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Improvements in Energy Saving and Thermal Environment after Retrofitting with Interior Insulation in Intermittently Cooled Residences in Hot-Summer/Cold-Winter Zone of China: A Case Study in Chengdu

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Abstract: Space cooling is currently the fastest-growing end-user in buildings. The global warming trend combined with increased population and economic development will lead to accelerated growth in space cooling in the future, especially in China. The hot summer and cold winter (HSCW) zone is the most densely populated and economically developed region in China, but with the worst indoor thermal environment. Relatively few studies have been conducted on the actual measurements in the optimization of insulation design under typical intermittent cooling modes in this region. This case study was conducted in Chengdu—the two residences selected were identical in design, but the south bedroom of the case study residence had interior insulation (inside insulation on all opaque interior surfaces of a space) retrofitted in the bedroom area in 2017. In August 2019, a comparative on-site measurement was done to investigate the effect of the retrofit work under three typical intermittent cooling patterns in the real-life scenario. The experimental result shows that interior insulation provides a significant improvement in energy-saving and the indoor thermal environment. The average energy savings in daily cooling energy consumption of the south bedroom is 42.09%, with the maximum reaching 48.91%. In the bedroom with interior insulation retrofit, the indoor temperature is closer to the set temperature and the vertical temperature difference is smaller during the cooling period; when the air conditioner is off, the room remains a comfortable temperature for a slightly longer time.

Keywords: interior insulation; cooling energy demand; indoor thermal environment; intermittent cooling operation; real-life scenario measurements

1. Introduction

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 ecological 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].

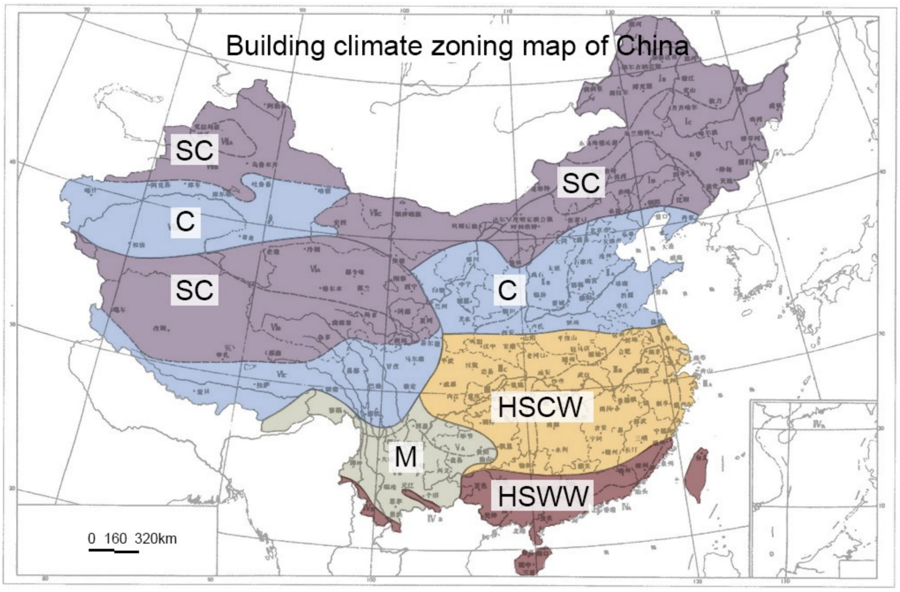


Figure 1. Building climate zoning map of China.

