Measurement and Simulation of Indoor Thermal Environment of Residential Building in Chengdu of China

Jinlong Ouyang[1*], Wenshen Mo[2], Lingxi Zhao[3] , Pawinee Iamtrakul[4]
[1,2,3] *College of Architecture and Environment, Sichuan University, Chengdu 610065, China*
[4] *Faculty of Architecture and Planning, Thammasat Univesity, Pathumthani 12120, Thailand*

* Corresponding author. E-mail: sow761202@scu.edu.cn
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Abstract

To better understand the current situation of indoor thermal environment of residential buildings in Chengdu of China, a house located in one typical residential building which met the thermal insulation requirements of the 50% energy-efficient design standard was selected as the research object. Then its indoor thermal environment was measured and the information about occupants' lifestyle was collected both in summer and in winter. The field-measured results showed the indoor thermal environment was poor. The mean indoor temperature in summer reached approximately 34.0 °C, while that in winter was only about 11.0°C and the relative humidity was often higher than 70%. Meanwhile, based on the information obtained from the survey, the indoor thermal environment of the case house was simulated by using DeST-h. The simulation results showed that the change trends of the simulated temperatures in the rooms of the case house in the typical days were close to those of the measured results. Finally, one conclusion could be drawn that the thermal insulation of envelope enclosure could not ensure a comfortable indoor thermal environment. Further, it revealed that perhaps such measures might not be good energy-efficient measures for the residential buildings in Chengdu.

Keywords: thermal insulation, energy-saving measure, energy-efficient design standard

1. Introduction of living environment in Chengdu

Always, Chengdu plays a leading role in the construction of the southwestern region of China. The city locates in the western part of the hot summer and cold winter zone (see Figure 1). Chengdu's climate is sultry in summer and wet cold in winter. Compared with other cities in the same zone, Chengdu keeps a relative moderate climate and is more livable. However, with the rapid urbanization of Chengdu, the environmental problems, such as Urban Heat-island effect, smog pollution, and so on, had been more serious. Thus, how to create a more comfortable and healthy urban living environment in the process of urbanization and to explore the relationships among buildings, environment and energy had become the hot topics of current research (Hui, 2010; Lei, 2017; Xiao, 2016, pp. 69-72). According to the statistics (Phillips, Field, Goldstone, Reynold, Lester & Perry, 1993, pp. 1743-1753; Shugui, Tan & Zhipeng, 1994, pp. 36-39), most of modern people spent about 70% to 90% of their time staying indoors, the elderly, disabled, pregnant, infants and young children even longer. Therefore, the indoor thermal environment was closely related to people's health and drew more and more attention. In the current situation of energy shortage, it was of great significance to construct residential buildings which could both ensure a comfortable indoor thermal environment and meet energy-efficient design standards.

In this article, one house located in a typical residential building in Chengdu was selected as the research object. Then, the indoor thermal environment of the rooms in the house was measured both in summer and in winter, and meanwhile simulated by DeST-h. Through analyzing and comparing the measured and simulated results, we hoped to propose some advice which would be beneficial to improving the living environment and the energy efficiency of the residential buildings in Chengdu.

