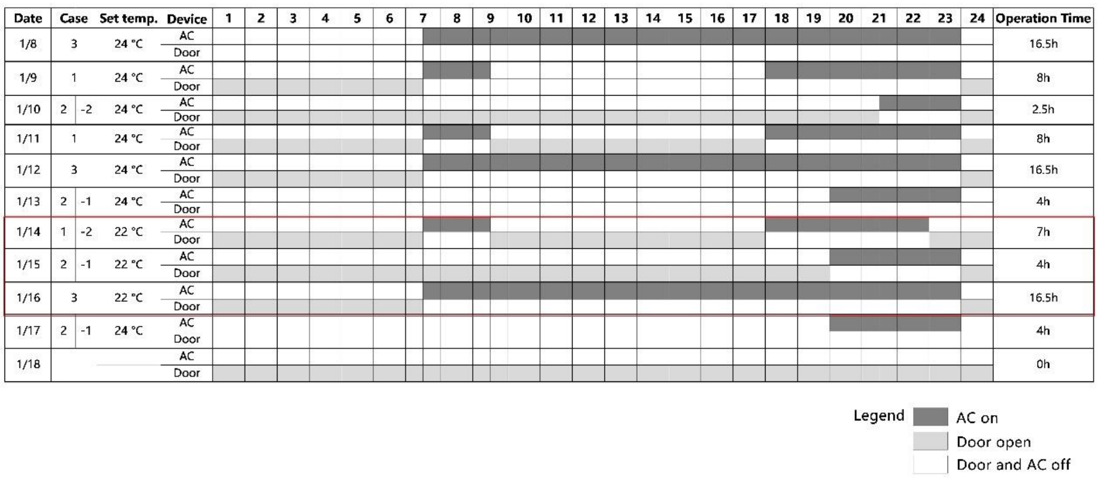

Figure 6-5. The operation schedule of the air conditioner and door.

Figure 6-5 shows the operation mode and set temperature of the air conditioner during the winter experiment. From January 8 to 13, the air conditioner was operated at a set temperature of 24 °C for the three selected intermittent heating modes for a total of 2 rounds. From January 14 to 16, the air conditioner was operated at a set temperature of 22 °C, and one round was run for the three selected intermittent heating modes.

It should be clarified that in order to ensure consistent experimental conditions, the experimental conditions were identical during the test except for the set temperature.

6.3 Comparison of orientation on residence retrofitted with interior insulation

This section shows the difference between the cooling energy consumption and the indoor thermal environment in the north and south bedrooms in the retrofitted units in the intermittent cooling mode.

6.3.1 Comparison of energy consumption in different orientations

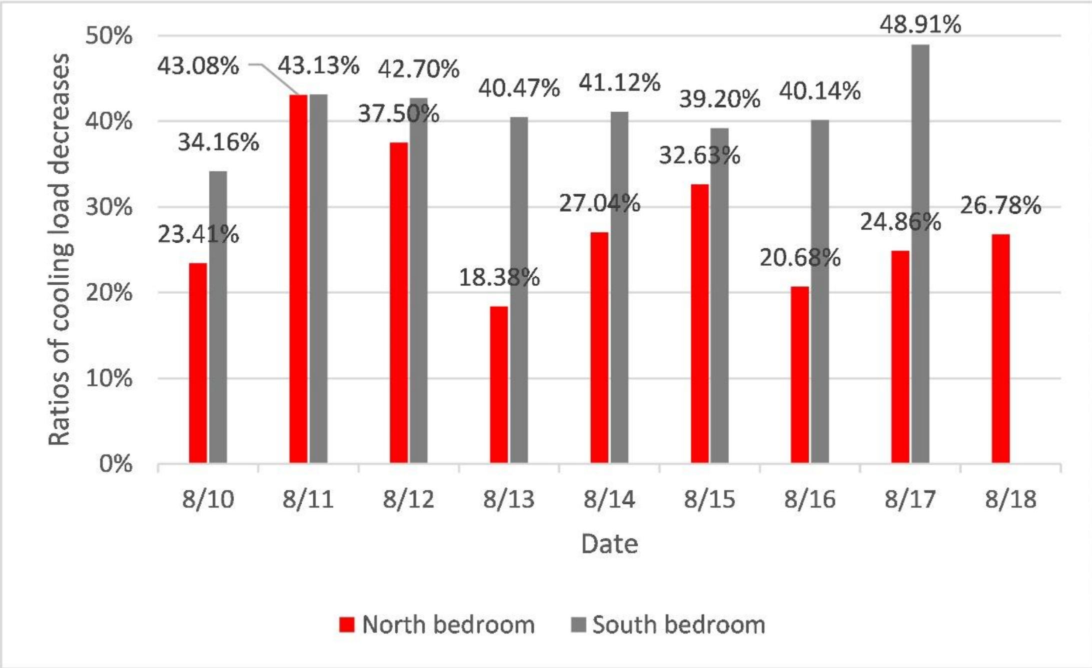

Figure 6-6. Comparison of daily cooling load decrease ratio between the north and south bedroom.

Figure 6-6 shows the daily cooling energy savings rate of the north bedroom of the retrofitted unit compared to the south bedroom during the 10-day experiment in summer 2019. The results show that both rooms, regardless of orientation, have very good energy savings after the interior insulation retrofit. The north bedroom, represented in red, for example, has the lowest energy savings rate of 18.38%, while the highest rate is 43.08% (August 11). However, comparing the daily energy saving rates, it can be found that the south bedroom always shows better energy saving results. The highest energy savings rate in the south bedroom was 48.91% (August 17).

Table 6-3. Daily cooling load decrease ratio in the north bedroom.

Date	Cooling load decrease ratio	Duration (h)
August 10	0.23	9
August 11	0.43	24
August 12	0.37	18
August 13	0.18	4
August 14	0.27	18
August 15	0.33	6
August 16	0.21	12
August 17	0.25	18
Average	0.28	

Since only the north bedroom used the air conditioner on August 18, this day was not included in the comparison of north and south orientation. Table 6-3 shows the daily and average energy savings in the north bedroom for the eight days from August 10 to 17, and the results show that the average daily energy savings for the air conditioning cooling load in the north bedroom was 28%.

Table 6-4. Daily cooling load decrease ratio in the south bedroom.

Date	Cooling load decrease ratio	Duration (h)
August 10	0.34	9
August 11	0.43	24
August 12	0.43	18
August 13	0.40	4
August 14	0.41	18
August 15	0.39	6
August 16	0.40	12
August 17	0.49	18
Average	0.41	

Table 6-4 shows the daily and average energy savings in the south bedroom for the eight days from August 10 to 17, and the results show that the average daily energy savings for the air conditioning cooling load in the north bedroom was 41%. The average daily energy savings in the south bedroom is 13 % higher than the north bedroom.

6.3.2 Comparison of indoor thermal environment in different orientations

6.3.2.1 Comparison of indoor thermal environment in the retrofitted and un-retrofitted north bedrooms

Before comparing the difference in indoor comfort in the retrofitted north and south facing bedrooms, it is necessary to have a clearer idea of the effect of the retrofitting of the north bedroom itself. Therefore, the Indoor thermal environment and hourly cooling load in the un-retrofitted north bedroom and the retrofitted north bedroom are shown in Figure 6-7 and Figure 6-8, respectively.

