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ORIGINAL ARTICLE

The significance for solar heat gain on the indoor thermal environment of passive houses in cold areas in China

Enliang Zhao · Li Zhao · Zhengnan Zhou

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Abstract In the passive house system in cold regions today, the strategies focus on reducing energy loss by enhancing the thermal insulation performance of the building's envelope. Yet, under the specific background, the application of passive house evaluation system lacks emphasis on the significance of solar heat gain. In this paper, two independent passive houses in cold areas in China were selected as research objects, which had almost the same geographic locations, building shapes, and floor plans, through simulation and on-site measurement to discuss the influence of solar heat gain on non-heating sunny and overcast winter days on the indoor thermal environment. The result shows that the house which had a weaker envelope in thermal insulation performance but more solar heat gain performed better than the one which had a stronger envelope but less solar heat gain. It indicates that in the passive house system in cold areas in China, solar heat gain is of great significance and has equal status with the thermal insulation performance of envelopes, which has significant reference value for the early stages of passive house designing and the evaluation criteria.

E. Zhao · L. Zhao · Z. Zhou (✉)
School of Architecture, Tsinghua University, Beijing 100084, China
e-mail: zznan@tsinghua.edu.cn

E. Zhao
e-mail: zel18@mails.tsinghua.edu.cn

L. Zhao
e-mail: zhaoli_arch@163.com

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Introduction

In 2015, China's total building energy consumption was equivalent to 857 million tons of standard coal, accounting for 20% of the country's total energy consumption (China Association of Building Energy Efficiency 2017). As people pay more attention to the protection for the environment and the earth's resources, the urgency of reducing energy consumption is widely recognized. In the field of construction, corresponding measures are also needed (Huang and Hwang 2016). Sartori and Hestnes (2007) surveyed energy consumption in more than 60 buildings worldwide in the life cycle, suggesting that the energy consumption of passive houses was only 1/3 of the traditional ones when the life expectancy is assumed to be 50 years, and the ratio will come to 1/4 when the lifetime is assumed to be 80 years. Therefore, we recognize the passive design strategies as one of the most effective means of energy conservation.

Bo Adamson and Wolfgang Feist firstly proposed the concept of "passive house" in 1988. In 1991, in Darmstadt, Germany, the world's first passive house was built. In general, "passive house" is buildings that do not rely on traditional heating and active air conditioning to maintain indoor thermal comfort in summer and winter (Feist 2014). These buildings were built in German-speaking countries originally. As time went on, a growing number of countries invested in the research and construction of passive houses. Due to the climate of the region, the European "passive house" technical measures focused on reducing the heat loss in winter. To minimize the demand for traditional heating, enhancing the insulation performance of the envelope has become the primary strategy (Kaan et al. 2006). Feist et al. (2005) suggested that the concept of "passive house" is a comprehensive method based on improving the performance of building envelopes. It provides a more comfortable thermal environment and affordable costs while significantly reducing energy consumption. In another article, they mentioned that the first passive house in Darmstadt achieved the goal of energy saving by enhancing the insulation performance and airtightness of the envelope, using an efficient heat recovery fresh air system and increasing the south facade glass area. Ninety percent of energy can be saved compared with traditional European buildings, which comes mainly from reducing heat loss in winter (Feist and Schnieders 2009). Yao et al. (2018) also pointed out that the basic principles of the passive strategy were reducing winter heat loss and unnecessary summer heat gain while achieving the heat balance. Ascione et al. (2016) studied the passive strategies by using a simulation tool to find an optimal balance to meet with the NZEB (Net Zero Energy Building) target in the Mediterranean climate, which includes the thermal insulation performance of envelope, phase change materials with different melting points, and changing the window-to-wall ratio. The research clarified the complexity of the selection of integrated strategies. Passive design strategies were also applied in building renovation projects. Biserni et al. (2018) used TRNSYS (Transient System Simulation Program) to simulate the energy consumption of passive strategies, including efficient exterior windows, enhancing insulation performance of exterior wall, and roof and mutual combination, and then evaluated them from an economic perspective. As an efficient energy-saving method, the selection and combination of passive design strategies are complex and comprehensive. Fortunately, the passive house system provides us a convincing reference to select the strategies and evaluate the actual performance of the buildings. The components of passive houses were given by Feist and Schnieders (2009), including excellent thermal insulation, airtight building envelopes, ventilation systems with highly efficient heat recovery, and the passive use of solar energy. In Kaan et al.'s (2006) article, it is mentioned that the measures in the project named Promotion of European Passive Houses to achieve the targets of passive houses "typically this includes very good insulation levels, very good airtightness of the building, whilst a good indoor air quality is guaranteed by a mechanical ventilation system with highly efficient heat recovery". Schnieders et al. (2015) pointed out that the standard for passive houses is "the peak daily average heating and cooling loads are typically below 10 W/m^2 and annual energy demands are below 15 kWh/(m^{2}a)". Passive houses use solar energy under some conditions, but whether they are defined as "passive solar houses" depends on whether the building is in a position where enough solar radiation can be obtained. Therefore, passive houses are not equivalent to passive solar houses. Grove-Smith et al. (2018) pointed out that passive house is a performance-based standard for optimizing the design and performance of buildings under local climatic conditions, and always specifying the efficiency of building envelopes through specific heating and cooling energy demand targets.

In the passive house system, there are five basic principles applied in the construction, including thermal insulation, passive house windows, heat recovery in ventilation, airtightness of the building, and reduction of thermal bridges, and passive houses are planned, optimized, and verified with the Passive House Planning Packages. As a passive energy-saving strategy, solar heat gain is associated with the "passive house window", and it is taken into consideration when calculating the space heating demand (Passive House Institute 2015). Affected by the weather conditions, solar heat gain cannot provide stable heating, so its status is lower than the basic principles. Nevertheless, in the researches and practices outside the "passive house" system, there are discussions about the impact on the indoor thermal environment caused by solar heat gain.