Figure1. Location of Chengdu city in hot summer and cold winter zone

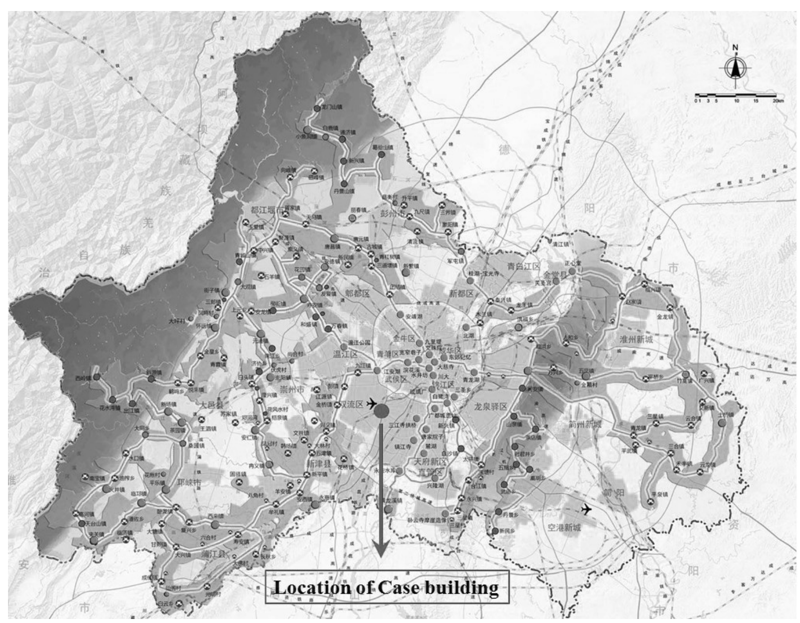

Figure 2. Chengdu's map and the location of case building

Figure 3. Selected building for study

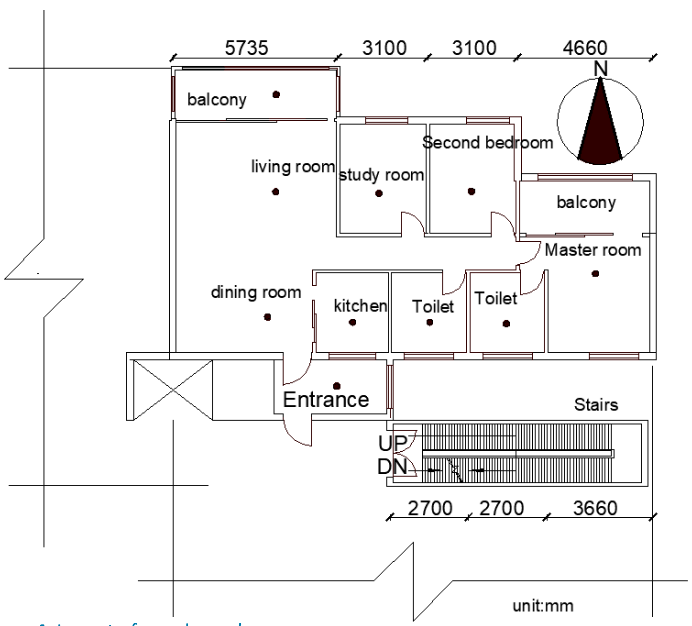

Figure 4. Layout of case house's rooms and measurement points (black dots)

2. Introduction of case building and case house

Since 2003 in Chengdu, about 6.5 million square meters of residential buildings had been constructed annually. Until 2017, there were totally 5.3 billion square meters of residential buildings in the city. Since 2005, more than 95% new residential buildings were required compulsively to be designed and constructed following the 50% energy-efficient design standard (Ministry of housing and urban-rural development of China, 2010) for residential buildings in hot summer and cold winter zone of China. Based on the statistical information about the residential buildings in Chengdu, a house on the top floor of a residential building in Chengdu was selected as the research object. The location of the case building is shown in Figure 2. There were 288 households living in the building with a total of 18 layers (shown as Figure 3) and the rooms' layout of the house is shown as Figure 4. The building's construction had been finished in 2006 and its envelope enclosure met the thermal insulation requirement of the 50% energy-efficient design standard (Ministry of housing and urban-rural development of China, 2010), shown as Table 1.

Table 1. Structure and thermal parameter of envelope enclosure of the case building

Main envelope enclosure	The main structure	Heat transfer coefficient ($W \bullet m^{-2} \bullet K^{-1}$)
Exterior wall	5mm cement mortar + 200mm reinforced concrete + 40mm glazed hollow bead insulation material + 20mm mixed mortar	1.07
Roof	40mm fine stone concrete + 40mm XPS + 20mm cement mortar + 120mm reinforced concrete	0.61
Exterior window	Plastic steel frame + hollow glass (6mm + 9A + 6mm)	2.68

3. Methodology

3.1 Framework of study

After the typical house had been chosen, the information about it would be collected. For example, the current situation of indoor thermal environment would be measured both in summer and in winter, occupants' lifestyle be surveyed and architectural drawings be mapped. At the same time, the indoor thermal environment would be simulated. Then, the measured and simulated results would be mutual compared to validate the effectiveness of the method of thermal simulation. Finally, based on the information, the indoor thermal environment, the effect of building envelope insulation and other energy-efficient measures would be evaluated through thermal simulation. The flowchart is shown in Figure 5.