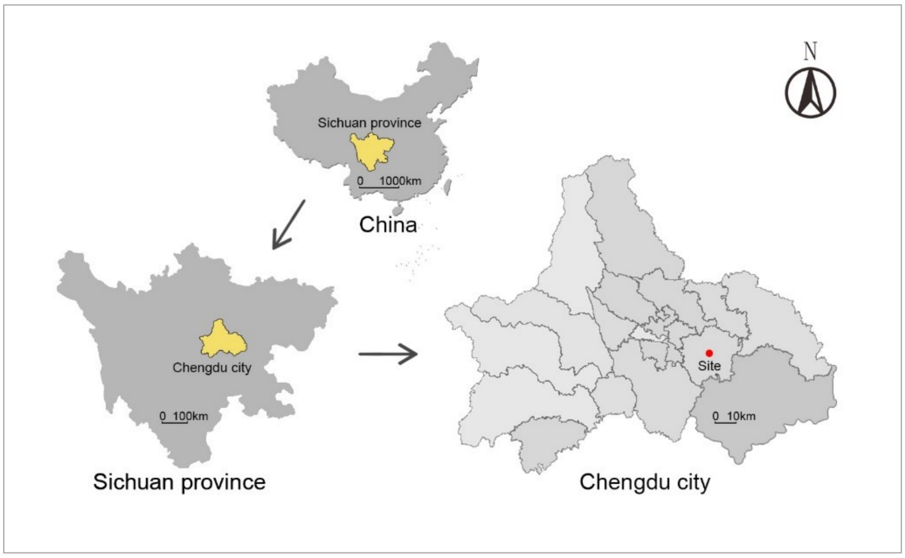


Figure 2. Location of Chengdu city.

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 h 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].

1.3. Research Gap

As we can see from the above studies, there are relatively more studies on outside wall insulation, and most of them show that this is the better method of insulation under continuous air conditioning energy use behavior. In an area such as the HSCW region of China, the most common mode of air conditioning use in summer is intermittent use in separate rooms. The factors that affect energy consumption are not only the exterior walls but also the interior envelope. Among the existing studies, research on internal insulation is still limited, let alone research on interior insulation. In our study, interior insulation means putting insulation on all the opaque structural surfaces inside a building or space. These three insulation methods mentioned in this article are compared in Table 1.

Table 1. 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	×	×	√

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 of 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.

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 2; the results of comparing the energy consumption and indoor thermal environment measured by experiments under real scenarios will be shown in Section 3; Section 4 is a discussion of the limitation and future research direction of this paper; and finally, Section 5 will be the conclusion of this paper.

2. Materials and Methods

2.1. Description of the Case Study Building

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, it has a hot and humid climate in summer. The case study building in this paper is in a community in the east of Chengdu (Figure 2). There are seven high-rise residential buildings in the community, built in 2010. The 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 practice locally. In terms of window types, they are single-framed and single-glazed, which is prevailing in the HSCW zone.

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 shows the geographical 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. A realistic view of the north and south elevations of both units is shown within the red circle in Figure 5. Based on the purpose of this study, the south bedroom 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. The bedroom areas of the experimental and comparison units are shown in Figure 6.

Figure 3. Site plan of the selected buildings.

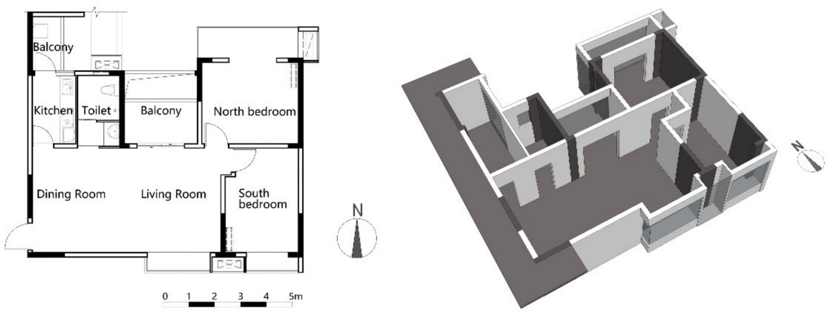
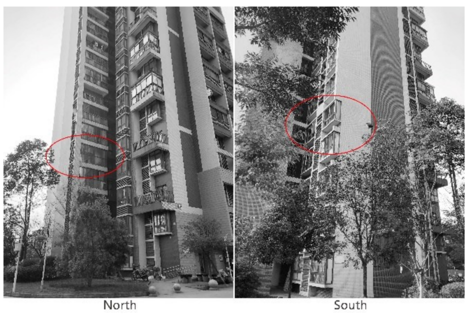


Figure 4. Original floor plan (left) and a perspective view (right) of the residence.

(**a**)



(**b**)

Figure 5. Overview of the selected residences: original unit (**a**) and renovated unit (**b**).

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

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

Figure 7. Overall view of the retrofit construction process.

A 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 8.