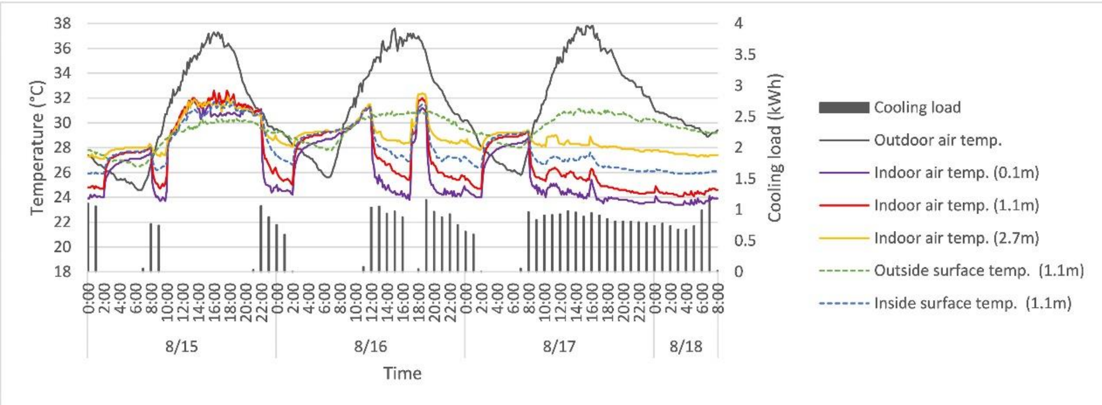

Figure 6-7. Indoor thermal environment and hourly cooling load in the un-retrofitted north bedroom.

The results in Figure 6-7 show that the overall temperature between the surface of the building structure and the interior in the unmodified north bedroom is shown below. First, the temperature difference between the inner surface of the building exterior wall and the outer surface is relatively small, with a maximum of about 4 degrees. Second, the temperature difference between the inner surface of the building exterior wall and the indoor temperature at the same height (1.1 m, red) is large, always around 2 °C. Thirdly, there is a temperature difference of close to 2 °C between the temperatures at all three heights indoors. At the same time, the energy consumption per hour is all around 1 kWh. These results indicate that when air conditioning is used in the north bedroom of this existing high-rise residential building with external insulation, the temperature difference in the room is relatively large both horizontally and vertically at higher air conditioning energy consumption.

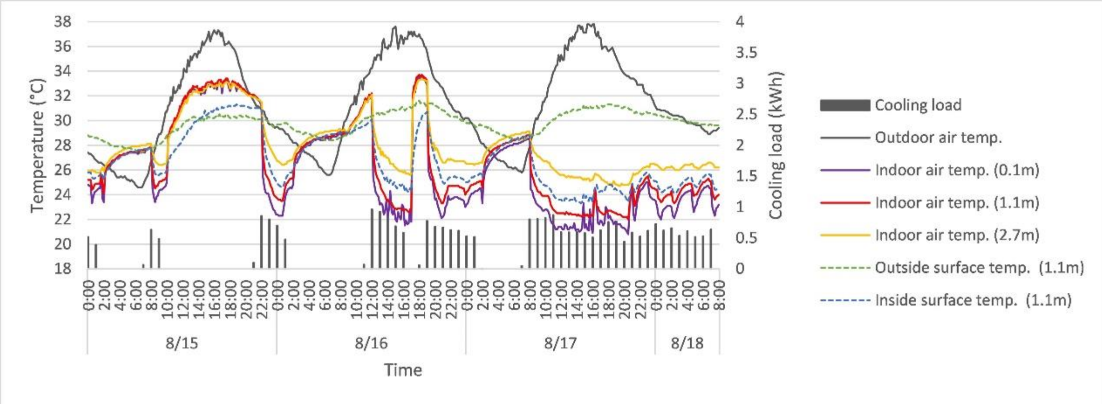

Figure 6-8. Indoor thermal environment and hourly cooling load in the retrofitted north bedroom.

The results in Figure 6-8 show that the overall temperature between the surface of the building structure and the interior in the renovated north bedroom is shown below. First, the temperature difference between the inner surface of the building exterior wall and the outer surface is much larger than that of the unremodeled one, at about 6 °C. Secondly, the temperature difference between the inner surface of the building exterior wall and the indoor temperature at the same height (1.1 m, red) is relatively small, especially when the indoor is opened for a few hours, the temperature of the two places is close. Third, the temperature at 2.7 meters indoors was around the set 26 degrees, while the temperature at the lower part was lower, at a minimum of 21 to 22 degrees. Fourth, the temperature was smaller between the three heights in the room, but showed a greater range of fluctuations. The above results are based on lower energy consumption per hour for cooling than in the un-retrofitted bedrooms. These results indicate that lower indoor temperatures can be achieved at lower air conditioning energy consumption when using air conditioning in the retrofitted north bedroom. Also, the indoor temperature differences are somewhat smaller in both horizontal and vertical directions.

6.3.2.2 Comparison of indoor thermal environment in the retrofitted north and south bedrooms

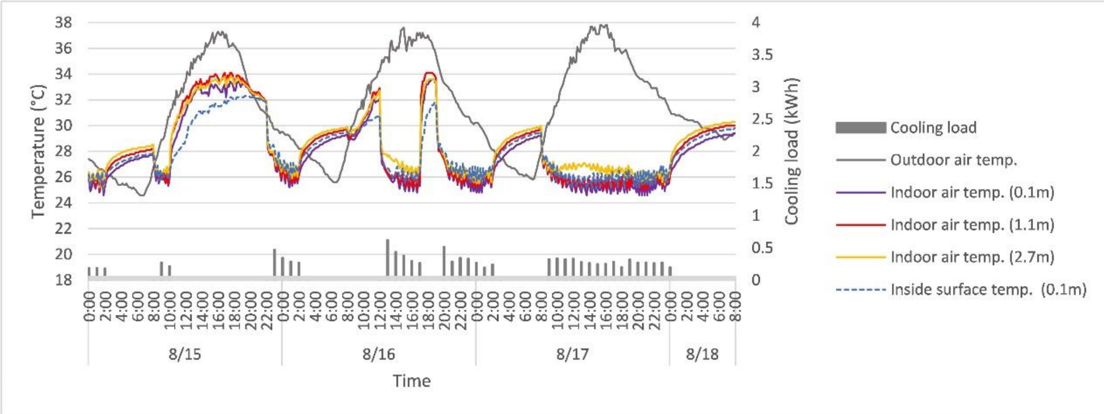

Figure 6-9. Indoor thermal environment and hourly cooling load in the retrofitted south bedroom.