Chandel and Aggarwal (2008) researched a low-tech and low-cost project under the guidance of the local government's energy-saving housing policy in Western Himalayas. The project improves indoor environmental quality by using direct benefit and the Trombe wall effectively, saving about 35% of energy consumption annually compared to traditional houses. Miller et al. (2012) investigated eight monitored independent houses, which can maintain indoor temperature fluctuations within the comfort range of 18–20 °C from 77 to 97% of a year. Llovera et al. (2011) discussed an independent energy-saving house put into use in Andorra in 2004. The building combines active and passive solar energy utilization for indoor heating and cooling. By setting the Trombe wall in the south to obtain direct solar radiation, it can maintain a comfort level of indoor temperature at 19–23.5 °C when the outdoor temperatures were 2–12 °C in winter. Zirnhelt and Richman (2015) evaluated single-family dwellings in eight typical Canadian climates and population zones and concluded that the optimized passive solar design strategies could contribute 32 to 74% of the heating demand. Albayyaa et al. (2019) analyzed two independent houses in Australia, noting that passive solar energy can reduce energy demand by 37% in winter. According to the results of these discussions, the proper use of solar heat gain is highly efficient and feasible in terms of improving indoor thermal comfort and energy saving.

Besides, solar energy can sometimes have a negative impact on the indoor thermal environment, such as the overheating problem, thereby increasing the building's thermal load (Fedorczak-Ciask et al. 2018). Considering that summer temperatures in southern Spain will increase significantly by 2050, Suárez et al. (2018) evaluated the influence of different passive strategies on future indoor thermal comfort conditions and indicated that strategies relating to solar radiation protection were the most efficient. Based on winter sunshade measures widely used in Tibet, China, Huang and Zhao (2017) analyzed the principles of solar design in winter. They discussed the problems caused by passive heating in winter and proposed a shading method using perforated thermal mass shading in proper configurations. Therefore, the discomfort problems caused by solar heat gain should be considered when making use of it, and advantages and disadvantages of the solar heat gain should be balanced in order to maximize the benefits of the strategy.

In cold areas of China's farmhouse building process, due to weather conditions and the roughness of the technique, the actual situation is slightly different from Europe. In the investigation of farmhouses in cold areas in China, Sun et al. (2011) found out that coal was the main heating source, the indoor temperature was maintained at 12 °C, and the users considered it acceptable. The result of Wang et al.'s (2014) research shows that 80% of the peasants considered 10.6 °C as the lower limit of the acceptable operative temperature, which was associated with clothing and lifestyle, and the value was much lower than the indoor temperature standards of space heating in urban areas. Besides, the authors used a temperature-frequency method to regress the operative temperature and figured out that when the indoor temperature changed 1 °C, the MTS (mean thermal sensation) value would only change about 0.094, which indicated that the peasants were not sensitive to the fluctuation of temperature. Huang et al. (2010) figured out that the lower limit of the acceptable temperature range for peasants was 10.9 °C and suggested that 14–15 °C could be the indoor heating temperature standard for rural areas. Besides, according to "Design standard for energy efficiency of rural residential buildings" issued by the Ministry of Housing and Urban-Rural Development of the People's Republic of China (2013), the recommended winter temperature is 14 °C. In this context, it is evident that the indoor temperature level of the farmhouses in cold areas in China is far from meeting the requirements of thermal comfort, and the low temperature is the main factor affecting the performance of farmhouses. As a passive strategy that can significantly improve the indoor thermal performance, the use of solar heat gain was discussed in the studies of farmhouses in cold areas in China.

Ji et al. (2015) investigated farmhouses in rural areas of Yushu, China, and found that the average temperature of passive solar houses was 13.7 °C, higher than that of ordinary farmhouses, which was only 10.5 °C. Furthermore, the indoor humidity of passive solar houses (65.3%) was also more comfortable than the ordinary farmhouses (90.9%). Chen et al. (2012) established a mathematical model to discuss the courtyard sunspace passive solar houses in Qingdao, China, and examined the accuracy of the model by simulation. The authors also figured out that the indoor temperature of the passive solar house was 13.7 °C, which was 3.1 °C higher than the old house without using passive solar energy. Long et al.'s (2016) research on the envelope of passive solar houses shows that we should select the materials adaptively for different parts of the envelope, which orient to different directions to maximize the solar heat gain to improve the indoor thermal comfort. In terms of improving the indoor thermal comfort of the farmhouses in cold areas in China, the proper use of solar heat gain achieved good results. Therefore, it is necessary to pay more attention to solar heat gain in the building process of farmhouses in cold areas in China when referring to the evaluation criteria of passive houses.

Using sunspaces is one of the most efficient methods to obtain solar radiation. Suárez-López et al. (2018) used a simulation, which is based on computational fluid dynamics to discuss the performance of a solar space in a demonstration container in the north of Spain and confirmed its ability to reduce the energy required for building heating. Babaee et al. (2015) discussed the influence of the size, glass material, and inclination angle of the attached sunspace; proved the contribution of sunspaces to passive heating in the cold region of Iran through simulation; and summarized a design strategy which can reduce the heating load of the target space by 46%. By studying a passive solar house in the Qinghai-Tibet area, Liu et al. (2018) found the optimum combination of different depths of sunspace and different window-to-wall ratios for the gain of indoor thermal environment, indicating that proper sunspace setting plays an important role in maintaining indoor thermal comfort. In another article, they tested the heating efficiency of active and passive solar heating for indoor environment in the project and drew a conclusion that under the evaluation criteria of 14 °C, passive solar heating contributes 49.8% of the heating time (Liu et al. 2017). Fernandes et al. (2015) compared the passive design strategies of local buildings in different climate zones of Beira Alta in northern Portugal and Alentejo in southern Portugal and found the differences in the treatments of passive heat gain: the former captured solar radiation in winter by setting a south-facing glass balcony, while the latter enhanced passive solar cooling in summer by using rammed-earth materials. Asdrubali et al. (2012) used two different stationary procedures, along with a dynamic simulation tool to simulate a sunspace in Umbria, Italy, and concluded that the use of sunspace reduces 20% of the energy demand in winter. Qiao et al. (2015) studied the passive solar houses with attached sunspace in the Beijing area, figured out that the strategy has a significant effect on the improvement of indoor temperature in winter, which increased the value by 1.91 °C during the heating season. In summary, sunspaces performed well in capturing solar radiation. In order to study the impact of solar heat gain on the design of passive farmhouses in cold areas in China, the amount of solar heat gain is taken as a control condition, which is easily achieved by altering the ability of the sunspace to capture solar radiation.