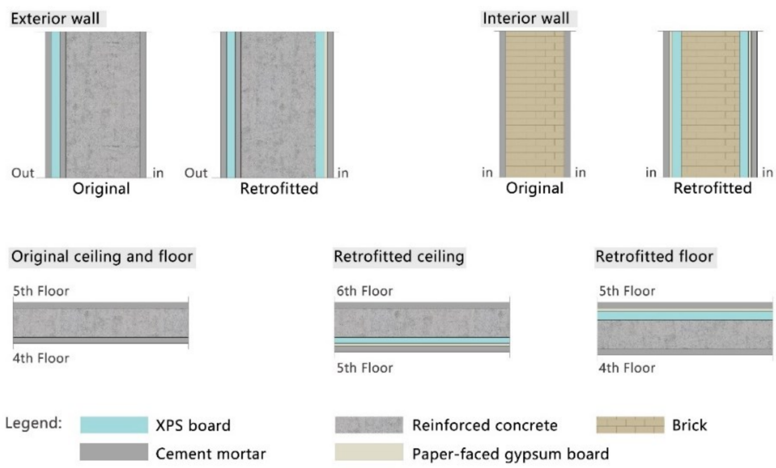


Figure 8. Configuration of the building envelope.

2.2. Measurements

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 10 August, 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 10 August 2019, to 18 August 2019. 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 min, 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 min 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 min. The layout of all the measuring instruments used in this case study is shown in Figure 9, and their actual photos are shown in Figure 10. Key parameters of the measuring instruments are shown in Table 2.

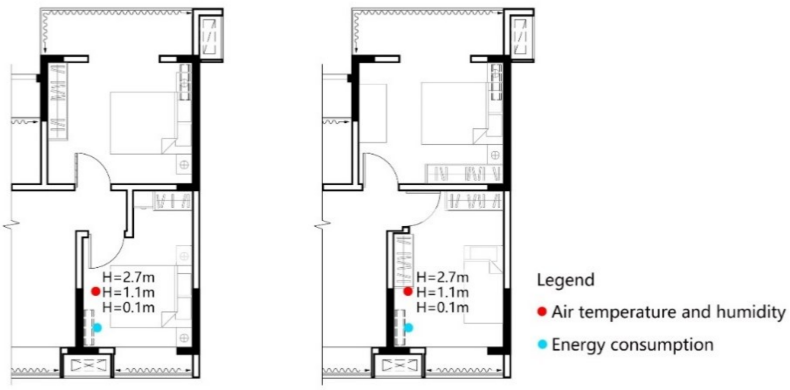


Figure 9. Layout of the measuring instruments, renovated unit (left), and original unit (right).

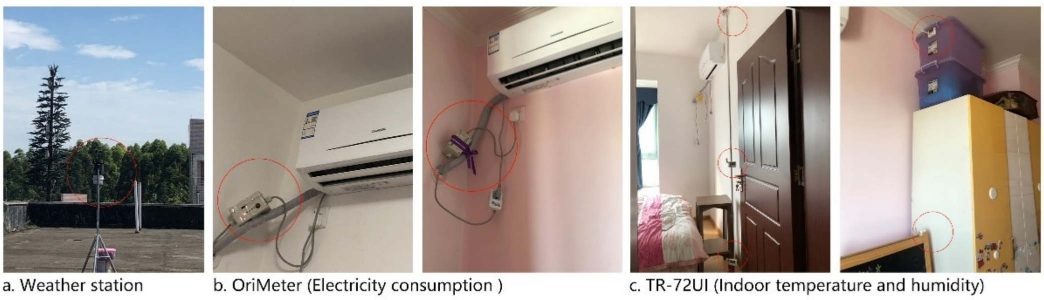


Figure 10. Actual view of the installed instruments.

Table 2. Key parameters of the measuring instruments.

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

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 3.

Table 3. The operation patterns of the air conditioners.

Operation	Cooling Period	Operation Duration	Operation Temperature	Cooling Area
Case 1	0:00–2:00; 22:00–24:00	4 h	26 °C	North and south bedroom
Case 2	0:00–2:00; 12:00–17:00; 19:00–0:00	12 h	26 °C	North and south bedroom
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 11.