Figure 6-9 shows the room temperature and hourly air conditioning energy consumption in the retrofitted south bedroom. The results show that when the air conditioner is on, the temperature difference between the inner surface of the exterior wall (blue dotted line) and the indoor temperature at the same height (purple line) is relatively small and fluctuates mainly around the set stable 26 °C. And the temperature between different heights also shows that the temperature difference between the interior vertical is relatively small, especially within the area below 1.1 m. The overall trend shows that the temperature is relatively stable in all parts of the room.

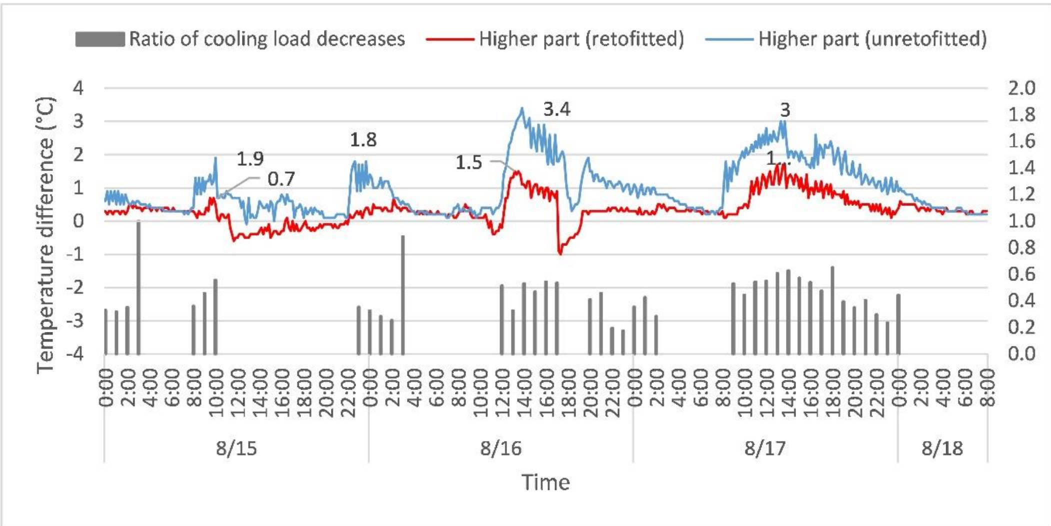

Figure 6-10. Comparison of temperature difference in the higher part of the south bedroom (2.7m-1.1m).

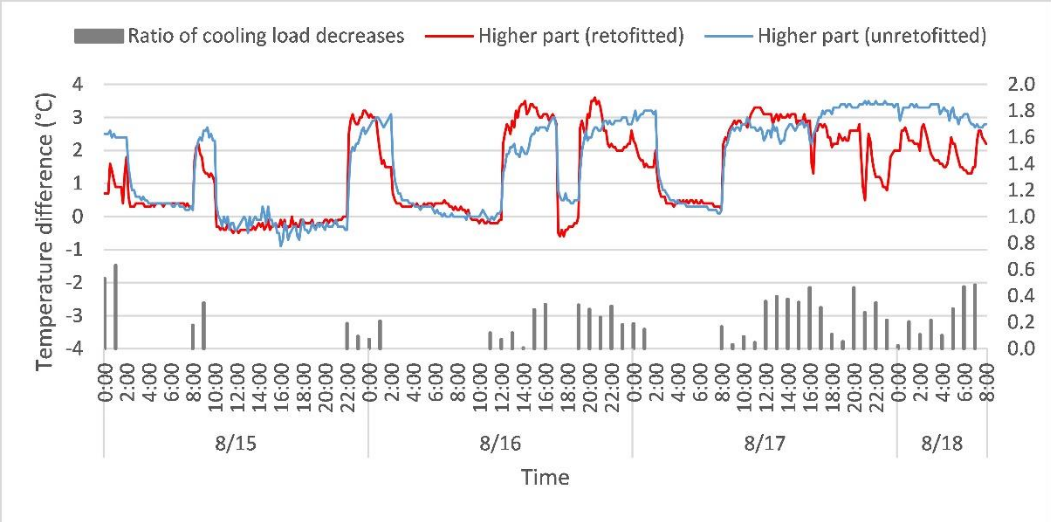

Figure 6-11. Comparison of temperature difference in the higher part of the north bedroom (2.7m-1.1m).

Figure 6-10 demonstrates the Comparison of temperature difference in the higher part of the south bedroom (2.7m-1.1m) and Figure 6-11 demonstrates the Comparison of temperature difference in the higher part of the north bedroom (2.7m-1.1m). The comparison in Figure 6-10 shows that the temperature difference in the higher part of the room is more stable and lower in the modified south bedroom. The results in Figure 6-11 show that there is no significant improvement in the north and south bedrooms after the renovation, when analyzed only from the perspective of temperature difference.

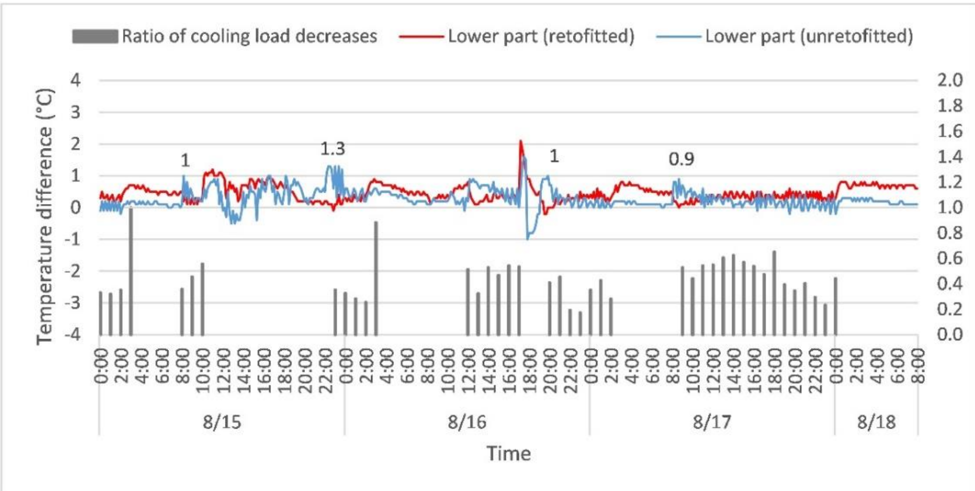

Figure 6-12. Comparison of temperature difference in the lower part of the south bedroom (1.1m-0.1m).

Figure 6-12 and Figure 6-13 show the comparison of the temperature difference in the lower part of the room (1.1 m-0.1 m) in the south bedroom and the north bedroom, where Figure 6-12 shows the situation in the south bedroom and Figure 6-13 shows the situation in the north bedroom. It can be concluded that no matter what the orientation is, the temperature difference in the lower part of the room is actually not significant.

