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The optimized matching of passive solar energy supply and classroom thermal demand of rural primary and secondary school in northwest China

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Abstract

The heating problems of rural primary and secondary school must be solved urgently in Northwest China. However, central heating systems are difficult to implement in rural areas due to the level of economic development. It is known that the solar energy resources are much richer in Northwest China. So, it is possible to improve the indoor thermal environment using passive solar technology. In this study, the temperatures of three types of passive solar houses were calculated using dynamic simulation. The accuracy of the model was verified by experiments. Combined with the particular demands of rural school, the indoor environment is analyzed at different modes in different areas to determine the optimal type of passive solar house. These areas were divided into four zones: most suitable areas, more suitable areas, less suitable areas and unsuitable areas. The priority degree for different types of passive solar houses under different modes was determined.

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Keywords: Solar energy; Thermal demand; Rural primary and secondary school; Passive solar classroom

1. Introduction

Environmental issues and energy consumption are increasingly alarming global concerns today. It is essential to adopt solutions to obtain more energy-efficient and sustainable buildings, both new and existing. The use of solar energy is a means of improving the use of natural energy, which can reduce energy consumption. Influenced by economic level, it is difficult to apply the traditional central heating system in rural areas. Thus, it is essential to expand the application of passive solar houses.

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Some scholars [1, 2, 3, 4, 5, 6, 7] have studied and optimized different combinations of heating components in depth, such as direct-gain window, Trombe wall + direct-gain window and attached sunspaces. The main purpose of such combinations is to improve the indoor thermal environment as much as possible using solar energy.

Overall, these studies indicate that the passive method can be an appropriate and effective system if properly designed to take full advantage of the local climate. But few references exist for designers to determine how to choose the most suitable style of passive solar house in practice. In this study, a dynamic calculation method, which was verified to be reasonable and accurate through the comprehensive experimental tests, for three different types of passive solar houses was used to analyze various indoor thermal environments at the same time. China's climate differs greatly in various region, the effects of passive solar house designs in different regions also vary. Combined with the particular demands of rural primary and secondary school buildings, the indoor thermal environment of the passive solar house is analyzed at different modes in different areas to obtain the optimal type. The area in the study was divided into four zones: most suitable area, more suitable area, less suitable area and unsuitable area. The priority degree of passive solar houses is recommended for each area.

2. Methods

2.1. Testing and modeling

The testing house is located in Changwu, Northwest China, and features three types of passive solar house designs: attached sunspace, Trombe wall + direct-gain window and direct-gain window, as can be seen in Figure 1. Measurements were performed in parts of the passive solar house from January 9 to 13, 2014. A building model was established in EnergyPlus to simulate the air temperature in different rooms.

Fig. 1. Experimental building, measuring point of indoor and outdoor thermal environment.

The thermal response was measured in different types of passive solar house. Under the same outdoor climate conditions, the average temperatures of the three room types according to the simulations and the field tests performed are shown in Figure 2. In the non-heating condition, the measured average indoor temperature remained at 9.1 ℃,11.7 ℃,and 9.6 ℃, respectively, mainly due to the high thermal capacity of the house, even as the outside air temperature decreased to -10.6 ℃ (7:00 am January 13th). The fluctuations in the outdoor air temperature were reduced by the buffering effect of the building envelope. The buffer potential depends on the thermal characteristics of the building envelope.

