A Comparative Investigation on Sustainable Strategies of Vernacular Buildings and Modern Buildings in Southwest China

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ABSTRACT: Vernacular architecture results from long-term growth with strong regionalism and passive methods responding to climate. Its sustainable design strategies are widely recognized as passive and effective solutions to the field of building energy efficiency. This research is proposed to comparatively investigate sustainable design strategies and evaluate environmental performance of vernacular buildings and modern buildings in the South-west China. We conducted an in-depth field investigation including questionnaires on 50 selected traditional buildings and two series of continued measurements (on April and Auguest) on 6 selected representative buildings in Tongzi, Chongqing. This paper focuses on the comparative analysis of thermal performance in vernacular dwellings and modern dwellings. The results reveal that certain efficient and effective passive design strategies exist in the vernacular buildings in South-west area of China.
Keywords: vernacular architecture, sustainable design, comfortable indoor environment

INTRODUCTION

In China, the building energy consumption shares about 30-40% of the total national energy [1]. Moreover, because rural buildings in China are related to about 60% of the whole building area, rural buildings accounted for over 67% of total building final energy consumption [2][3]. Facing this fact, Chinese Ministry of Housing and Urban-Rural Development has already set a series of plans to promote energy efficient strategies for rural buildings, such as certain energy-saving materials implementation [4]. Because many rural consumers currently still have limited access to district heat and gas, and limited access to electric power [3], passive strategies in promoting energy-efficient rural buildings have become important in recent years.

By contrast, vernacular architecture is widely recognized as a passive and effective solution in the field of building energy efficiency. In China, many detailed studies have noted that Chinese vernacular buildings have valuable sustainable design strategies, such as Yaodong dwellings [5], and Kang system for heating [6]. Generally, vernacular architecture results from a long-term growth with strong regionalism and traditional culture. Therefore, how to design contemporary buildings with vernacular features has long been the challenge for architects in China. Furthermore, it will have more needs in current rapid construction development of China.

Facing the huge amount of energy consumption of Chinese rural buildings, and the challenges of vernacular architecture along with the rapid development, the long term goal of this research is to explore and integrate traditional passive strategies into the sustainable design of the contemporary rural buildings. Prior to turning to the design translation from vernacular to modern rural buildings, there is a great demand for fundamentally comparisons on sustainable design strategies used in vernacular buildings and modern buildings in terms of environmental performance (e.g. thermal quality).

Various climates in China drive an abundant variety of vernacular building styles. In this research, we selected Tongzi of Chongqing as a characteristic case with the Hot-summer and Cold-winter climate in Southwest area of China. The authors have conducted a number of investigations on vernacular buildings in Tongzi. This paper presents a qualitative and quantitative analysis on different envelope materials and roof strategies related to thermal performance in the selected vernacular buildings and contemporary buildings.

METHODS OF INVESTIGATION

The areas, buildings, and typologies

The investigation was conducted in Wulong, Chongqing from August of 2011 to April of 2012. The climate belongs to the Hot-summer and Cold-winter climate

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Zone of China, as it shown in figure 1. Among all current available buildings in this area, there are 20% timber dougong-through structure dwellings which are characteristic southwest vernacular architecture. This investigation selected totally 50 representative dwellings. All modern dwellings were made of concrete and built in recent years, and the vernacular dwellings were made of timber or stone and built in 100~300 years ago.

The method framework

For the whole research, to comprehensive test and review sustainable design strategies in this area, we combine surveys on social context information and scientific measurements on physical environments. Therefore, this study proposes a comprehensive approach for analysing and evaluating vernacular dwellings in China in term of building environmental performance. The process of this study can be divided into five subsequent steps as the following figure 2.