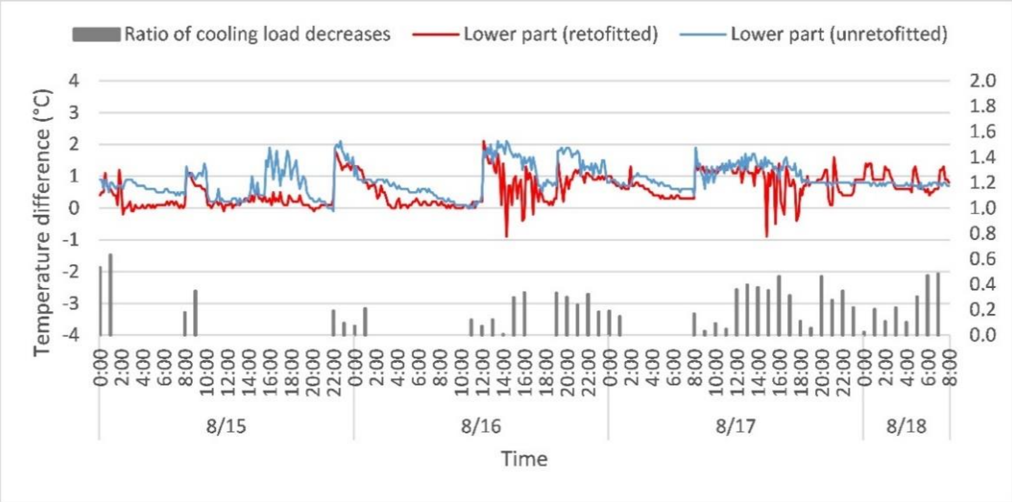

Figure 6-13. Comparison of temperature difference in the lower part of the north bedroom (1.1m-0.1m).

6.3.2.3 Comparison of indoor relative humidity between the north and south bedrooms

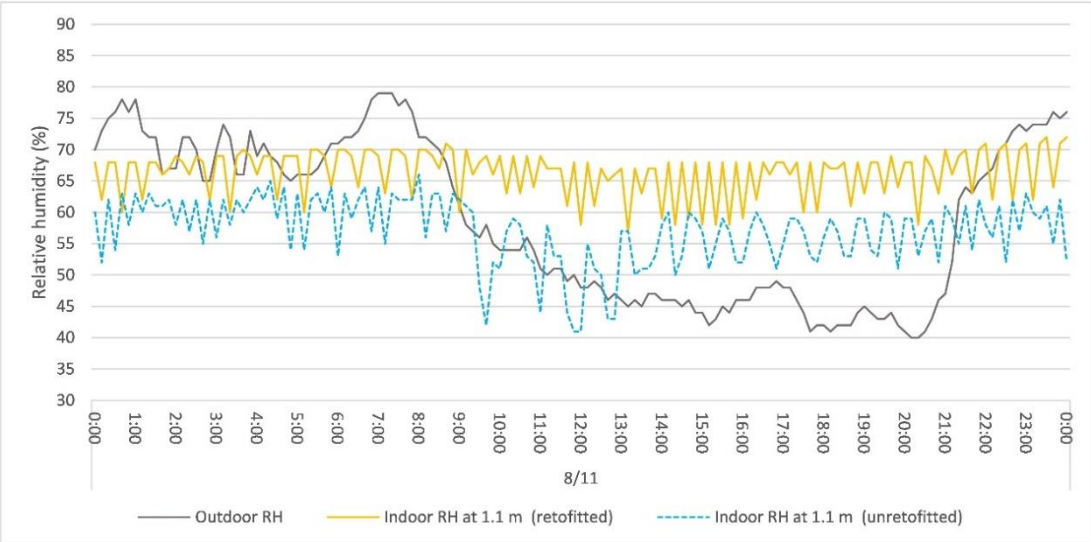

Figure 6-14. Comparison of relative humidity in the south bedroom before and after retrofit on August 11th.

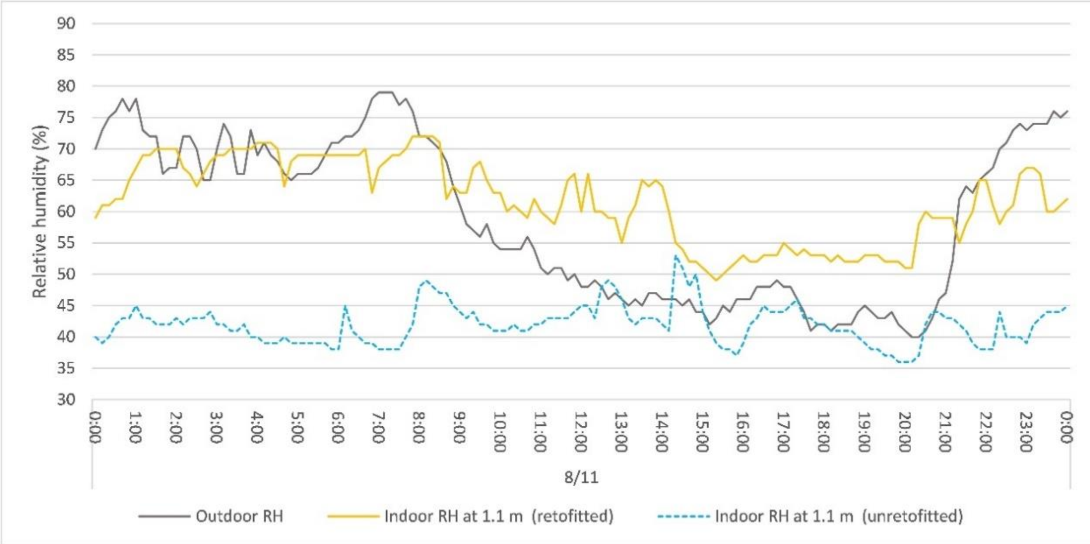

Figure 6-15. Comparison of relative humidity in the north bedroom before and after retrofit on August 11th.

August 11 is the pattern of using air conditioning 24 hours a day. Figure 6-14 shows the comparison of relative humidity in the south bedroom before and after retrofit on August 11th, and Figure 6-15 shows the comparison of relative humidity in the north. It can be clearly observed that the indoor relative humidity is higher in the retrofitted bedrooms (yellow line), but it is obvious that the air conditioning in the south bedroom has better control of relative humidity.

Table 6-5. Comparison of indoor relative humidity between the north and south bedrooms on August 11th.

Parameters	Mean (%)	Maximum (%)	Minimum (%)	S.D.
Outdoor relative humidity	59	79	40	12.79
Indoor relative humidity of retrofitted south room	66	72	57	3.69
Indoor relative humidity of retrofitted north room	62	72	49	6.64

Table 6-5 shows the Comparison of indoor relative humidity between the north and south bedrooms on August 11th, and the data results show that the S.D. value of the relative humidity in the retrofitted south bedroom on August 11th was 3.69, while in the retrofitted north bedroom it was 6.64. The above evidence indicates that the relative humidity in the south bedroom was better controlled after the internal insulation retrofit, as far as the actual situation of this experiment is concerned.

6.4 Comparison of heating set temperature in the retrofitted bedroom

For the winter 2020 experiment, the air conditioning operation patterns were identical on January 8, 12, and 16, so these three days were chosen to analyze the effect of the 24 °C and 22 °C set temperatures on the retrofitted south bedrooms.