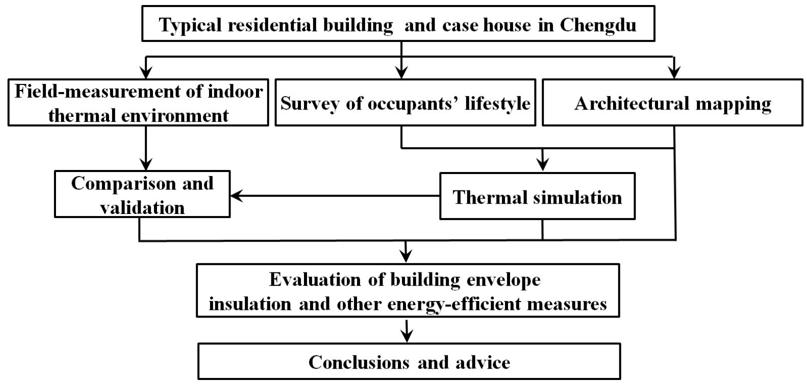

Figure 5. Research flowchart

3.2 Thermal simulation tool

In this study, the Designer's Energy Simulation Tool (DeST) would be applied to simulate the indoor thermal environment of the case house in the whole year. The thermal simulation tool was developed by researchers at Tsinghua University (Tianjin eco-city green building research institute, Building energy conservation research center of Tsinghua University, 2014), and due to its authority and accuracy, DeST was widely used for analysis on the building thermal environment design simulation in China (Changhai, Ling & Xiaosong, 2014, pp. 123-131; Qin, Yan, Zhou & Jiang, 2012, pp. 214-220; Xiaohang, Da & Tianzhen, 2012).

3.3 Measurement of indoor thermal environment

The indoor thermal environment of the case house was measured by the temperature and humidity self-recording instruments type TESTO-174H. Because occupants mostly moved or stayed at the center of the rooms, the instruments were placed near the middle of each room, shown as Figure 2. At the same time, two same instruments which had extra shielding to prevent solar radiation were placed on the roof to monitor the outdoor temperature and humidity. The instruments were fixed at the height of 1.5m from the ground and began to automatically record the data every hour during the periods from Aug. 22 to Aug. 26, 2016 and from Dec. 30, 2016 to Jan. 3, 2017.

During the measuring period in summer, only one adult male was living in the house. Because it was hot, all push-pull exterior windows were keeping half-open for natural ventilation cooling, and one electric fan was always open unless occasionally being out for something, while no air-conditioning had been turned on. During the measuring period in winter, one couple and their little child were living in the house. Because it was not so cold for them, no heat equipment had been turned on, but usually the exterior windows were keeping open a little for fresh air. According to the hourly weather data throughout the typical year of Chengdu from the authoritative weather data set (Resource room of meteorological information center of meterological administration of China, 2010), Aug. 23, 2016 and Jan. 1, 2017 were respectively chosen from the measurement periods as the typical summer day and winter day in this study. Thus, the data recorded in the two days would be analyzed to evaluate the indoor thermal environment of the case house both in summer and in winter.

4. Result of analysis

4.1 Analysis of measured results in summer

The data of several typical measurement points were selected to analyzed, such as those in the master bedroom, the second bedroom, the living room, and the outdoor. The record data on Aug. 23, 2016 were summarized in Table 2. According to the change of air temperature shown as Figure 6 and that of relative humidity shown as Figure 7. Some conclusions were drawn as follows:

Table 2. Measured results of air temperatures and relative humidity in summer

Main room	Air temperature/°C			Relative humidity/%		
	Maximum	Minimum	Average	Maximum	Minimum	Average
Master bedroom	35.6	32.3	34.3	58.0	46.8	54.5
Second bedroom	35.2	33.8	34.6	55.6	48.6	53.6
Living room	34.3	31.0	33.0	65.1	49.9	58.5
Outdoor	38.2	28.6	33.4	70.6	35.7	56.9