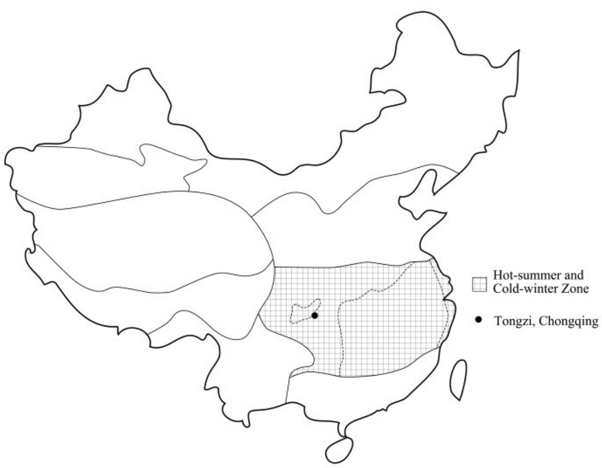

Figure 1: Climate zone of Tongzi in Chongqing

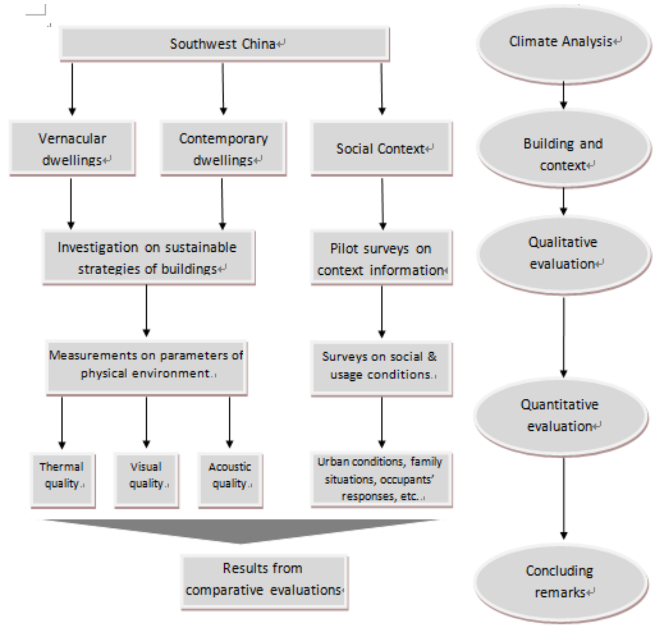

Figure 2: The framework for this investigation

INVESTIGATIONS AND MEASUREMENTS

Step 1 Climate zones and selected city's features

According to the Chinese Building Energy Code, the city, Tongzi, we selected, is located in the Hot-summer and Cold-winter Zone of China. It has a long and hot summer from June to September, and about 30^{o}C average temperature. On the other hand, the winter is from December to February, and the average low temperature in winter is around 6^{o}C. The figure 3 shows the monthly average temperature, solar radiation, and prevailing wind data of this selected city.

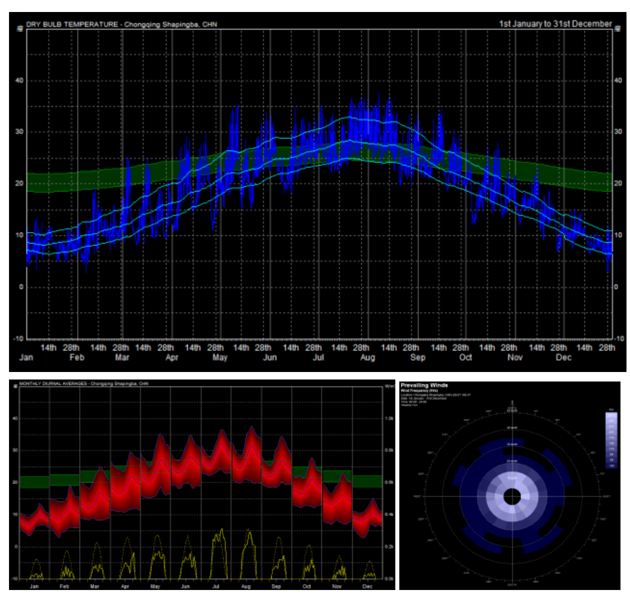

Figure 3: Climatic analysis on this city

Step 2 Building information

This study investigated 50 building cases among which two cases were built around the year of 1700. The figure 4 shows the year and the materials information of for these cases. The buildings' orientation and layout varied considerably. Generally, the building geometry is the L or the courtyard layout when they have only 1-2 storeys, and the building geometry with 3-6 storeys tends to the cubical type of layout.