6.4.1 Energy consumption under different heating set temperature

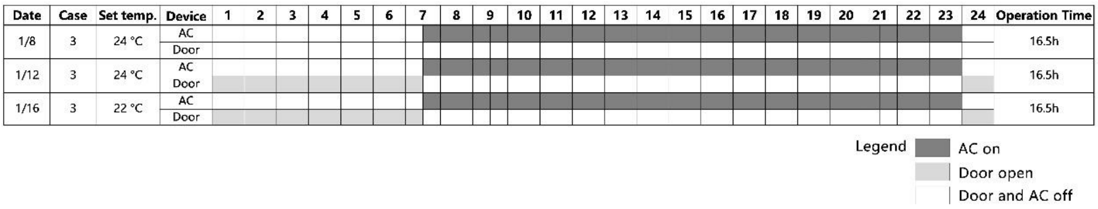

Figure 6-16. The operation schedule of the air conditioner and door.

Figure 6-16 shows the air conditioning operation pattern for the three days, all running from 7:30 am to 24:00 pm.

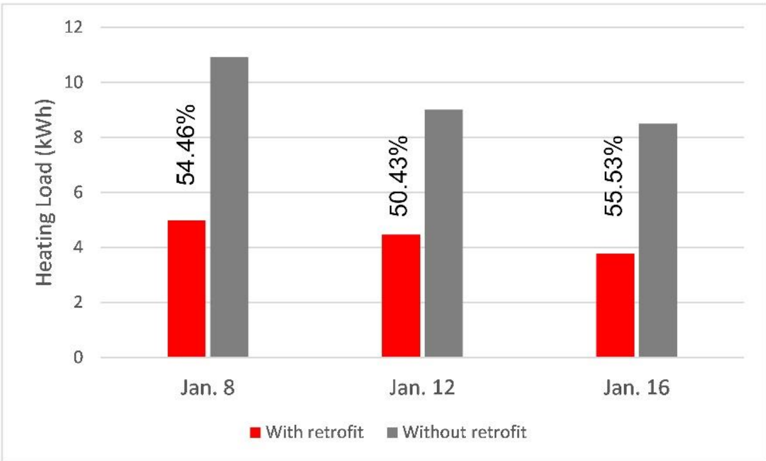

Figure 6-17. Comparison of daily heating load and daily heating load decreases ratio.

Figure 6-17 shows the comparison of daily heating load and daily heating load decreases ratio of the south bedrooms in these three days. The results show that the daily energy savings were all above 50%. In particular, the operating temperature was 24 °C on January 8 and 12, while the operating temperature was 22 °C on January 16.

6.4.2 Indoor thermal environment under different heating set temperature

Figure 6-18, Figure 6-19 and Table 6-6 show the general situation on January 8. In particular, Figure 6-18 shows the indoor air temperature and hourly heating load in the retrofitted south bedroom, and Figure 6-19 shows the indoor air temperature and hourly heating load in the un-retrofitted south bedroom. and the analysis of indoor and outdoor temperature data during the heating time period of this day is presented in Table 6-6.

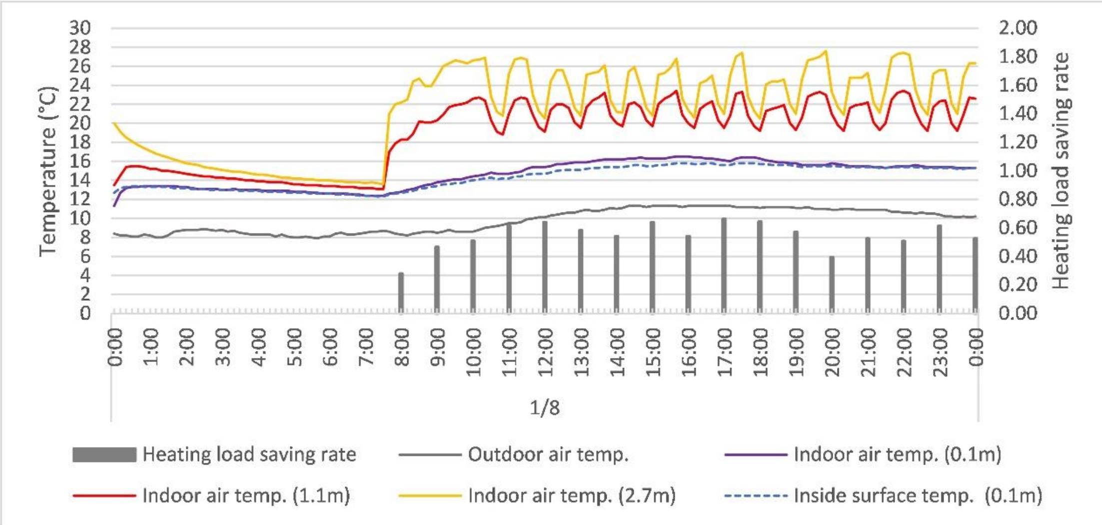

Figure 6-18. Indoor air temperature and hourly heating load in the retrofitted south bedroom (January 8th).

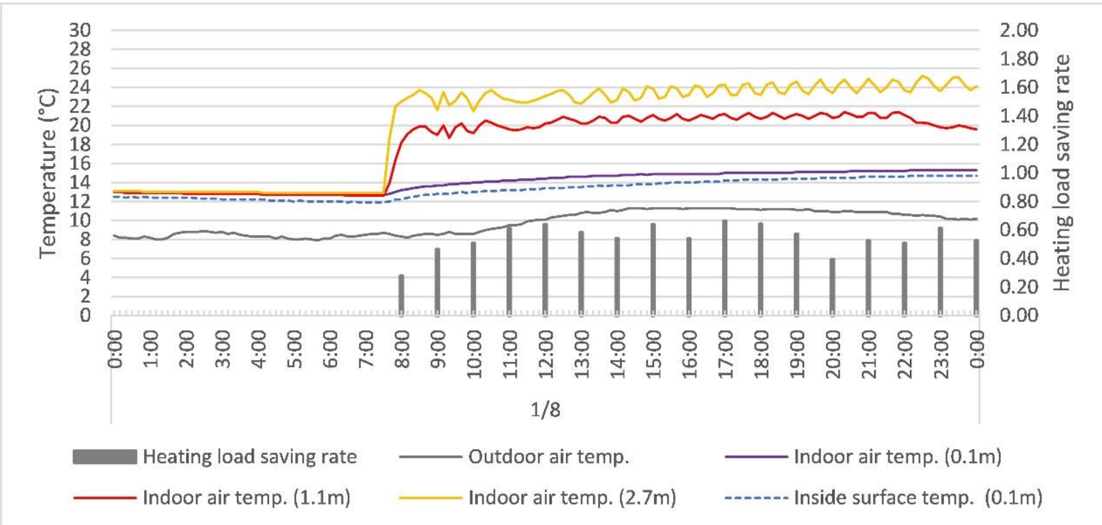

Figure 6-19. Indoor air temperature and hourly heating load in the un-retrofitted south bedroom (January 8th).