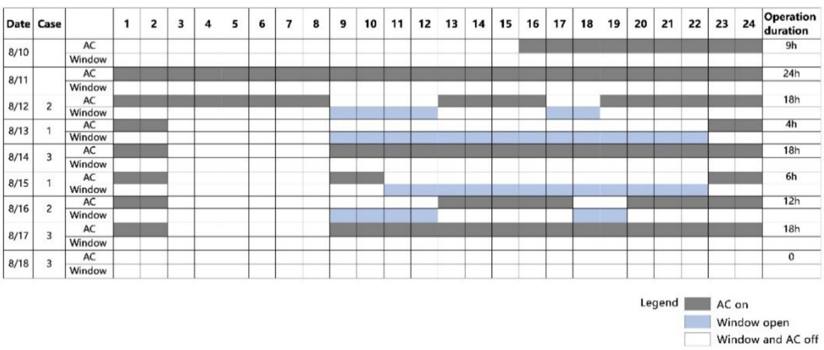


Figure 11. The operation schedule of the air conditioner and window.

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 11 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 11, 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.

3. Results

3.1. Analysis of Outdoor Air Temperature and Relative Humidity

Figure 12 shows the outdoor temperature and relative humidity measured every 10 min by the weather station in August 2019, which was one of the hottest months of the summer. In Figure 12, it can be observed that 12 August to 18 August 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 12 August) 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 14 August). The data above demonstrate the typically hot and humid climate characteristics of Chengdu in summer.

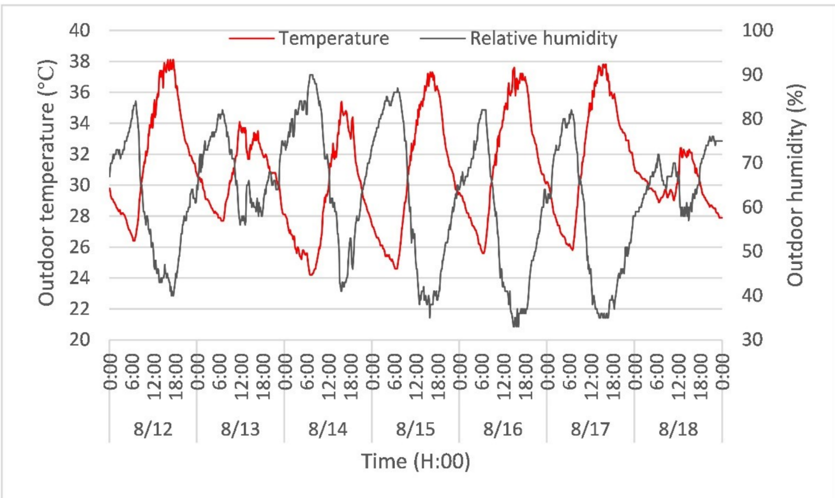


Figure 12. Outdoor temperature and relative humidity during the measurement.

3.2. Comparison of Daily Cooling Load

A fixed cooling operation strategy was used from 10 August to 17 August, and the daily power consumption of the air conditioner during this period is shown in Figure 13. 10 August 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 12 August to 17 August.

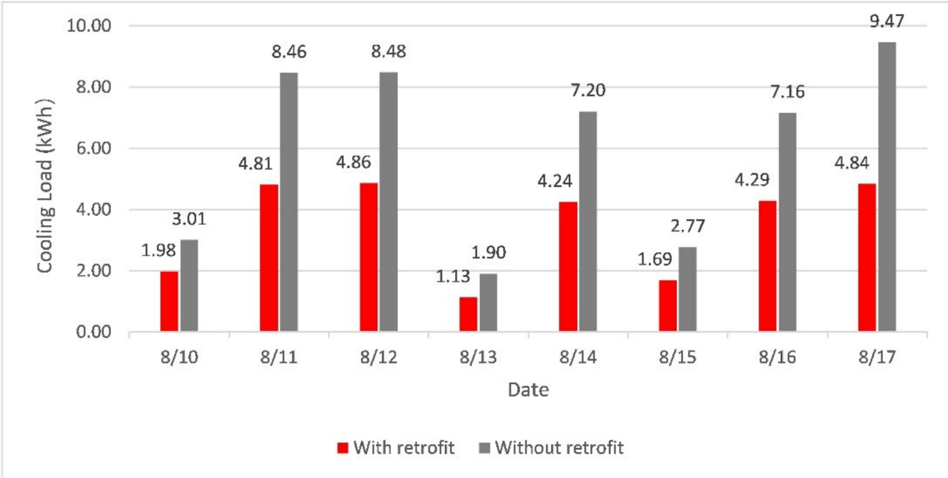


Figure 13. Comparison of daily cooling load in the south bedroom.