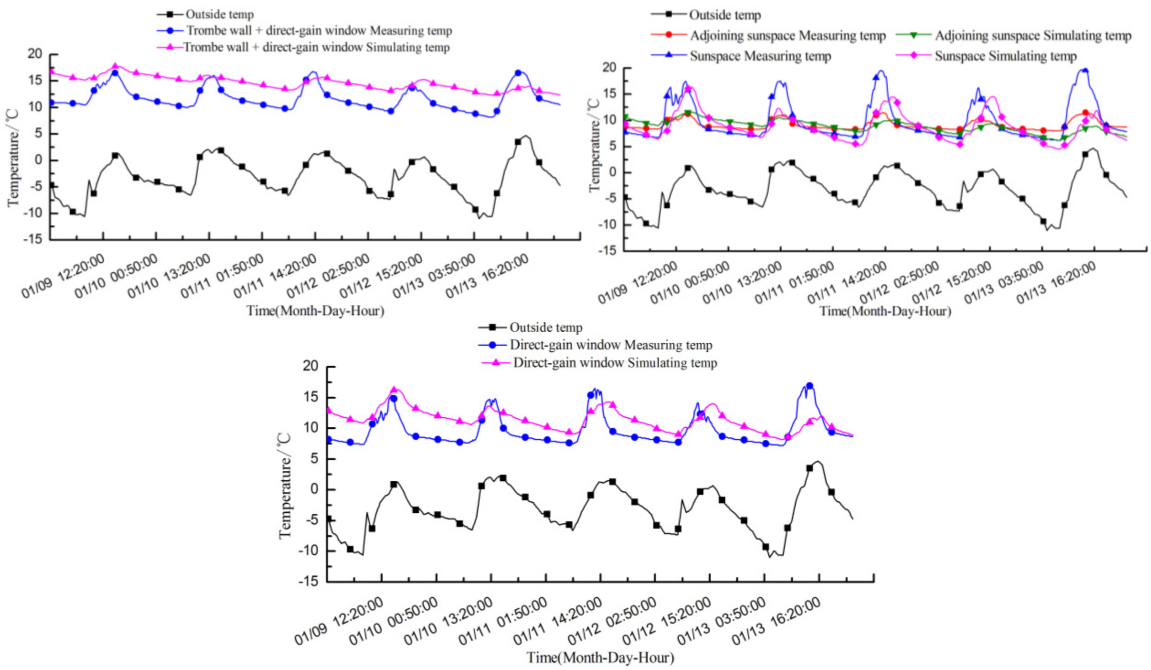

Fig. 2. Comparison results of the simulated and measured temperatures.

2.2. Validation of the reference building model

The average relative errors associated with the simulated were 1.1%, 9.4%, and 9.3%, respectively, compared to the measured values. The simulated temperature curve and the measured temperature curve are generally consistent. The agreement between the curves in some regions is good, whereas it is poor in other regions. Such error is likely related to random human activity, such as the opening or closing of the doors or turning on/off the lights. These activities may lead to extra infiltration. The error was determined to be acceptable; therefore, this model was suitable for the subsequent analysis.

3. RESULTS

3.1. Analysis the thermal demand mode

A survey revealed that school buildings rooms that serve many different functions, such as classrooms, teachers' offices, dormitories, apartments and duty rooms. These rooms may be used for different purposes, but the general goal is to meet the demand for thermal comfort during the rooms' period of demand. The classification of heating demand is presented in Table 1.

Table1. Thermal demand for different rooms .

Type	Demand Time	Note
Mode1	0:00-24:00	applied all day long, such as a duty room
Mode2	7:00-21:00	applied during the day and part of the night,such as a classroom or office
Mode3	7:00-17:00	applied during the day

Mode4	21:00—7:00 the next day	applied during the night, such as dormitories

The base temperature of a passive solar house is the minimum indoor air temperature. When the indoor temperature is below the minimum, an auxiliary heat source should be installed. According to the level of heating in China, the value is set to 14 ℃ during the day. Some studies [8, 9]Lin and Deng 2008 and Pan 2009) have indicated that to attain partial thermal comfort, when the indoor temperature is 12 ℃ at night, clothing's thermal resistance is 0.72 $m^2 \cdot K/W$, and the human PMV is calculated to be 0.24. In this study, the daytime temperature was set to 14 ℃ from 7:00 to 21:00 and the nighttime temperature was set to 12 ℃ during sleeping hours, from 21:00 to 7:00 the next day.

3.2. The ratio of the glass area to the wall

Taking Pingliang as an example, for different ratios of the glass area to the wall of a passive solar house, the performances of different heat-collecting components were simulated using numerical analysis. For the direct gain of a passive solar house, the ratio of the south glass area to the wall should not be less than the ratio of the south glass area to the floor and not greater than the standard value [10]. According to the design specifications of primary and secondary schools, the ratio of the south glass area to the floor is not less than 1:5, the limiting value of the ratio of the south glass area to the wall in cold areas is 0.5, and the corresponding limiting value in severe cold areas is 0.45. Thus, in the new model, the ratio of the south glass area to the wall is between 0.3 and 0.5/0.45. The ratio of the south glass area to the wall is denoted Ag/Aw.

As shown in Figure 3, although the temperature fluctuations increase with the glass area, the overall temperature increases. For the direct-gain window design, the ratio of the glass area to the wall that corresponds to the maximum value should be met. Thus, a ratio of 0.5 in cold areas and a ratio of 0.45 in severe cold areas are chosen. The dimensions of the vent of the Trombe wall + direct-gain window design are set to 200 mm × 200 mm [11]. The limiting values of the ratio of the south glass area to the floor and the ratio of the south glass area to the wall must satisfy the requirements for the direct-gain window design.