Case studies and methodology

Case description

In cold regions, the passive strategies aim at reducing the winter heat loss to maintain the indoor thermal environment and keep the temperature at a comfortable level. Therefore, we can evaluate the performance of passive houses by the indoor temperature during winter days without active heating.

The research selected two 2-storey independent houses in the rural areas of Daxing, Beijing, and Xinji, Shijiazhuang, which were designed and constructed by the Architectural Design and Research Institute of Tsinghua University, hereafter referred to as BJ and SJZ. The sites of the buildings in the two cases were similar, both of which were open areas, without tall buildings around. Apart from the similar geographic environment and climate, they both had good sky conditions and faced the due south direction, and passive design strategies combined with appropriate equipment to fully utilize solar energy were adopted to meet the needs of winter heating and the reduction of daily maintenance costs. The strategies include enhancing the thermal insulation performance of the envelope, improving the airtightness of the windows, and sunspace attached to south facade so that the buildings can maintain the indoor thermal environment at a comfortable level through solar heat gain and enhanced thermal insulation performance. As the occupiers were similar (both were peasants' self-use houses), the design of SJZ was an upgraded version based on BJ. The main adjustment was the improvement of the materials, including the envelope of the main structure and the sunspace according to the constructing conditions and the performance of BJ; minor adjustments had been made to other details while the shape and the floor plans remained the same, which mitigates the impact caused by the architectural design.

The selected cases were similar in climate, site condition, architectural design, function, and adopted passive design strategies while the specific materials of the envelopes and sunspaces were different. In researches based on comparative experiment, we must control irrelevant variables to deduce the disturbance, and the condition is difficult to be satisfied in cases which were built and put into use. Therefore, there is an individual uniqueness in case selection. The influence of solar heat gain on indoor thermal comfort is the research content.

Basic information of the cases

Beijing and Shijiazhuang, where the two houses are located, belong to the monsoon climate of medium latitudes according to the Köppen-Geiger classification system, hot and rainy summer, cold and dry in winter, and have distinct seasons. In the climate division of China which is based on heating degree days and cooling degree days, they belong to the cold II(B) climate zone (2000 ≤ HDD18 < 3800, 90 < CDD26, where HDD18 and CDD26 mean heating degree days based on 18 °C and cooling degree days based on 26 °C) according to "Code for Design of Civil Buildings (GB 50352-2005)"(Ministry of Construction of the People's Republic of China 2005). The average winter outdoor temperatures in Beijing and Shijiazhuang are 0.1 °C and 0.9 °C, which are almost the same. Other meteorological parameters may be selected from the provisions in "Design Standard for Energy Efficiency of Residential Buildings in Severe Cold and Cold Zones (JGJ26-2010)" (Ministry of Housing and Urban-Rural Development of the People's Republic of China 2010), as shown in Table 1:

The two houses are located on flat sites with excellent exposure to the sun. In order to passively gain solar heat, two-storey sunspaces were designed attached the south facade, where the exterior insulation of the building was inside the sunspaces. The complete scene parameters of the two cases are given in Table 2.

BJ was completed in 2011 with a floor area of 188 m^2. The floorplan adopted a typical passive independent house design method, allocating the living rooms and bedroom on the south side of the building where there is most solar radiation. The dining room and bathrooms lie in the middle, and auxiliary rooms such as stairwell and utility room, which require little indoor heating, were placed on the north. The floorplan fits the functional requirements of the farmhouses well, meanwhile effectively utilizing solar radiation. In consideration of the actual situation of the construction, red bricks were used as the main material of the external wall, which is commonly used in the local area. It was completed by the villagers' self-construction method, which means the villagers were the constructors, and the designers provided necessary technical guidance. It guaranteed the low cost and low technology of the construction that can be affordable for ordinary peasants. The external thermal insulation structure was applied to the envelope; the material was 80-mmXPS, whose *U* value was 0.36 W/(m^2 K). The roof material was cellular concrete, whose *U* value was 0.31 W/(m^2 K). In order to reduce the heat loss, the designer chose small exterior windows on the east, west, and north sides that meet the requirements of daylighting and natural ventilation while setting attached sunspaces on the sun-facing south facade. The exterior windows used ordinary plastic steel windows with double glazing which are commonly used in rural areas of Beijing, and the *U* value of the total window including frames and thermal bridges is 2.4 W/(m^2 K). The sunspace used ordinary single glazing clear glass whose transmittance was 0.89. A fresh air preheating system was designed in the sunspace, in a purpose of preventing the cold air from entering the room directly during winter ventilation and avoiding the accumulation of hot air in the sunspace. In winter operation mode, the fresh outdoor air was inhaled through the upper air inlet of the preheating track, heated by solar radiation, and then sent indoor by a small-power photoelectrically driven fan installed at the bottom of the preheating track. In summer operation mode, the fan span in the opposite direction to discharge the hot air from the sunspace. The photovoltaic panel mounted on the top of the preheating track supplied the power of the fan, and the speed of the fan is positively correlated with solar radiation intensity. The working method of the preheating track is shown in Fig. 1. On sunny winter days, the solar heat gain can meet the heating needs. Meanwhile, the water storage tank with a solar energy collector installed on the roof can generate hot water in the daytime to heat the room through the radiant floor heating coil pipe at night.