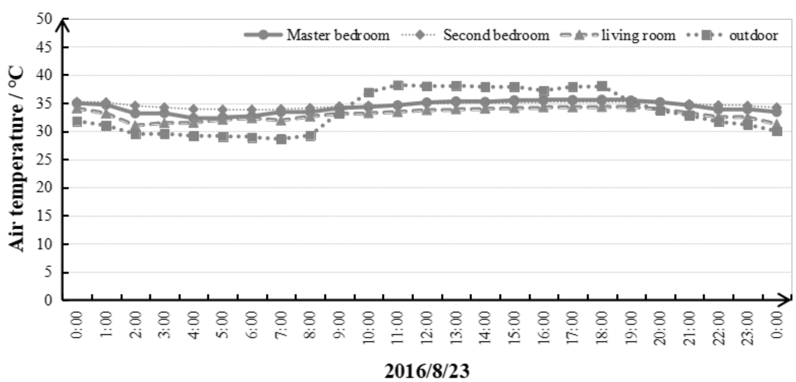

Figure 6. Measured results of outdoor and indoor air temperatures in summer

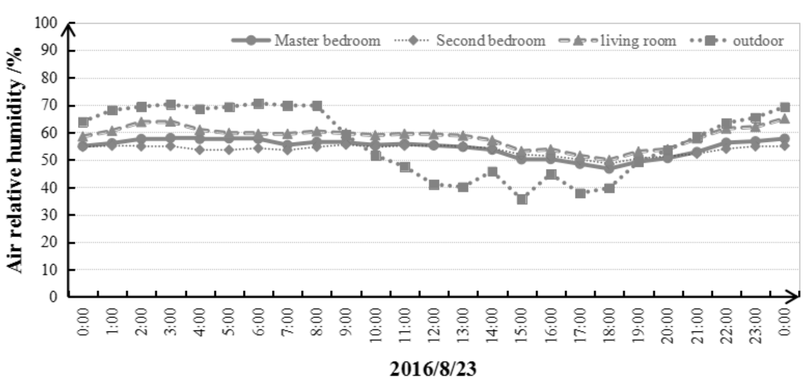

Figure 7. Measured results of outdoor and indoor humidity in summer

1) During the measurement period, the maximum indoor air temperature was 35.6°C, the minimum was 31.0°C, and the average was about 34.0°C. The indoor air temperature was the most important index to evaluate the comfortable degree of indoor thermal environment, and its value would directly affect the hot or cold feeling of a person. When the air temperature was lower than 18°C or higher than 28°C, the work efficiency of people would drop sharply. If the working efficiency was 100% at 25°C, then it would drop to only 50% at 35°C, only 30% at 10°C (Xiaoping, Baoguo & PengFei, 2010, pp. 44-47). Obviously, the indoor thermal environment in the case house on Aug. 23, 2016 was very hot, far beyond the comfortable range.

2) The variation trend of the air temperature of the rooms was almost the same. The living room was situated in the middle of the whole house. The two bedrooms were facing north or south, and some of the envelope was exposed directly to the ambient hot air. Thus, the average indoor air temperature in the living room was 1~2°C lower than those in the two bedrooms.

3) The fluctuations of the air temperature in the rooms were different, 3.3°C for the master bedroom, 3.3°C for the second bedroom and 1.4°C for the living room. It meant that the air temperature in the south-facing or north-facing room was more volatile than that in the middle of the house.

4) The outdoor hourly temperatures were lower than those in the three bedrooms except when the solar radiation was intensive in daytime. As a whole, the outdoor average temperature were lower than those in the two bedrooms respectively by 0.9°Cand 1.2°C, only higher than that in living room by 0.4°C. It showed that the envelope enclosure did not protect the indoor thermal environment of the house well.

5) The relative humidity in the house was in the comfortable range, fluctuating from 46.8% to 65.1%, with an average of 55.5%.

4.2 Analysis of measured results in winter

The record data on Jan. 1, 2017 were summarized and shown in Table 3, Figure 8 and Figure 9. So some conclusions could be drawn as follows:

1) In the master bedroom, the highest air temperature was 11.8°C, the lowest was 10.3°C, and the average was 11.0°C. In the second bedroom, the highest air temperature was 11.4°C, the lowest was 11.2°C, and the average was 11.3°C. In the living room, the highest temperature was 12°C, the lowest was 11.6°C, and the average was 11.79°C. Because 12°C is the lowest limit of building thermal environment in hygiene (Xiaoping, Baoguo & PengFei, 2010, pp. 44-47; Nianping, Yougui & Yoshino, 2004, pp. 94-98), the indoor thermal environment in all of the three rooms was uncomfortable in winter absolutely.

2) The indoor temperature in the house was cold and kept relatively stable, while the outdoor temperature varied a little greater. The variation of the air temperature in the master bedroom was 1.5°C; that in the second bedroom was 0.4°C; that in the living room was 0.4°C; while that of the outdoor temperature was 4.9°C.