The air conditioning heating setting temperature on January 8 was 24 °C, and the comparison between Figure 6-18 and Figure 6-19 concludes that the room temperature was higher in the retrofitted bedroom, especially in the higher areas. The specific data from Table 6-6 shows that the average temperatures in the renovated bedroom at 2.7 m and 1.1 m are 24.0 °C and 21.0 °C, respectively. And the average temperatures of these two heights in the original bedroom were 23.4 °C and 20.3 °C, which were 0.6 °C and 0.7 °C lower than after the renovation. And the overall average temperature in the three heights was 20.1 °C and 19.4 °C in the remodeled and un-modeled bedrooms, respectively.

Table 6-6. Results of measured temperature data during the heating period on Jan. 8.

Parameters		**Height Above Floor (m)**	**Mean (°C)**		**Maximum (°C)**	**Minimum (°C)**	**S.D.**
Outdoor temperature			10.4		11.3	8.2	0.98
Temperature in retrofitted room	Indoor	0.1m	15.4	20.1	16.5	12.4	0.98
		1.1m	21.0		23.4	13.1	1.66
		2.7m	24.0		27.6	13.6	2.39
	Inside surface	0.1m	15.0		15.8	12.3	0.89
Temperature in un-retrofitted room	Indoor	0.1m	14.7	19.4	15.3	12.7	0.62
		1.1m	20.3		21.4	12.6	1.26
		2.7m	23.4		25.2	12.9	1.40
	Inside surface	0.1m	13.8		14.7	11.9	0.73

Figure 6-20, Figure 6-21 and Table 6-7 show the general situation on January 12. Figure 6-20 shows the indoor air temperature and hourly heating load in the retrofitted south bedroom, and Figure 6-21 shows the indoor air temperature and hourly heating load in the un-retrofitted south bedroom. and the analysis of indoor and outdoor temperature data during the heating time period of this day is presented in Table 6-7.

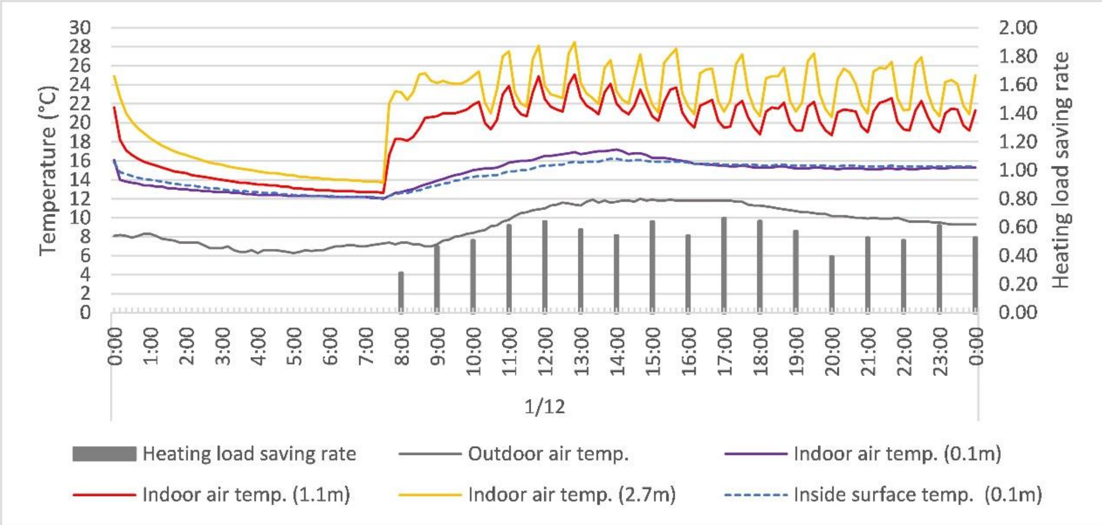

Figure 6-20. Indoor air temperature and hourly heating load in the retrofitted south bedroom (January 12th).

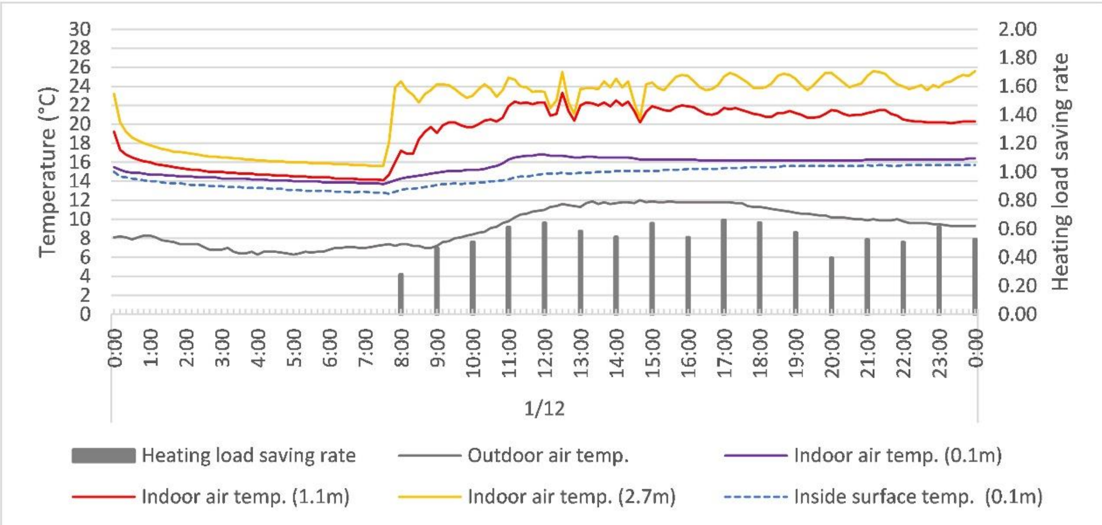

Figure 6-21. Indoor air temperature and hourly heating load in the un-retrofitted south bedroom (January 12th).

As with January 8, the air conditioning heating set temperature was 24 °C on January 12, and as can be summarized from the comparison of Figure 6-20 and Figure 6-21, the room temperature was higher in the retrofitted bedroom, especially in the higher areas. The specific data from Table 6-7 shows that the average temperatures in the renovated bedroom at 2.7 meters and 1.1 meters are 23.8 °C and 21.0 °C, respectively. The average temperature of these two heights in the original bedroom was 23.9 °C and 20.8 °C, respectively, which is very little difference from the renovated one. And from the overall average temperature of the three heights, it was 20.1 °C and 20.2 °C in the remodeled and un-modeled bedrooms, respectively, which was also almost the same.

Table 6-7. Results of measured temperature data during the heating period on Jan. 12.