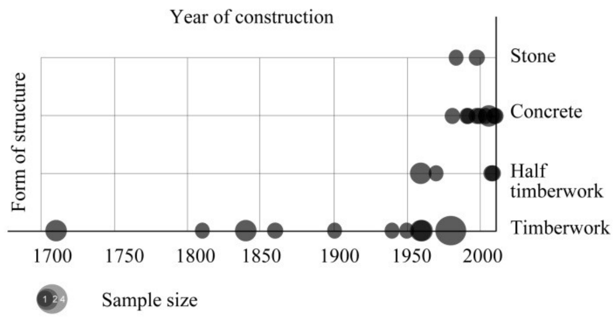

Figure 4: Completion year and materials of construction

The six typical buildings in which we conducted the measurements include one stonework house (two storeys built in 1960), two timberwork houses (one-storey house built in 1961 and two-storey house built in 1930), three concrete houses (two three-storeys houses built in 2000 and one one-storey house built in 2009). The purpose of this selection was to find the building performance and sustainable design strategies corresponding to different types of construction materials.

Step 3 Qualitative investigations on sustainable design strategies and context information

Based on our studies, there are 10 major categories related to sustainable design strategies used to examine the 50 selected cases. These categories embrace building orientation and geometry, construction type and materials properties, windows shading, natural ventilation, daylighting, earth cooling, passive solar energy, rainwater discharge, moisture prevention, and others. All these strategies were investigated, documented and analysed for the 50 building cases. For instance, table 1 shows the average values of those key material properties for all samples.

Table 1: key material properties of selected buildings

Material	ρ kg/m³	k* W/m²·K	c kg/m³·K
Concrete Hollow Brick	1380	0.51	1100
Stone	2810	3.50	2351
China fir	330	0.13	428
Tile	2400	1.30	1980

* K value is coefficient of heat transmission in Chinese building energy code

Step 4 Quantitative measurements

In order to have a more accurate assessment than the qualitative analysis, some field measurements were carried out on six representative buildings. All measurements were in relation to seven environmental indexes: outside air temperature, inside air temperature, outside relative humidity, inside relative humidity, outside wind velocity, outside illuminance level, and inside lighting level. This paper places more attention on thermal qualities of the rooms. The table 2 shows the instruments and the types used in the measurements. In each major room, we put thermometers at the 1.5m height level, and recorded the temperature for each 20 minutes for two periods of Aug. 23-27 in 2011 and Apr. 13-22 in 2012. The following figure 5 shows an example of distribution of test points in a room floor plan.

Table 2: instruments used in thermal quality measurements

Instrument	Model
Thermographic Camera	VarioCAM hr inspect
Thermograph Meter	WZY-1
Hygrothermograph Meter	WSZY-1
*PMV and PPDIndices Meter	AM-101PMV-PPD

Step 5 Results recorded

As we conducted the measurements on six buildings which have three types (timberwork, stone, and concrete), recorded results will be explained in this section on three aspects.