3) The difference between indoor and outdoor temperature was very small, 1.2°C for the master bedroom, 1.5°C for the second bedroom and 2.0°C for the living room. It still proved that the envelope enclosure with good thermal insulation could not ensure a warm indoor environment in winter.

4) The indoor relative humidity ranged from 60.5% to 76.8%, with an average of 70.3%, a little higher than the comfortable maximum. It meant that the indoor thermal environment in the case house was not only cold but also wet.

Table 3. Measured results of air temperatures and relative humidity in winter

main room	Air temperature/°C			Relative humidity/%		
	Maximum	Minimum	Average	Maximum	Minimum	Average
Master bedroom	11.8	10.3	10.9	76.8	64.3	71.9
Second bedroom	11.4	11.2	11.3	72.4	67.0	70.2
Living room	12.0	11.6	11.8	73.4	60.5	68.7
Outdoor	12.6	7.7	9.8	81.2	62.7	73.2

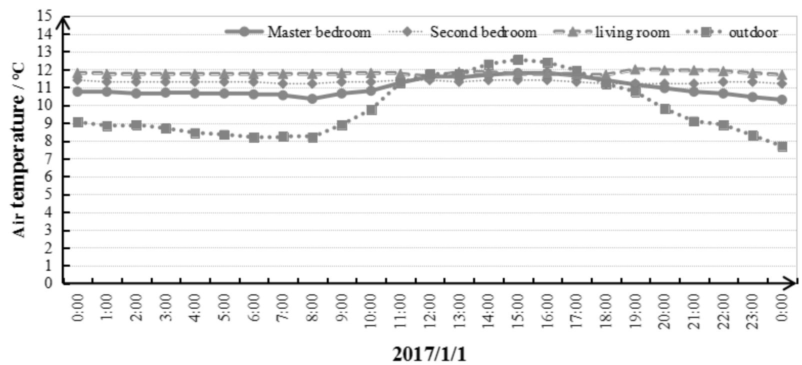

Figure 8. Measured results of outdoor and indoor air temperatures in winter

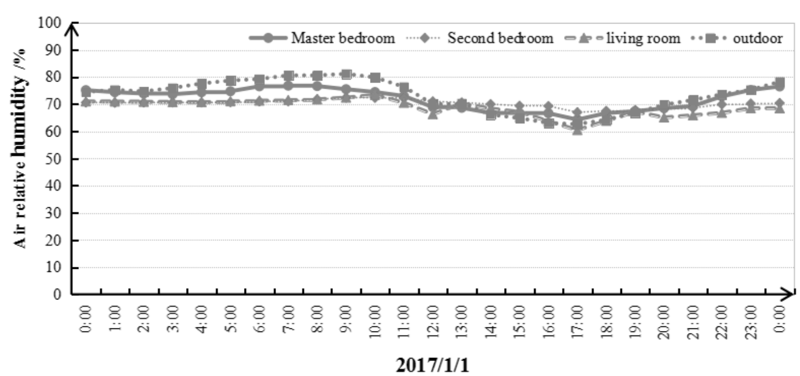

Figure 9. Measured results of outdoor and indoor humidity in winter

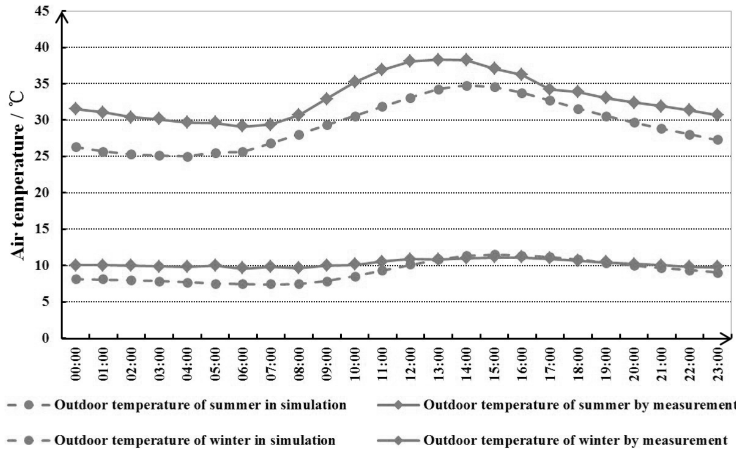

Figure 10. Comparison of outdoor temperature in simulation and by measurement

Figure 11. Simulated results of indoor temperature in rooms of case house in typical summer day