In BJ, setting attached sunspace was the main strategy to improve its performance in winter, but it also brought the problem of overheating in summer. In order to prevent overheating, the designer set a reed sunshade on the external side of the sunspace, which could be adjusted according to activities of the user and designed a double-layer heat rejection roof to discharge the hot air in the sunspace. An air inlet was set at the bottom of the sunspace, and an air outlet was set at the top of the

Table 1 Meteorological parameters of Beijing and Shijiazhuang

City	Beijing	Shijiazhuang
Climate zone	II(B)	II(B)
Latitude	39.93° N	38.03° N
Longitude	116.28° E	114.42° E
HDD18	2699	2388
CDD26	94	147
Heating time (day)	114	97
Average outdoor temperature in winter (°C)	0.1	0.9
Average horizontal total solar radiation intensity (W/m^2)	102	95
Average southbound total solar radiation intensity (W/m^2)	120	102

Table 2 Basic information of the case study buildings

Name of projects	BJ	SJZ
Completed scene		
Floor area		
Ground structure		
Roof structure		
U value of the roof		
Wall structure		
Insulation materials		
U value of the external wall		
Type of exterior windows	Ordinary double-layer insulating glass	Triple-layer low-E coated insulating glass
U value of the exterior windows	2.4 W/(m^2 K)	1 W/(m^2 K)
Material of the glazing of sunspace	Ordinary single-layer clear glass	Brown double-layer coated insulating glass
SHGC	0.89	0.41

building between the roof and suspended ceiling, generating a ventilating duct to enhance the performance of passive air exhausting in summer. The section of sunspace in BJ is shown in Fig. 2.

SJZ was completed in 2016 with a floor area of 210 m^2. The design philosophy and floor plan were similar to BJ. The living rooms and bedrooms were allocated on the southern side with the most solar heat, stairwell and bathroom were in the middle of the building, and auxiliary spaces like kitchen, dining room, storage room, and utility room were placed on the north. It was a project as residential industrialization demonstration with a pre-fabricated structure. The external walls are a pre-fabricated reinforced concrete wall, and the material of the external thermal insulation was 100-mmXPS, whose *U* value is 0.29 W/(m^2 K), which is slightly better than that in BJ and meets the standard of 65% energy-saving target in China (Ministry of Housing and Urban-Rural Development of the People's Republic of China 2016). The roof material was cellular concrete, whose *U* value is 0.2 W/(m^2 K). Small windows were designed on the east, west, and north sides, and attached sunspace was set on the south facade, which is almost the same as BJ. However, summer overheating occurs in BJ. Under the similar climates, the main problem to solve is still the low indoor temperature in winter, and then balance the heat gain in summer. Therefore, we used solar protective glazing for the sunspace to replace reed sunshade, and meanwhile kept the shape of the farmhouse. The material of the glazing was triple-layer low-E coated insulating glass, and the *U* value of the total window including frames and thermal bridges is 1 W/(m^2 K). Brown double-layer coated insulating glass, whose transmittance is 0.41, was used in the sunspace. Compared to BJ, SJZ adopted an independent ventilation system without the pre-heating device and an underfloor heating system.

Methodology

Simulation and parameter settings

Solar radiation is the primary source of passive heat gain of buildings. Firstly, we need to know the quantitative of the solar heat gained by sunspaces of BJ and SJZ during the heating season.

The solar heat gain is computed using the following equation:

$$I_0 = S \times (I_s \times \sin\theta + I_H \times \cos\theta) \times \text{SHGC}$$

where:

S is the total area of south-facing glass of the sunspace, whose value is the same in BJ and SJZ.
I_s is the average southbound total solar radiation intensity.
I_H is the average horizontal total solar radiation intensity.
θ

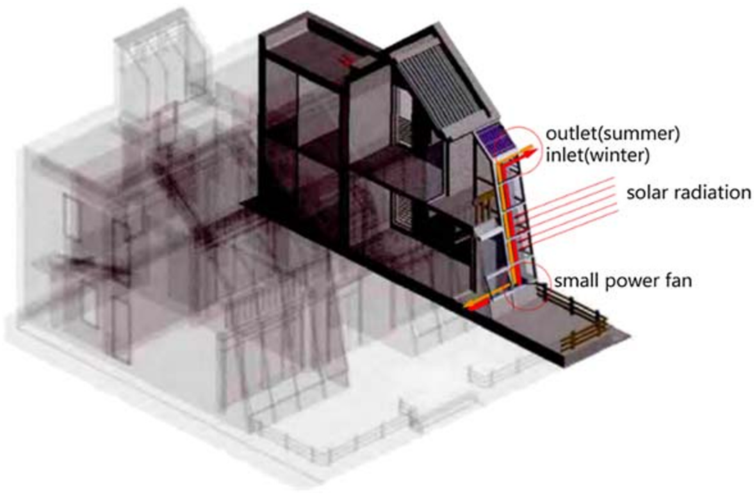

Fig. 1 The working method of the preheating track

is the angle between the horizontal direction and the south-facing glass, and the value of θ is 78^{o} in the two cases.

According to the average total solar radiation intensity in Table 1 and SHGC in Table 2, we can estimate that the solar heat gain of BJ was 2.5 times as much as that of SJZ.

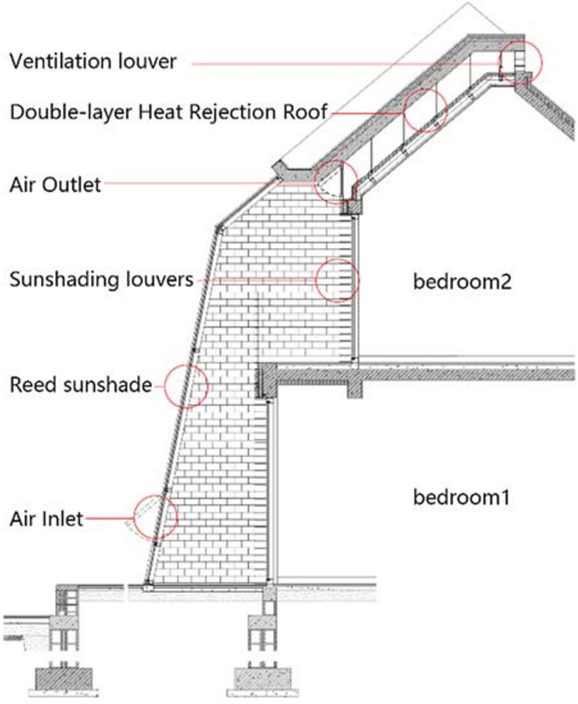

Fig. 2 The section of sunspace in BJ

Secondly, we need to study the influence on the performance of BJ and SJZ caused by solar heat gain. As setting attached sunspaces was the main way to gain solar heat in both of the cases, it is necessary to know the quantitative relationship of the solar radiation onto the south-oriented walls that face the sunspace. A simulation was used to get the relationship and examine the estimated results. It is a reference for the subsequent analysis.