The energy consumption results in Figure 13 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 14 shows that during the 6 days of intermittent use, the average energy saving rate in the retrofitted south bedroom was 42.09%, and the highest energy saving rate was 48.91% (17 August).

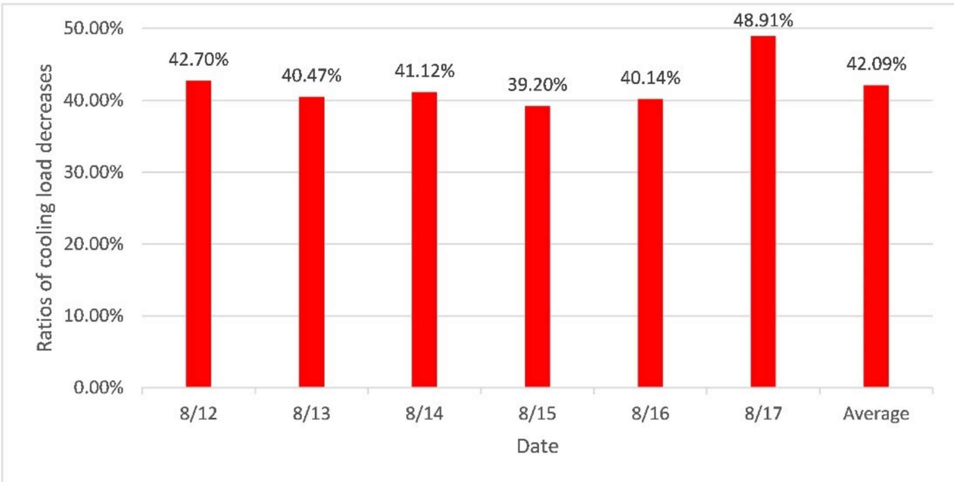


Figure 14. Daily cooling load decreases ratios of the south bedroom.

3.3. Comparison of Indoor Thermal Environment

A period of three consecutive days and eight hours (15 August 0:00 to 18 August 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. 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 17 August.

Table 4. 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

The overall picture of all cooling periods during this period (Table 4) shows that the indoor temperature in the retrofitted bedroom fluctuated less and was closer to the operating temperature value than in the un-retrofitted bedroom. At an operating temperature of 26 °C, the average indoor temperature of the un-retrofitted bedroom at three heights (0.1 m, 1.1 m and 2.7 m) during the summer experiment was 26.5 °C, which was 0.4 °C higher than that of the retrofitted bedroom. This indicates that the change in outdoor temperature has less effect on the indoor temperature of the retrofitted bedroom. Also, the retrofitted bedrooms showed an advantage in terms of indoor temperature at the same height compared to the un-retrofitted one. The largest difference was at 2.7 m indoors, where the average indoor temperature in the remodeled bedroom was 26.6 °C, closer to the operating temperature. While in the original bedroom it was 27.7 °C, 1.7 °C higher than the operating temperature.

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 Figures 15–17.