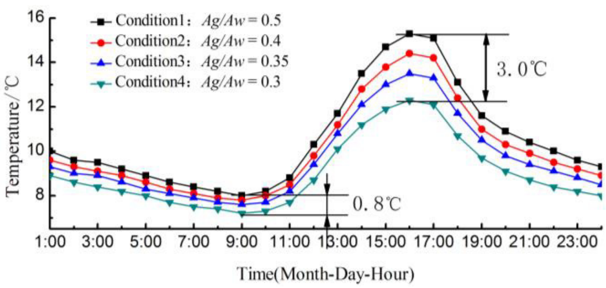

Fig. 3. Temperature difference corresponding to variable volume.

The temperature curves of the Trombe wall + direct-gain window passive solar house design with different ratios of the glass area to the wall are shown in Figure 4. The corresponding average temperatures of Conditions 1, 2, 3, and 4 are 12.8 ℃, 12.1 ℃, 12 ℃, and 11.8 ℃, respectively. With the decrease in the value of Ag/Aw, the temperature fluctuations over the entire day are reduced. The larger the glass area is, the greater the amplitude of the temperature fluctuations becomes, and the corresponding average indoor temperature increases. Thus, to determine whether a larger or smaller ratio should be selected, different demand situations must be further analyzed.

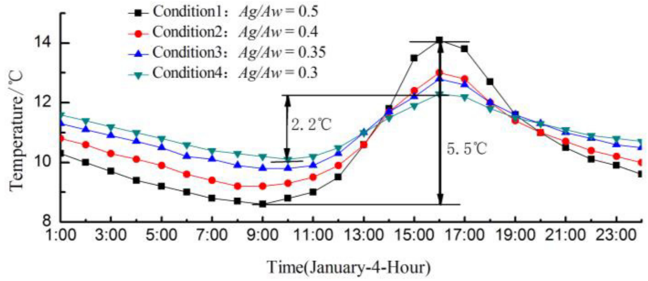

Fig. 4. The temperature curve of the Trombe wall+ direct-gain window passive solar house with different Ag/Aw.

For the attached sunspaces, the use of an all glass south wall is the best choice. Due to the amount of solar radiation received, the temperature of the room adjoining the attached sunspaces will increase the maximum temperature. By establishing a buffer between incident sunlight and each room, e.g., curtains, a larger loss at night will decrease to the minimum [12].

4. DISCUSSION

4.1. Analysis of typical zones

According to the indoor temperature, the thermal environment improved by different degrees for different types of passive solar houses. The area in the study was divided into four zones: most suitable area, more suitable area, less suitable area and unsuitable area. Take the most suitable area as example, the analysis in detail are as follows.

The outdoor average temperature of a typical day in Lhasa is -6.3 ℃. The temperature is lower than the local heating design temperature, which is set to 0.5 ℃. That is, the typical day is more reliable to use for calculations than any other day in winter. The lowest and highest temperatures occur in the morning at 8:00 and at 17:00 in the evening, with values of -13.3 ℃ and 0.3 ℃, respectively. Figure 5 shows that the temperature of Room 2 with the direct-gain window is below 14 ℃ from 4:00 to 12:00. The other rooms can satisfy the requirements for indoor heat at all other times. The temperature fluctuation of Room 2 with a direct-gain window is greater than any others. It is clear that the Trombe wall+ direct-gain window and attached sunspace design are superior to the direct-gain window design in this area, which experiences the highest solar radiation during the cold period, as observed for Lhasa.

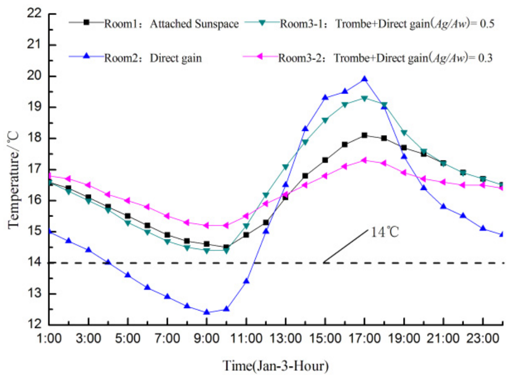

Fig. 5. The temperature curve of different passive solar houses in Lhasa.

Due to the buffer provided by the sunspace, the temperature fluctuation of the room adjoining the attached sunspace is reduced. As a result, the room does not overheat during the day and does not become too cold at night.

Compared to that of the other room types, the temperature fluctuation of the Trombe wall + direct-gain window is the smallest. As the ratio of the glass area to the wall decreases, the indoor temperature fluctuation decreases. Comparing Room 3-1 with Room 3-2 reveals that the latter exhibits a smaller fluctuation in temperature at low ratios. At such ratios, assuming the lighting requirement met, the south glass area should be reduced as much as possible.