The research used Ecotect to simulate the two cases. The meteorological data was collected from Energyplus's official website. The date range of simulation was the heating season in Beijing and Shijiazhuang between November 15 and March 15, the calculation mode was "Incident Solar Radiation," and the time range of each day was from 0:00 to 24:00. The parameters of the envelope structure are shown in Table 2. In the simulation, the top of the vertical plane of the grid coincides with the top horizontal line on the outside of the bedrooms where the sunspace was attached, and other elements were not covered to avoid the influence of the shadows on the results.

On-site measurements

After BJ and SJZ were built and put into use, we measured the indoor thermal environment parameters. According to the quantitative relationship of solar radiation acquired between the two cases in the simulation, we can get the ability of BJ and SJZ in capturing solar heat. However, due to the materials used in the envelopes, there were differences in the thermal insulation performances between BJ and SJZ. Meanwhile, there were also some random meteorological factors in using the process, so the simulation results cannot represent the specific performance of BJ and SJZ. Thus, we can obtain the actual performance of BJ and SJZ through on-site measurements, and then evaluate the effectiveness of solar heat gain as a passive strategy in the current passive house system by comparing the relationship among “the thermal insulation performance of the envelope,” “the ability to gain solar heat,” and “the actual performance of BJ and SJZ”.

Equipment

There were two types of equipment used in the measurement. One was a long-term testing instrument, which was used to obtain 24-h real-time temperature data, including DT-171 temperature and humidity self-recording instrument manufactured by Shenzhen Everbest Machinery Industry Co., Ltd. and SSN-20 single-temperature self-recording instrument manufactured by Shenzhen Yuanhengtong Science & Technology Co., Ltd., as shown in Fig. 3. For DT-171, the temperature measuring range is − 40~70 °C, measuring accuracy is ± 1 °C, resolution ratio is 0.1 °C, the humidity measuring range is 0~100%RH, and the data storage was 32,000. The data is read by a USB connection to the computer. For SSN-20, the temperature measuring range is − 35~80 °C, measuring accuracy is ± 0.3 °C, and resolution ratio is 0.1 °C. Another was a HT-8500 multi-function tester manufactured by Beijing Jintaikeyi Detection Equipment Co., Ltd., which was used as a field test instrument. During the measuring period, we used this instrument to measure indoor temperature occasionally to check the accuracy of the temperature data by comparing the results with the data recorded by long-term testing instruments. The temperature measuring range is − 20~60 °C with measuring accuracy of ± 0.3 °C, resolution ratio of 0.1, humidity measuring range of 0~95%RH, and measuring accuracy of ±5%RH.

Fig. 3 DT-171 temperature and humidity self-recording instrument and SSN-20 single-temperature self-recording instrument

Test site configuration

In order to obtain comprehensive and objective temperature data, measuring points were arranged in each main function room of the two projects including the living rooms, bedrooms, and dining rooms on the ground floor and first floor; the total number was 7 (as shown in Figs. 4 and 5). Point 1 and point 4 were set in the bedrooms with attached sunspace, the aim of which is to get the temperatures of the rooms that obtained the solar heat gain directly. The other measuring points were set to obtain the global indoor temperature. By comparing the temperatures of the parts with attached sunspaces and the global temperature, the effectiveness of solar heat gain on improving the indoor temperature can be verified; by comparing the same types of data from different cases, the impact of different passive strategies on the indoor thermal environment can be evaluated.

All test instruments were set at a sampling interval of 0.5 h. The instruments were set at the height of 1 m above the floor, far away from direct sunlight and other cold and heat sources, and kept at a distance of 0.6 m from the inner surface of the exterior wall. The outdoor measuring points were set in the ventilated and cool place on the north side of the building, which was not exposed to direct sunlight and other cold and heat sources. The sampling interval is consistent with the indoor measuring points. The purpose of the setting is to obtain the fluctuation of the outdoor temperature, to find the data of the periods of the same outdoor temperature conditions in the two cases for comparative analysis. The measuring procedures followed “Standard for energy efficiency test of residential buildings (JGJ/T 132-2009) (Ministry of Housing and Urban-Rural Development of the People’s Republic of China 2009)”.

Results and analysis

Analysis of simulation results

Figures 6 and 7 show the simulation results of BJ and SJZ. The target parameter is the average daily solar radiation per unit area in the south direction of the

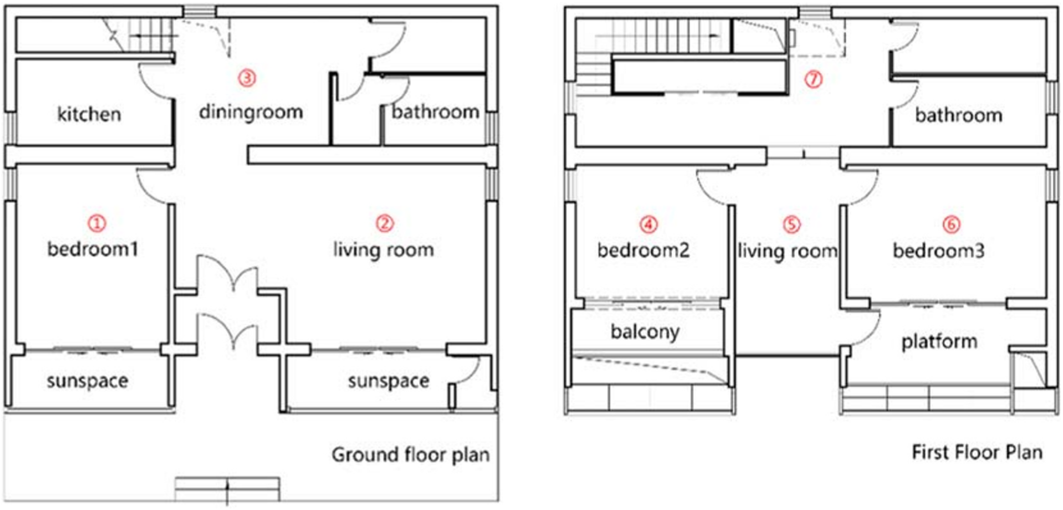

Fig. 4 Measuring points in BJ

attached sunspace during the heating season. The range of scale value is 320~1520 Wh, and the color temperature has a positive correlation with solar heat gain. According to the simulation, the value of the average daily solar radiation of BJ is 1227.38 Wh/(m^2 day), while SJZ is 648.71 Wh/(m^2 day).