Parameters		Height Above Floor (m)	Mean (°C)		Maximum (°C)	Minimum (°C)	S.D.
Outdoor temperature			10.2		12	7	1.48
Temperature in retrofitted room	Indoor	0.1m	15.4	20.1	17.2	12	1.06
		1.1m	21.0		25.1	12.6	1.75
		2.7m	23.8		28.5	13.7	2.28
	Inside surface	0.1m	15.2		16.2	12.1	0.95
Temperature in un-retrofitted room	Indoor	0.1m	16.0	20.2	16.8	13.7	0.67
		1.1m	20.8		23.3	14.1	1.50
		2.7m	23.9		25.6	15.6	1.38
	Inside surface	0.1m	14.9		15.7	12.7	0.82

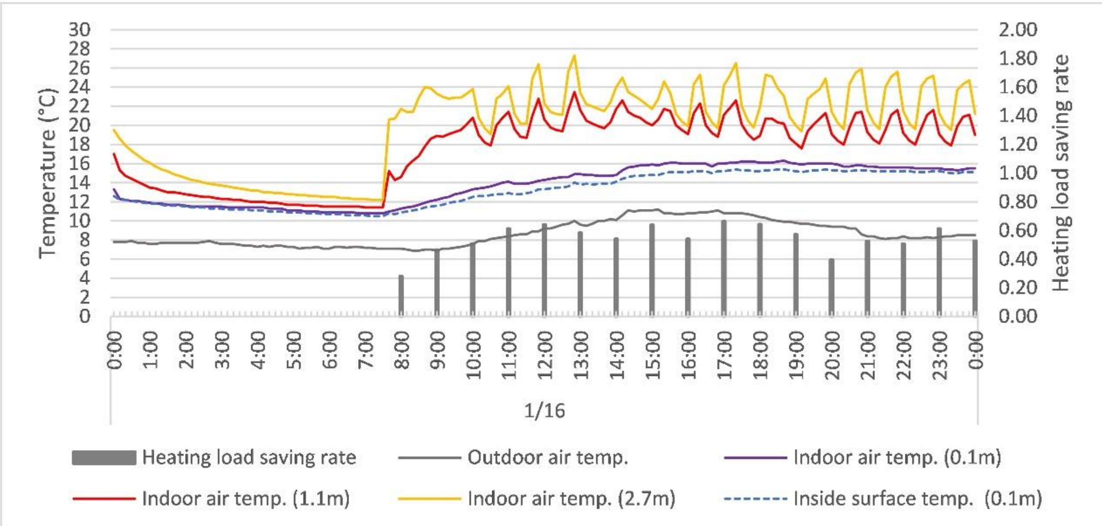

Figure 6-22. Indoor air temperature and hourly heating load in the retrofitted south bedroom (January 16th).

Figure 6-22, Figure 6-23 and Table 6-8 show the general situation on January 16, a day when the heating temperature was 22 °C. Figure 6-22 shows the indoor air temperature and hourly heating load in the retrofitted south bedroom, Figure 6-23 shows the indoor air temperature and hourly heating load in the un-retrofitted south bedroom. And the analysis of indoor and outdoor temperature data during the heating time period of this day is presented in Table 6−8.

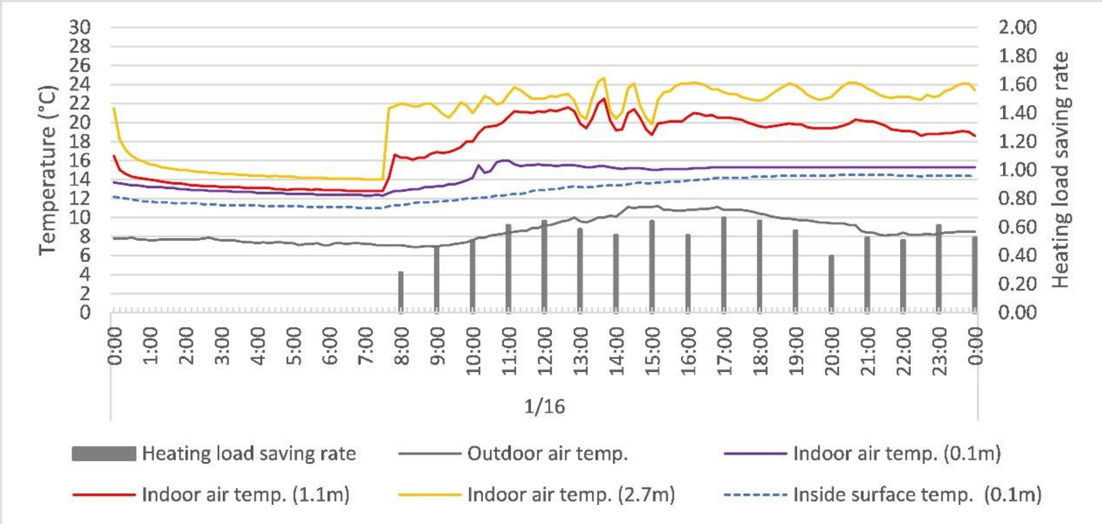

Figure 6-23. Indoor air temperature and hourly heating load in the un-retrofitted south bedroom (January 16th).

At a heating temperature of 22 °C, it can be summarized from the comparison of Figure 6-22 and Figure 6-23 that the room temperature is higher in the retrofitted bedroom, especially in the high places. The specific data from Table 6-8 shows that the average temperatures in the retrofitted bedroom at 2.7 m and 1.1 m are 22.5 °C and 19.6 °C, respectively. The average temperature of both heights in the original bedroom was 22.6 °C and 19.4 °C, which is almost the same as the value after the renovation. And from the overall average temperature of the three heights, it was 19.0 °C in both the remodeled and unmodified bedrooms.

Table 6-8. Results of measured temperature data during the heating period on Jan. 16.

Parameters		**Height Above Floor (m)**	**Mean (°C)**		**Maximum (°C)**	**Minimum (°C)**	**S.D.**
Outdoor temperature			9.1		11.2	6.9	1.30
Temperature in retrofitted room	Indoor	0.1m	14.8	19.0	16.3	10.8	1.46
		1.1m	19.6		23.5	11.4	1.86
		2.7m	22.5		27.3	12.2	2.21
	Inside surface	0.1m	14.1		15.4	10.5	1.43
Temperature in un-retrofitted room	Indoor	0.1m	15.0	19.0	16	12.3	0.81
		1.1m	19.4		22.5	12.8	1.61
		2.7m	22.6		24.7	14	1.34
	Inside surface	0.1m	13.5		14.5	11	1.05

Comparing the temperature data of Jan. 8， Jan. 12, and Jan. 16, it can be observed that the 2-degree difference in setting temperature actually had a slight impact on energy consumption and indoor temperature of the south bedrooms.

6.5 Discussion

6.5.1 Limitations

This study is limited by the physical layout of the case building, where the south-facing bedrooms and the north-facing bedrooms are inevitably influenced by factors other than orientation, such as window-to-wall ratio, room size, etc.

Also, when setting the temperature, there was no way to conduct a longer-term experiment as the comparison experiment required the full cooperation of the comparison family. This therefore resulted in only two temperature values being chosen for this study, making it more difficult to obtain comprehensive and more obvious data to support this.

6.5.2 Future work

In future simulation studies, if the layout of the north-south facing rooms can be set up in the same way, the effect of orientation on the effectiveness of internal insulation retrofitting can be better compared.

In the simulations, the effects of multiple set temperatures can be compared and verified to obtain a comprehensive knowledge of the effects of the set temperature values on the experiment and the recommended set temperature range and corresponding usage patterns.