Figure 5: location of measurement sports in a room

1) Timberwork houses

During the period of August test on the wooden frame houses, the average outdoor air temperature was 22℃. The average indoor air temperature was around 21.9℃, and the maximum temperature was 4.5℃ lower than outside maximum temperature. The maximum outdoor temperature 29.5℃ happened at 16:00, and the indoor temperature was 25.5 ℃ at this time. The indoor maximum temperature was 25.8 ℃ at 16:40, thus the thermal delay was not obvious. 5:20 in the morning, the night minimum temperature of 17.55 ℃ indoor air temperature was about 1℃ higher than that in outdoor. During the period of April, the average outside air temperature was 12.5 ℃ , and the average indoor temperature was 11.4℃. The highest temperature 14.1℃ in April was at 14:40, the minimum temperature was 11 ℃ at 8:00. The indoor temperature was lower than the outdoor temperature was 0.5-2℃ almost throughout a day. The figure 6 shows the measurement points' records on each room for April and August. In addition, by using the Infrared Thermographic Camera, we recorded the south facade thermal radiation, as it shown in figure 7. The purpose of this measurement was to compare the thermal performance on each components of the building envelope.

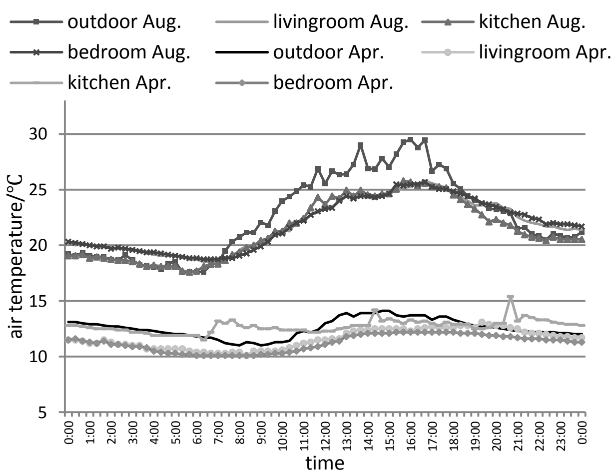

Figure 6: Indoor and outdoor air temperature of timberwork house (on typical days in August and April)

Figure 7: Infrared thermographs of timberwork house (from top to bottom:2011-8-26 10:30am /2012-4-13 15:20pm/ 2012-4-14 15:20pm)

2) Stone-envelope houses

During the test period of August on the stone-envelope houses, the average outdoor air temperature was 22.8℃. The maximum temperature was 30.1 ℃ , and the minimum one was 19.4 ℃ . The average indoor air temperature was 23.1℃ which was higher than outdoor air temperature.

The highest record 30.1℃ was at 13:20, and the indoor temperature was 25.5 ℃ at this time. The indoor maximum temperature was 25.8 ℃ at 16:20, thus the thermal delay was around 3 hours. The highest temperature difference was around 5.8℃. At 4:20 in the morning, the outdoor temperature dropped to 19.4℃, and the indoor air temperature was about 1.3-2℃ higher than that in outdoor. During the period of April, the average outside air temperature was 12.2℃, and the average indoor temperature was 12.3℃. The highest outdoor temperature 17.2℃ in April was at 16:00, the minimum outside temperature was 9.1 ℃ at 5:40. The temperature records can be found in figure 8.

Similarly, by using the Infrared Thermographic Camera, we recorded the south facade thermal radiation, as it shown in figure 9. The purpose of this measurement was to compare the thermal performance on each components of the building envelope. The lowest thermal radiation areas were located at the shadings and the wall bases.

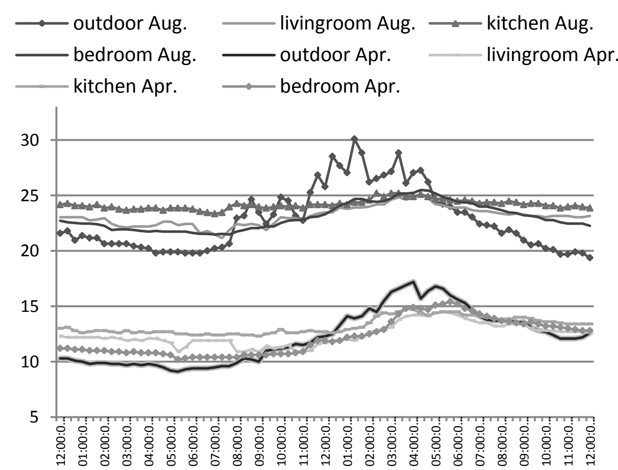

Figure 8: Indoor air temperature of stone house (on typical days in August and April)