The difference is caused for the following reasons: Though BJ and SJZ have the same orientation and almost the same area to obtain solar radiation, due to the geographical environment and other factors, the solar radiation gain of the two buildings cannot be precisely the same at the same time. From Table 1, the average intensity of the total solar radiation in the horizontal direction of Beijing and Shijiazhuang is 102 W/m^2 and 95 W/m^2, respectively, while in the south direction, it is 120 W/m^2 and 102 W/m^2; BJ is slightly higher than SJZ. Meanwhile, considering the overheating phenomenon in summer, the latter built SJZ used brown double-layer low-E coated insulating glass as the material of the envelope of the sunspace whose SHGC is 0.41, which is lower than that 0.89 of BJ.

According to the simulation results, we understand that during the heating season, the solar radiation that reached onto the south-oriented walls of BJ was much higher than

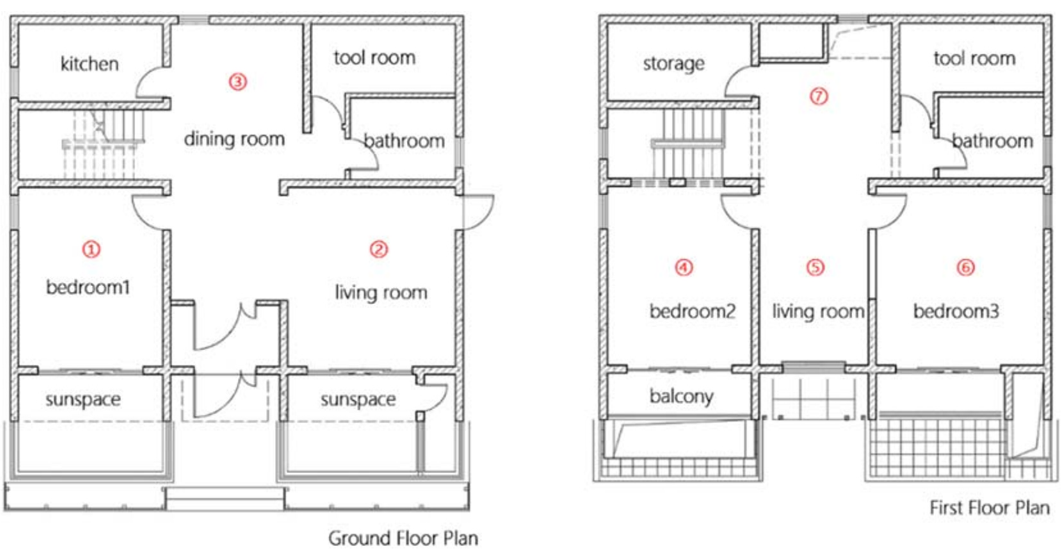

Fig. 5 Measuring points in SJZ

Fig. 6 The simulation result of BJ

that of SJZ, and the former was about 1.9 times of the latter. This is an important reference value in the subsequent analysis based on the on-site measuring results.

Measuring results

Temperature data of BJ and SJZ in heating season during days when active heating was off were recorded per 0.5 h. Due to different geographic locations of the two buildings, the outdoor weather and temperature fluctuation were not precisely the same, so it is difficult to compare the temperature data of BJ and SJZ synchronously. Besides, in the heating season, due to the special meteorological factors (cloudy, snowy days, etc.), BJ and SJZ were not using passive heating mode all the time. In un-sunny weather, the attached sunspaces cannot work effectively. Therefore, we chose two sets of typical data in each of the cases. One was three consecutive sunny

Fig. 7 The simulation result of SJZ

winter days, and the purpose was to explore the impact of the ability to gain solar heat on the indoor thermal environment. Another was six consecutive days, during which the first, fifth, and sixth days were sunny days, and the second, third, and fourth days had weak solar exposure, and the purpose was to examine the effectiveness of the passive heating method. During the selected period, the passive heating method was used throughout, and the outdoor temperature fluctuation was similar in the same set. Three types of data were used in the analysis, including the outdoor temperature, the average indoor temperature, and the average temperature of the two bedrooms that shared the same attached sunspace.

The results of consecutive sunny winter days

Figure 8 shows the temperature fluctuation of BJ in 3 consecutive non-heating sunny winter days at the end of November, during which the minimum outdoor temperature was − 2.9 °C, the maximum outdoor temperature was 12.0 °C, and the average temperature was 3.9 °C. The indoor average temperature curve is the average value of temperature records per 0.5 h for seven measuring points, which represents the indoor thermal environment. According to the measuring results, the minimum average indoor temperature during the measuring period was 14.5 °C, the maximum average indoor temperature was 22.4 °C, and the global average indoor temperature was 17.7 °C, which was 13.8 °C higher than the average outdoor temperature.

The average temperature of the two bedrooms could well represent the part of the house which is directly influenced by solar heat gain. As shown in the figure, when getting solar heat during the daytime, the temperature of the two bedrooms rose rapidly during the abundant sunshine period (12:00–16:00), keeping a particular gap from the global average indoor temperature. The maximum temperature was 25.2 °C, the minimum temperature was 14.0 °C, and the average value was 18.9 °C. As a result, the indoor temperature of BJ was able to be maintained at a relatively comfortable level without an active heating system on sunny winter days (for the users of the farmhouses). Using attached sunspace was beneficial to the indoor thermal environment in winter days, which was more evident in the rooms next to the sunspace (the average temperature was 1.2 °C higher than the global indoor temperature).