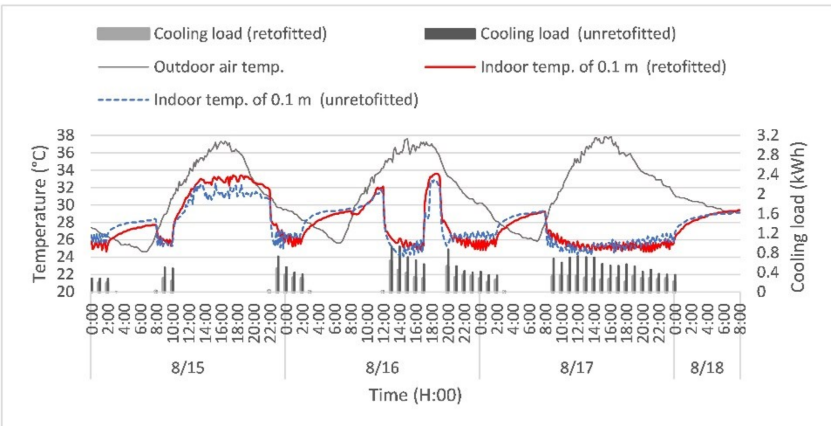


Figure 15. Comparison of indoor temperature and hourly cooling load at 0.1 m.

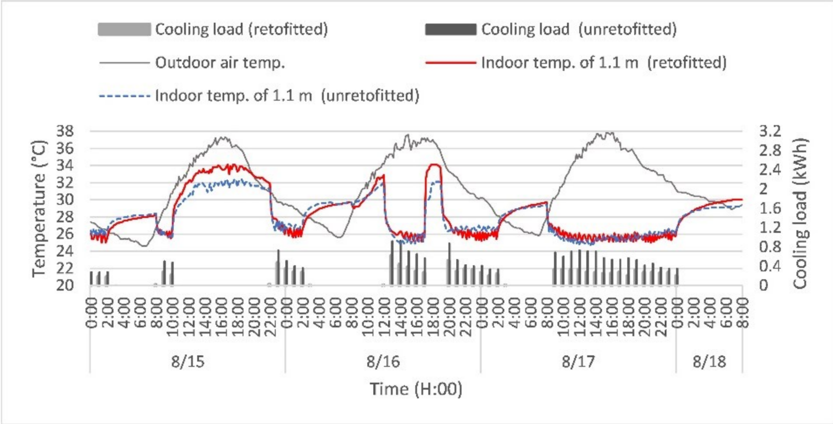


Figure 16. Comparison of indoor temperature and hourly cooling load at 1.1 m.

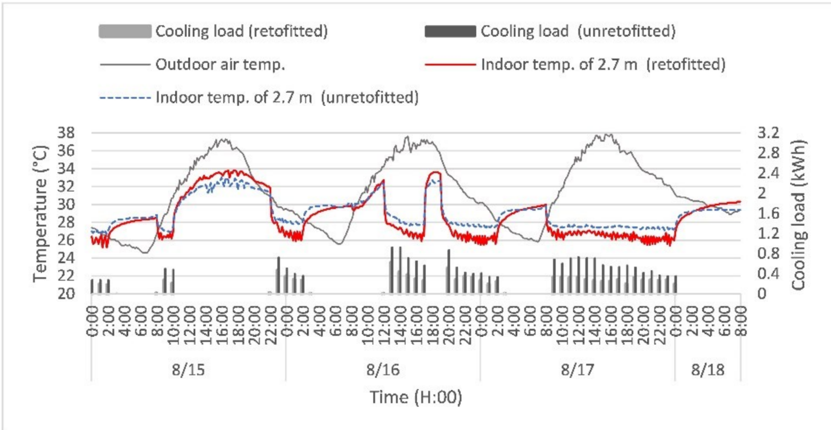


Figure 17. Comparison of indoor temperature and hourly cooling load at 2.7 m.

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 (16 August, 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 Figures 15 and 16. Subsequently, the room temperature usually rose above 26 °C and even reached a maximum of 27 °C (16 August, 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 Figures 15 and 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 17 August. 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 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 time period (0:00 to 8:00) in Figures 15–17 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. 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 h 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 5. 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 5. 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.

5. Conclusions

In this research, a residence in a high-rise building in the HSCW zone of China was chosen as a case study, and the influence of interior insulation retrofit to a bedroom of it were comparatively analyzed. This study set out with the aim of quantifying 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 south bedroom in the selected residence was retrofitted in the summer of 2017 by adding insulation panels to all the interior surfaces of the opaque envelope. 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:

1. During the 6 days of intermittent cooling (12 August 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%.
2. 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).

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%.

This paper quantifies the improvement of energy-saving and the indoor thermal environment by adding interior insulation to a single room of a case study residence in the HSCW region. 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. 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.

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