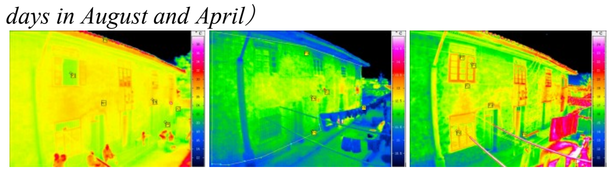

Figure 9: Infrared thermographs of stone house (from top to bottom:2011-8-26 11:00am /2012-4-13 15:40pm/ 2012-4-14 15:50pm)

3) Concrete houses

During the test period (August), the average outdoor air temperature surrounding the concrete houses was 22.6℃. The maximum temperature was 27.8℃, and minimum one was 23.2℃. The average indoor air temperature was 23.2℃ which was higher than outdoor air temperature. The average lowest indoor air temperature of bedrooms on the second floor was 22.3℃, and it was 4.2℃ higher than the minimum value of average outdoor air temperature. The highest outdoor air temperature of representative days in August was 27.8℃, and it was occurred at 16:20. At the same time, air temperature in the rooms at first floor was around 24℃, which was around 3-4℃ lower than outdoor air temperature. Major rooms achieve their highest air temperature at 16:40 with unobvious thermal delay. Outdoor temperature dropped to its lowest point at between 5:00 am and 6:00 am. Night indoor temperature was 4.2℃ higher than night outdoor temperature. The measurement records can be shown in figure 10.

During the April test period, the average outdoor air temperature was 13.4℃. The maximum value of it was16.2℃, and minimum value was 11.8℃. The average indoor air temperature was approximately 13.6℃. The highest outdoor air temperature of representative day in April was 16.2℃, and it was occurred at 15:20; the lowest outdoor temperature was 11.8℃ at 6:20am. During the representative day in April, indoor air temperature changes smoothly, e.g. diurnals of second floor bedrooms and living room are less than 1℃.

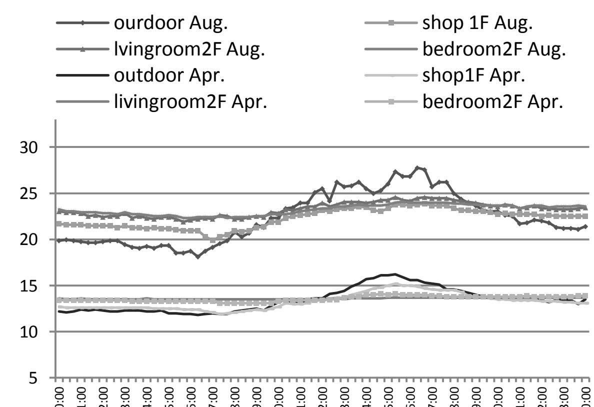

Figure 10: Indoor air temperature of concrete house (on typical days in August and April)

In addition to the temperature measurements, by using the Infrared Thermographic Camera, we recorded the south facade thermal radiation, as it shown in figure 11.

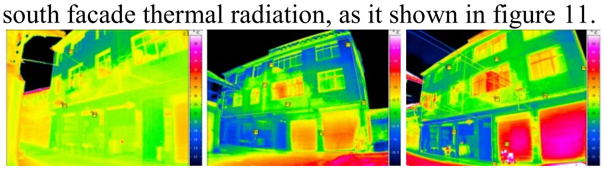

Figure 11: Infrared thermographs of concrete house (from top to bottom:2011-8-26 11:00am /2012-4-13 15:50pm/ 2012-4-14 15:50pm)

Step 5 Comparisons

To begin with, during the test period of August, the comparisons of three types of houses under similar outside climatic conditions shows (table 3): 1) the timberwork houses can provide lower indoor temperature at the night time because of thermal properties of timber. Also, the maximum indoor and outdoor temperature difference was around 4.5℃. 2) The stone-envelope houses had best thermal performance at the daytime, which had around 5.8℃ temperature difference between the indoor and outdoor conditions. However, those houses had average higher indoor temperature during the night. 3) The contemporary houses made of concrete materials have higher average temperature at the night and smaller outside and inside temperature difference (2.3℃) during the daytime.