Figure 9 shows the temperature curve of SJZ in 3 consecutive non-heating sunny winter days at the end of February, during which the minimum outdoor temperature was − 3.1 °C, the maximum outdoor temperature was 13.1 °C, and the average temperature was 5.6 °C. The indoor average temperature curve is the average value of temperature records per 0.5 h for seven measuring points, which represents the indoor thermal environment. According to the measuring results, the minimum average indoor temperature during the measuring period was 15.5 °C, the maximum average indoor temperature was 18.8 °C, and the global average indoor temperature was 16.6 °C, which was 11.0 °C higher than the average outdoor temperature.

The maximum average temperature of the two bedrooms was 20.2 °C, the minimum average temperature was 16.9 °C, and the average value was 18.4 °C, which was 1.8 °C higher than the global average indoor temperature. In this case, there was a specific temperature rise during the daytime, and the average temperature was always higher than the global temperature, keeping the indoor thermal environment at a comfort level on non-heating sunny winter days, but the gap also indicates that the building's northward rooms have lower thermal comfort.

The results of consecutive winter days within days with weak solar exposure

Figure 10 shows the temperature curve of BJ in 6 consecutive non-heating winter days. The weather of the second, third, and fourth days was cloudy to overcast, sleety, and sleety respectively. During the third and fourth days, BJ cannot gain solar radiation, and the outdoor temperature was relatively stable. The maximum outdoor temperature was 6.6 °C, the minimum outdoor temperature was − 1 °C, and the average temperature was 2.5 °C. The maximum value of the global indoor temperature was 17.9 °C, the minimum value was 14.9 °C, and the average value was 16.6 °C. Meanwhile, the maximum temperature of the bedrooms with attached sunspace was 17.9 °C, the minimum temperature was 14.4 °C, and the average value was 16.4 °C, which was very close to the global temperature.

According to the curve, the temperature change of BJ shows clear differences between sunny and overcast days. On sunny winter days, the fluctuation trends of indoor and outdoor temperature were the same, and reached peak value between 12:00 and 15:00 every day; the change of bedrooms with attached sunspace was more prominent. In overcast winter days, the indoor temperature fluctuated little, when the temperature of

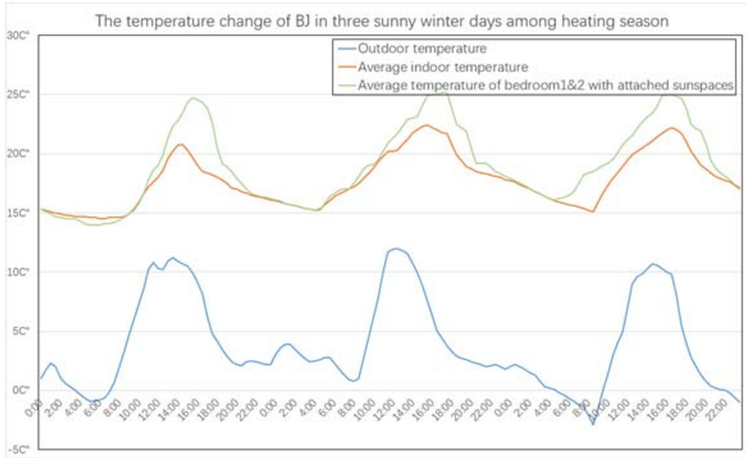

Fig. 8 Measuring result of sunny winter days of BJ

the bedrooms with attached sunspace was almost the same as the global temperature. Therefore, using solar heat gain as a passive design strategy works well in BJ.

Figure 11 shows the temperature curve of SJZ in 6 consecutive non-heating winter days. The weather of the second, third, and fourth days was sunny to overcast, moderate snow, and overcast respectively. During the third and fourth days, SJZ cannot gain solar radiation, and the outdoor temperature was relatively stable. The maximum outdoor temperature was 2.2 °C, the minimum outdoor temperature was − 6 °C, and the average temperature was − 1.7 °C. The maximum value of the global indoor temperature was 15.2 °C, the minimum value was 14.0 °C, and the average value was 14.2 °C. Meanwhile, the maximum temperature of the bedrooms with attached sunspace was 17.4 °C, the minimum temperature was 15.7 °C, and the average value was 16.2 °C.

During this period, the temperature change of SJZ shows slight differences between sunny and overcast days. On sunny winter days, the global temperature and the temperature of bedrooms with attached sunspace reached peak value between 12:00 and 15:00 every day, yet the overall fluctuation of the temperature was not obvious. Meanwhile, the temperature of the bedrooms remained a certain gap higher than the global temperature. As a result, the influence of solar heat gain on the indoor temperature of SJZ was weaker than that of BJ.

Influence of solar heat gain on indoor thermal environment

Under the conditions of basically the same building types, floorplans, outdoor temperatures, and climates, the variation trends of the curve of global average indoor