As previously mentioned, any form of the passive solar house in this study can satisfy the demand patterns except for the direct-gain window design from 7:00 to 12:00, for which an auxiliary heat source is required. In most suitable area, Room 3-1 with the Trombe wall + direct-gain window design is recommended to have the ratio of the glass area to the wall of 0.5. During the daytime, the temperature for this design is only lower than that of the direct-gain window design. For Room 3-1 at night, the temperature is higher than that of any of the other types of rooms. The other types are available as alternatives to meet the established requirements.

4.2. Map of new classification zones

Figure 6 shows a map of the new classification zones. With the increase in latitude, i.e., moving along a northwest direction, the suitability of the passive solar house designs decreases in general. However, in the central and east areas, there is a slight difference in the suitability of the passive solar house designs, which may be due to topographical differences. However, topographical differences were not considered in this study; thus, further analysis is required.

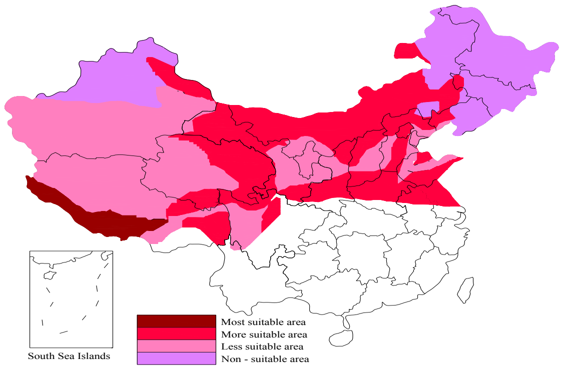

Fig. 6. The map of the different zones of suitability in China

4.3. The priority degree table

The priority degrees of different types of passive solar house designs under different operation modes in China are presented in Table 2. The selection order of the different house designs is also presented. The table should enable designers to clearly review pertinent information, thus providing an important reference for practical applications. Taking the more suitable area as an example, the preferred design for all-day use is the Trombe + direct-gain window design with a small Ag/Aw ratio. The optimal design for daytime use is the direct-gain window design. For nighttime use, priority is given to the attached sunspace design.

Table.2 The priority degree of different types of passive solar houses

Zone	Mode	AS	DG	T+D Ag/Aw=0.5	T+D Ag/Aw=0.3	District	Representative City
Most suitable	Mode1	B	D	C	A	Ⅰ-C	Lhasa、Alear
	Mode2	B	D	A	C		
	Mode3	B	D	A	C		

	Mode4	B	D	C	A		
More suitable	Mode1	B	D	C	A	III-C & II-SC	Beijing、Shijiazhuang 、Jinan、Lanzhou、Taiyuan、Tianjin、Xi'an、Zhengzhou & Altay、Dunhuang、Erenhot、Kumul、Great Harmony、Xi ning、Yi ning、Yushu、Hohhot、Nagchu
	Mode2	D	A	B	C		
	Mode3	D	A	B	C		
	Mode4	A	D	C	B		
Less suitable	Mode1	B	D	C	A	I-SC & II-C	Golmud &Ka shi、Kuqa、Turpan、Yinchuan、Lanzhou、Khotan、Korla、Kumul、Pingling
	Mode2	B	D	C	A		
	Mode3	B	D	C	A		
	Model4	B	D	C	A		
Un-suitable	Mode1	-	-	-	-	III-SC、IV-SC &IV-C	Chifeng 、Changchun、Harbin、Shenyang Heihe、Kiamusze、Mohe、Urumqi 、Yining、Tuscaloosa、Karamay、Hailar、Yanji、Dandong
	Mode2	-	-	-	-		
	Mode3	-	-	-	-		
	Mode4	-	-	-	-		

Notes: 1. AS = the room adjoining the attached sunspace, DG = the room with the direct-gain window passive solar house, T+D = the room with the Trombe wall+ direct-gain window passive solar house; Ag/Aw = the ratio of the glass area to the wall;

2. SC = severe cold, C = cold; Ⅰ, Ⅱ, Ⅲ, and Ⅳ represent the richest, rich, common, and poorest solar radiation resources.

3. A/B/C/D represent the priority degree. "A" is the first preferred choice, "B" is the second, "C" is the third, and "D" is the least.

5. Conclusion

The optimal ratio of the direct-gain window design was determined to be 0.45 in the severe cold area and 0.5 in the cold area. With respect to the indoor temperature, the thermal environment was improved in different degrees for the different types of passive solar house. The area in the study was divided into four zones: the most suitable area, the more suitable area, the less suitable area and the unsuitable area. A new map was produced for the different suitable zones in the severe cold and cold areas in China. A priority degree table was obtained for different types of passive solar house designs of different modes in China.

Acknowledgements

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