Within the test period of April, the indoor temperature of the timberwork houses apparently followed the changes of the outside temperature, so the thermal performance is not better than other two types. In contrast, the store houses have the better indoor thermal conditions.

Table 3: Temperature comparison in the test period of August for three types of vernacular houses

AUG(℃)	Max	Min	Avg	DTR*
TIMBER				
Indoor	25.7	**18.6**	21.9	7.1
Outdoor	29.5	17.6	22.6	11.9
T_{out}-T_{in}	4.5	**-1.4**	0.7	5.9
STONE				
Indoor	25.3	21.4	23.1	3.9
Outdoor	30.1	19.4	22.8	10.7
T_{out}-T_{in}	**5.8**	-3.3	-0.3	9.1
CONCRETE				
Indoor	24.3	**22.1**	23.2	2.2
Outdoor	27.8	18.1	22.3	9.7
T_{out}-T_{in}	**3.5**	**-4.2**	-0.9	7.7

*DTR: diurnal temperature range

Table 4: Temperature comparison in the test period of April for three types of vernacular houses

APR(℃)	Max	Min	Avg	DTR
TIMBER				
Indoor	12.6	**10.1**	**11.4**	2.5
Outdoor	14.1	11	12.5	3.1
T_{out}-T_{in}	2.2	0.15	1.13	2.05
STONE				
Indoor	**14.9**	10.5	12.3	**4.3**
Outdoor	17.2	9.1	12.2	8.1
T_{out}-T_{in}	**2.95**	**-1.95**	-0.1	1.0
CONCRETE				
Indoor	13.9	13.3	**13.6**	0.6
Outdoor	16.2	11.8	13.4	4.4
T_{out}-T_{in}	2.3	-1.6	-0.2	3.9

Furthermore, the infrared thermographs can reveal the differences on facade thermal radiation with different materials. 1) The timberwork envelope had the highest rate of temperature increment because of deeper color and lower specific heat capacity of the envelopes, compared to other two types of envelopes. 2) The stone houses showed very uniform distribution of thermal radiation, and higher surface temperature during the sunset period. 3) The concrete houses had the lowest surface.

Table 5: The records of the infrared thermographs on 2011-8-26 10:00-11:00am. 2012-4-13 15:00-16:00pm, and 2012-4-14 15:00-16:00pm

(℃)	Avg.	Min	Max	DTR
AUG(Clear day)				
Timber	**26.51**	21.55	31.1	9.54
Stone1	25.45	22.73	30.06	**7.33**
Concrete	**23.88**	18.84	29.1	10.18
APR(Cloudy day)				
Timber	11.91	10.46	25.96	15.50
Stone	**12.09**	8.10	14.39	**6.29**
Concrete	11.64	5.07	13.68	8.30
APR(Clear day)				
Timber	16.89	13.38	31.28	17.90
Stone	**16.95**	12.89	21.91	**11.02**
Concrete	16.67	10.03	22.40	12.37

Lastly, timberwork and stone houses were built with certain traditional roof design strategies. The roof tiles were placed onto the rafters of the wood-frame roofs without any stuffing or adhesives. Thus, a certain range of air infiltration by this type of roof design facilitates heat exchange and air circulation. Comparatively, the concrete houses were built with water pool (300-400mm) roofs made of concrete, which is a normal design strategy in local modern dwellings. By using the infrared thermographic camera (figure 12 and figure 13), we recorded the inside surface temperature of the wooden frame roofs in the vernacular buildings, and found they can provide a comfortable thermal environment during August. Regarding the water pool roofs, they can reduce 1.2℃, compared to the regular flat concrete roofs. Also, as it shown in figure 14, the space under the water pool roofs had more stable thermal conditions.