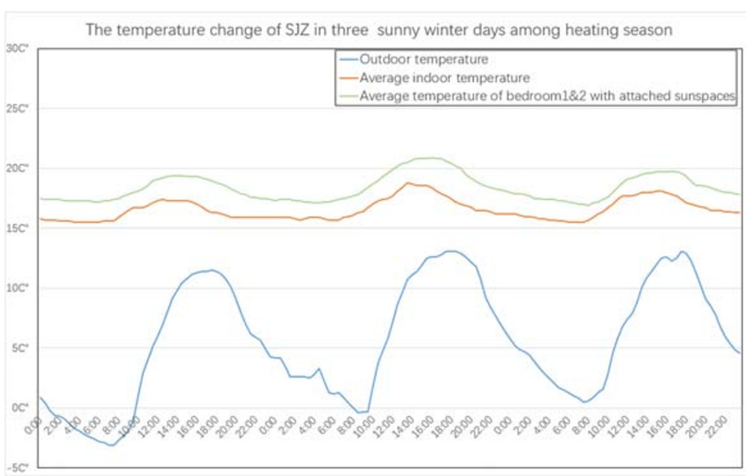

Fig. 9 Measuring result of sunny winter days of SJZ

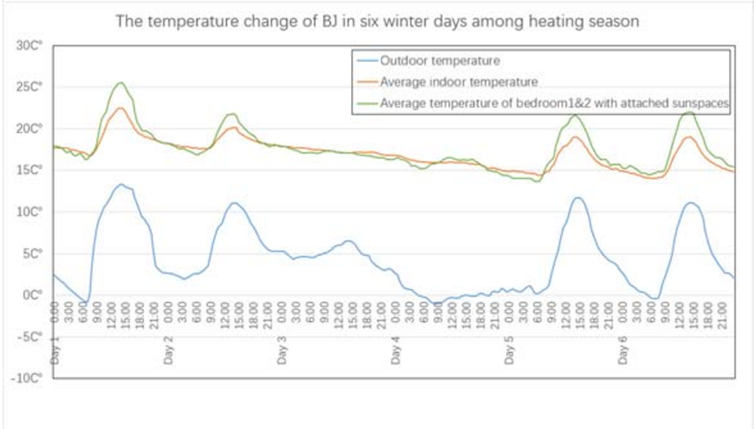

Fig. 10 Measuring result of six consecutive days of BJ

temperature and average indoor temperature of bedrooms with attached sunspace were similar, but there was some difference in the fluctuations and specific data changes.

Indoor temperature is a significant parameter for evaluating the thermal comfort of passive houses. For the design of farmhouses in cold areas in China, the users could accept the temperature fluctuation in a particular range, and raising the indoor temperature was the main problem. According to Figs. 8 and 9, the average indoor and outdoor temperature difference of BJ was 13.8 °C, and SJZ 11.0 °C. Under such a background, the performance of passive strategies of BJ was significantly better than SJZ. The results of the simulation showed that the solar heat gain of BJ was far more than SJZ (about 1.9 times). Though the temperatures during the day of both cases were higher than the night, the range of BJ that gained more solar heat was 7.9 °C, and SZJ was 3.3 °C; the improvement of BJ was more prominent.

In the measuring period during sunny winter days, the standard deviation of BJ's average indoor temperature was 3.322 °C, while SJZ was 0.882 °C. The temperature of SJZ was more stable than BJ. Combined with the temperature fluctuation in overcast winter days in Figs. 10 and 11, it can be understood that sunny days had a greater effect on the temperature of BJ. It is caused by the quantity of solar heat gain and thermal performance of envelopes. The solar radiation that reached south-oriented walls that face the sunspace in SJZ was lower than that of BJ, and the stronger envelope blocked the heat transfer. As a result, the temperature rise in SJZ was less than BJ on sunny winter days. However, it also prevented heat loss in SJZ effectively. The temperature dropped slower at night in non-heating days and always stayed above the global temperature.

In BJ and SJZ, the multiple relationships between the U value of the envelopes and the amount of solar heat gain were almost the same. In terms of the "passive house" system, which is based on enhancing the thermal

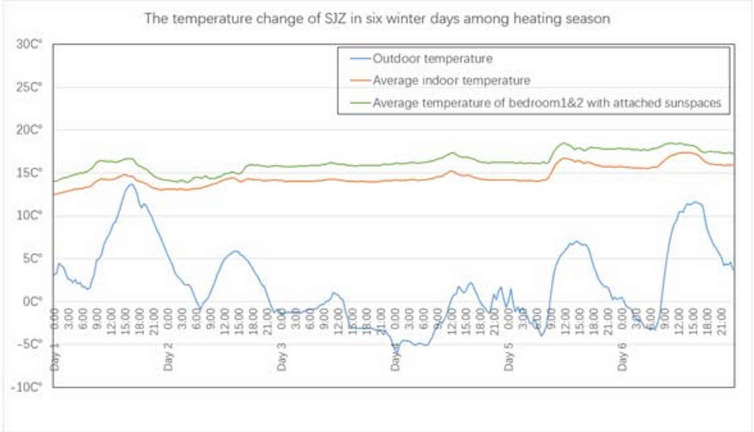

Fig. 11 Measuring result of six consecutive days of SJZ

insulation performance of the envelopes, as the *U* values of the roof, external wall, and exterior window in SJZ were smaller than those in BJ, SJZ should have a better performance theoretically. Yet influenced by solar heat gain, BJ had a better performance. Therefore, in the "passive house" system in cold areas in China, solar heat gain has an unneglectable effect on improving the performance of farmhouses. From the measuring results, it has an equal status on improving the actual performance of the farmhouses as the thermal insulation performance of the envelope, while the latter sometimes plays the opposite role in raising the indoor temperature. Under the background of the main problem is increasing the indoor temperature and while temperature fluctuation is acceptable in a particular range, solar heat gain should not merely be regarded as a means to improve the evaluation indexes, but also as important as the basic principles.

Limitations

There are some interference factors and limitations in this study: due to the change of the design, the shape of BJ and SJZ is not identical. The users' activities cannot be entirely consistent during the test period. Though the two cases are in the same climate zone, there are still some differences in meteorological conditions, and the amount of solar heat gain in the same condition is slightly different; in order to keep the outdoor temperature consistent, the selected measuring period is different.

Conclusions and outlook

The paper discussed the contribution of solar heat gain as a passive strategy to maintaining indoor thermal comfort by measuring two independent passive houses with similar geographic locations, building shapes, and floor plans. The conclusions are as follows:

1. Solar heat gain is of great significance in the "passive house" system in cold areas in China. An appropriate capture of solar heat gain can improve the performance of passive houses in winter effectively.
2. When other factors are similar, the thermal insulation performance of the envelope is not the only major interfering factor of the actual performance of passive houses. By proper design strategies of controlling the solar heat gain, the relationship predicted by the strength of the envelope can be reversed. In cold areas in China, the passive strategy of solar heat gain and enhancing the internal performance of the envelope have an equally important role in improving the thermal performance of farmhouses.

It is aimed in this study to reinforce the designers' emphasis on solar heat gain in the early stages of passive house designing rather than blindly focus on enhancing the thermal insulation performance of the envelope. The limitation of this study is that the measurement and analyzing methods were not perfect, as the results were not strictly quantitative: the simulation results were used to compare the relationship of solar heat gain rather than the measured data, and merely represent cold regions or similar climate zones. Limited to the number and characteristics of the cases, no quantitative evaluation standard that applies to general passive houses is proposed. The future study will base on the result of this research and discuss the feasibility of establishing solar heat gain as one of the passive house evaluating standards in cold areas in China.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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