6.6 Summary

Firstly, to investigate the effect of different orientations on energy efficiency, we conducted experiments in the summer of 2019 in both the retrofitted south and north bedroom. Overall, the retrofitted south bedroom had the advantage in terms of cooling energy consumption and indoor temperature. The average daily energy savings for the same air conditioning usage pattern was 28% for the retrofitted north-facing bedroom and 41% for the retrofitted south-facing bedroom. Both the temperature difference between the interior surface of the exterior walls and the interior temperature, and the temperature difference between the different heights of the interior, are clearly smaller in the south bedroom. The temperatures in the retrofitted south bedroom both exhibit smaller fluctuations.

Secondly, to study the influence of different set temperatures in the retrofitted south bedrooms, we chose January 8, January 12, and January 16 for the winter 2020 for comparison. It was found that the 2-degree difference in setting temperature actually did not have a particularly significant impact on energy consumption and indoor climate in the retrofitted south bedrooms.

Reference

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Chapter 7

CONCLUSION

CHAPTER SEVEN: CONCLUSION

7.1 Conclusion

China's hot summer and cold winter region suffers from one of the worst indoor thermal environments among the country's five climate divisions. Currently, the insulation of residential buildings in this region is mainly external insulation, and the insulation effect is not ideal. People's requirements for indoor thermal environment are becoming higher, and the energy consumption per unit area of air conditioning is growing rapidly, putting great pressure on the future energy saving target. Since the main air conditioning use habit in this region is intermittent energy use in separate rooms, this study proposes to optimize existing residential buildings with interior insulation that is more suitable for this energy use characteristic.

In view of the lack of systematic studies on the optimization of envelope insulation performance under intermittent energy use in hot-summer and cold-winter regions of China, this study investigates the improvement of urban existing high-rise residential units after retrofitting with full internal insulation, taking Chengdu city as an example. The extent of improvement of the retrofitted dwellings in terms of air conditioning energy consumption and indoor thermal environment from the original units was measured and comparatively studied.

The main work and results can be summarized as follows.

Chapter 1, Research Background and Purpose of The Study. First, the global context is analyzed, including climate change trends, and regional differences in future population and economic growth. China accounts for a large portion of future global economic growth, energy consumption, and will face enormous pressure to save energy. Then, at the national level, China's urbanization rate and the current status of energy use in urban residential buildings are analyzed, with the growth rate of energy use in HSCW region being very prominent. Finally, at the regional level, the characteristics of the HSCW region are analyzed. It is a densely populated and economically developed region but the energy consumption performance of residential buildings. The improvement of the thermal performance of the envelope of a large bulk of existing buildings is a matter of great urgency.

Chapter 2, Literature Review. Firstly, the characteristics and overall energy use features of residential buildings in the HSCW region are summarized and analyzed. Due to following the external insulation method of centralized heating regions and not paying enough attention to insulation, the indoor thermal environment in this region is very poor and the energy use increases at a very fast rate. Secondly, the usage habits of users in this area are sorted out and summarized, which mainly present the characteristics of intermittent energy consumption in separate rooms. Finally, the common measures to improve the thermal performance of existing building envelope are summarized and analyzed, and the optimization of thermal insulation is usually the way with more ideal effect.

Chapter 3, Research Method. Firstly, the framework for the retrofit and actual measurements in this paper is presented. Secondly, it is introduced the basic information of the selected high-rise residence in a district of Chengdu city. Thirdly, it is the process, materials and construction levels of the internal insulation retrofit are shown. Finally, the layout and parameters of the equipment for the actual measurements are presented.

Chapter 4, Improvements After Interior Insulation Retrofit Under Intermittent Cooling Condition. First, it was analyzed that the future cooling demand in the HSCW region is four times higher than the heating energy consumption in current actual use versus future climate trends. Therefore, for three typical local intermittent cooling modes, actual measurements were conducted in experimental and comparison dwellings in summer 2019, where eight of the hottest days were selected as comparison experiments. The main findings of the intermittent cooling comparison experiment were as follows. The retrofitted room showed a good energy-saving effect. The average daily energy-saving rate was 42.09% and the highest daily energy-saving rate was 48.91%. During the cooling time, compared to the original bedroom, in the retrofitted room: the indoor temperature was more stable, and closer to the set point (26 °C). Horizontally, the temperature difference between the indoor temperature and the inner surface of the external wall was quite small. Vertically, the indoor temperature was more concentrated after retrofit. Besides, indoor relative humidity was higher and much more stable after the retrofit.

Chapter 5, Improvements After Interior Insulation Retrofit Under Intermittent Heating Condition. First, the current status of building heating in the HSCW region was analyzed, and the poor indoor environment in winter led to a high public call for centralized heating. However, related studies indicate that the current energy use pattern is the most suitable one. Therefore, three typical local intermittent heating models were measured in the winter of 2020 in experimental and contrast residential unit, with 10 of the coldest days selected for the comparison experiment. The main findings of the intermittent heating comparison experiment are as follows. The retrofitted room showed a good energy-saving effect. The total heating energy saving rate was 45.10%. The average daily energy saving ratio was 41.58%, the maximum energy savings of 55.53%. During the heating time, compared to the original bedroom, the temperature was well controlled at 1.1 m and 2.7 m. But the temperature in the retrofitted bedroom showed a greater range of fluctuations. The statistical analysis shows that when the heating temperature is 24 °C, the overall average indoor temperature was 0.7 °C higher. Besides, indoor relative humidity was lower and fluctuated more after the retrofit.

Chapter 6, Impact of Orientation and Set Temperature on Energy Consumption and Indoor Thermal Environment. First, the same experimental arrangement was done in both the south and north bedrooms during the intermittent cooling experiment in the summer 2019 to compare the impact of orientation after interior retrofit. The results showed that the retrofitted north-facing bedroom had 28% of daily average energy saving rate. In addition, the south-facing bedroom had an advantage in terms of indoor temperature. Both the temperature difference between the interior surfaces of the exterior walls and the interior temperature, as well as the temperature difference between the different heights of the interior, were significantly smaller in the south-facing bedrooms. The temperatures of all the south-facing bedrooms exhibit smaller fluctuations. Secondly, during the intermittent heating experiment in the winter of 2020, January 8, 12 and 16 were used to compare the effect of the set temperature on the retrofitting effect. The results showed that a 2-degree difference in set temperature had no particular effect on energy consumption or indoor temperature.

Chapter 7, Conclusion. The results of every chapter were summarized, and the contribution of this research was presented.

7.2 Contribution

This paper quantifies the improvement of energy-saving and the indoor thermal environment by adding interior insulation to bedrooms of a case study residence in a high-rise residential building of Chengdu, China. The main innovation of this paper lies in that it is based on the actual interior insulation retrofit of an existing residence, conducted in real-life scenarios using real-time weather data, and therefore the results will be more convincing than simulations or calculations.

This case study can be a reference to insulation retrofit of existing residential buildings in Chengdu or similar climate zones, and it also can be an inspiration for the optimized design of insulation systems in new residential buildings under a similar climate.