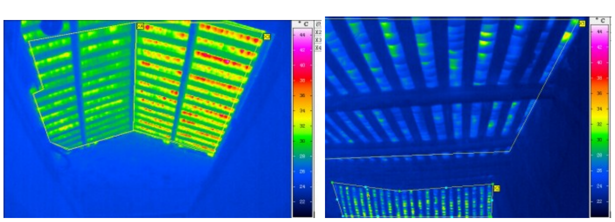

Figure 12: Infrared thermographs of the wood-frame roofs

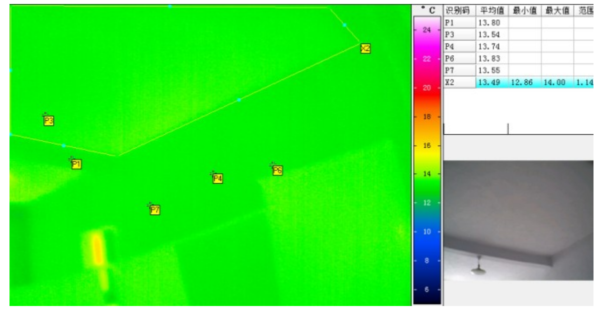

Figure 13: Infrared thermographs of the water pool roofs

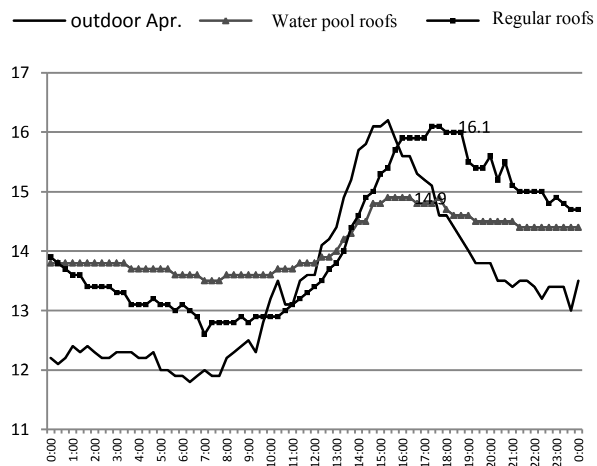

Figure 14: The indoor temperature in the space under the water-pool roofs and the regular roofs.

CONCLUSION

The investigation and measurements have attempted a comparative analysis of thermal performance of vernacular and contemporary buildings in the southwest of China by two series of continuously monitoring the thermal quality parameters in the selected buildings.

It was found that, during the summer, the timberwork envelopes and roofs of vernacular buildings in this area may facilitate air circulation and comfort indoor thermal quality at the night time. However, the measurement results from the period of April reveal that this type of envelope can't provide comfort thermal quality without other heating solutions. The stone type of envelope in the vernacular dwellings may obtain better indoor thermal comfort when outside temperature was low. Nonetheless, the stone houses may have problems during the summer but still better than the concrete houses in terms of the indoor thermal performance. Time lag between outdoor and indoor temperature, the wooden envelope houses and the concrete houses are negligible while that in the stone and the concrete houses are over 3 hours. In addition, the water pool roofs in the modern houses may enhance the thermal comfort levels. Comparatively, the wood-frame roofs may achieve better thermal performance during the summer.

Not only the investigations on thermal performance, we also conducted measurements on daylighting and acoustic parameters of the selected vernacular buildings and modern buildings. In this paper, it can thus be concluded that the vernacular houses of Tongzi have certain effective passive sustainable design strategies related to wood-frame roofs, store materials and others. However, they still need to get some development and new utilizations since these strategies also some negative performance in some conditions. In future, we will continue to work on the comparative studies about sustainable design and technologies.

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