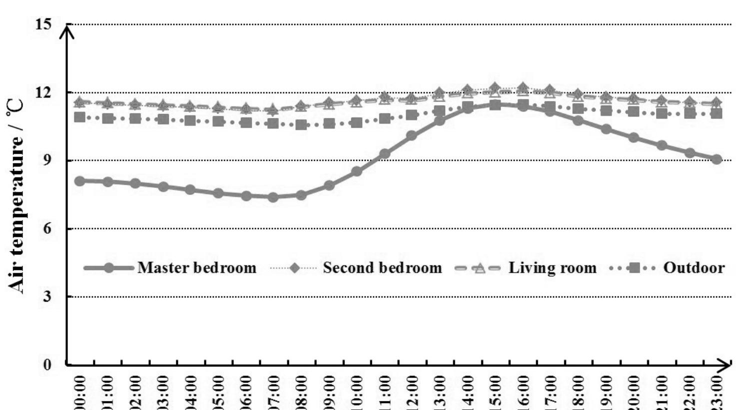

Figure 12. Simulated results of indoor temperature in rooms of case house in typical winter day

4.3 Simulation of indoor thermal environment

Firstly, the thermal model was made based on the envelope's information of the house. Secondly, after reviewing the weather data set (Resource room of meteorological information center of meterological administration of China, 2010), one day in July and the other day in January were selected to simulate the indoor thermal environment of the house by using DeST-h software, because the climatic data of the two days were the closest to those of Aug. 23, 2016 and Jan. 1, 2017 respectively. Shown as Figure 10, due to the impact of Urban Heat-island effect, the measured outdoor temperature in summer was hotter by 1.5~5.2°C than that of the hottest day in typical meteorological year. Thirdly, according to the standard [6], the indoor heat disturbance in the main rooms was set as follows: 0.0141kWh/m^2 for indoor lighting and 4.3W/m^2 for indoor personnel equipment; Then, to make full use of natural ventilation to reduce cooling energy consumption in summer, variable ventilation time was set in simulation. Considering the characteristics of large ventilation in summer and small ventilation in winter in Chengdu, the ventilation range between the rooms and the surrounding atmosphere was defined as the two calculation modes: one was G_{min} = 2 times/h (minimum air change times) and G_{max} = 5 times/h (maximum air change times) in summer, and the other was 1 time/h in winter. Finally, the indoor thermal environment was simulated by running DeST-h. Through simulation, the results of the indoor temperature of the two typical days in summer and in winter were summarized and shown as Figure 11 and Figure12.

Figure 11 Showed that in summer the indoor temperature varied from 30.0°C to 33.8°C when the outdoor temperature varied from 25.0°C to 34.8°C; Figure 12 showed that in winter the indoor temperature was relatively stable at about 11.0°C when the outdoor temperature varied from 7.4°C to 12.2°C. Compared to the measured results of indoor temperature in Figure 6 and Figure 8, although the fluctuation ranges of the simulated ones were a little bigger, the change trends were similar. The difference between the simulated and measured data was about 0.4~4.8°C in summer and -0.8~3.2°C in winter, which could be explained by the differences between the actual climatic data and the typical one inputted in DeST-h, between the actual thermal performance of building envelope and the theoretical one (Ya, Yanli & Huizhi, 2012, pp. 21-25), between the actual occupants' lifestyle and the fixed one. Therefore, the error between the simulated results and the measured ones was within the acceptable limit. It proved once again that the simulation method by using DeST-h could be convincing and the indoor thermal environment in the house was not comfortable.

5. Conclusions and discussions

Through field-measurement and thermal simulation, the indoor thermal environment of a top-floor house of a residential building in Chengdu had been studied in this article. According to the results, some conclusions can be drawn as follows:

1) The indoor thermal environment in the house was very poor during the measuring period. The average indoor temperature of the house reached about 34°C in summer and dropped to about 11°C in winter, which was beyond the comfortable range.

2) DeST-h software was applied to simulate the indoor thermal environment of the house. Although the fluctuation ranges of the simulated ones were a little bigger, the change trends in the rooms were close to those of the measured results. Thus, the simulated results proved once again that the measured results were right.

3) The thermal insulation of envelope enclosure cannot assure a comfortable indoor thermal environment, and perhaps might not be suitable energy-efficient measures for the residential buildings in Chengdu.

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