A comparative case study of volcanic-rock vernacular dwelling and modern dwelling in terms of thermal performance and climate responsive design strategies in Hainan Island

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ABSTRACT
The volcanic-rock dwellings are a special kind of traditional vernacular architecture with high value of research, which located in the north of the Hainan Island in China. In order to clarify the thermal mechanism differences between volcanic-rock dwellings and modern dwellings in Haikou, the main factors affecting the thermal comfort of dwellings are analyzed through investigations of indoor thermal environment in the Yangshan lava area of Haikou. The results show that the volcanic-rock dwelling can achieve 10 h (from 23:30 to 9:30 the next day) with air temperature under 28.7°C in a comfortable thermal indoor environment without air-conditioning cooling equipment, while the rooms on the ground floor of modern dwelling can achieve 1 h around sunrise, and the room on the top floor is completely outside the thermal comfort zone. Temperature difference between exterior and interior of volcanic-rock wall and wooden window can reach a maximum of 6.7°C and 2.8°C respectively, which shows that the envelope of volcanic-rock dwelling has a good thermal insulation performance. It is necessary to inherit the space prototypes and climate-adaptive strategies of traditional residential buildings when designing a new building, which play a significant role on providing a comfortable indoor thermal environment.

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1. Introduction
Vernacular architecture is referred to use locally available resources to address the local needs of construction (Coch 1998). Most of the vernacular buildings are well preserved in the underdeveloped rural areas (Ministry of Housing and Urban-Rural Development of the People’s Republic of China (MOHURD) 2005). As limited resources and fewer technologies available in the old days, vernacular dwellings are mainly designed to optimize the use of natural resources like the sun and wind (Shanthi Priya et al. 2012; Dili, Naseer, and Varghese 2010). Vernacular dwellings consider the climate, economic, religious beliefs, national culture, and process great value under trial and error for thousands of years (Oliver 1997). It is necessary to thoroughly understand and reflect on the climate-responsive strategies, which is the key to optimizing the indoor thermal performance of residential buildings.

A literature review revealed that some researchers (Philokyprou et al. 2017; Bodach, Lang, and Hamhaber 2014) have conducted field studies on the environmentally responsive design strategies applied in the vernacular dwellings in different climatic regions. There are completely comprehensive researches on the comparative assessment of passive design techniques of vernacular dwellings (Upadhyay, Yoshida, and...
Rijal 2006; Fernandes et al. 2019). These studies focus on the sub-regional research, and only carry out qualitative research on traditional dwellings.

Previous studies (Widera 2021) identify different kinds of vernacular dwellings and establish the baselines for affordable housing model. Some researchers (Ank-Tuan et al. 2011; Mohammadi et al. 2018) propose a new research methodology to describe the complex relationship in terms of climate. Few authors (Anna-Maria 2009; Saljoughinejad and Sharifabad 2015) evaluate specific vernacular dwelling types and their response to climate, based on passive design principles and classify climatic strategies into different levels of space. Several studies (Chyee Toe and Kubota 2015; Dili, Naseer, and Zacharia Varghese 2010) have examined the various passive cooling and heating design techniques inherent in the conception of vernacular dwellings can result in significantly improved thermal comfort conditions, which (Oikonomou and Bougiatioti 2011) also made analysis of the architectural aspects concerns the building typology, the form, the materials and the construction techniques.

Some researches (Jayasudha et al. 2014; Idham 2018) have identified the natural and social sustainable principles in traditional and vernacular architecture. These studies exist in different countries and regions especially for a particular typology and research region. There is a limitation study on comparison thermal performance and climate responsive strategies between volcanic stone dwellings and modern dwellings in Hainan region.

Few studies (Du, Bokel, and van den Dobbelsteen 2016; Lin and Juan 2018) have compared vernacular architecture and modern dwellings in regard to climate responsiveness. But it is more inclined to a certain level of the building. Some detailed studies (Lin and Juan 2018; Ying and Yongping 2013) in China have shown that volcanic-rock vernacular architecture is multiform and valuable. The above researches are only from the qualitative aspect, lack of measured data as support. Other research (Gui 2015) focus on the appropriate renovation strategies of traditional vernacular houses and new design. Yet, the previous studies on volcanic-rock dwellings have some limitations for only qualitative description without investigation measurement for evidence. There are rarely specific comparative studies on volcanic-rock dwellings and modern dwellings under free running conditions in Hainan Island.

The literature review demonstrate that comprehensive quantitative and qualitative of thermal performance and climate responsive strategies applied in vernacular dwellings in Hainan region have never been carried out so far. In this paper, the authors first clarify the geography and climate in the research area which is located in the southwest of Haikou. Next, the authors discuss the field measurements conducted to investigate the thermal performance in a traditional volcanic-rock dwelling and a modern dwelling which are nearby in the same village. These two houses are free-running, situated in a hot and humid climate region of China, including of multiple spaces. The results of measurements were compared with air temperature and relative humidity. Also surface temperature of the eastern wall and window, and air velocity were analyzed in the typical volcanic-rock dwelling. The authors expect their findings to contribute to more comfortable and more energy-efficient buildings using climate responsive design strategies in hot and humid climate. The advantages and disadvantages of two kinds of buildings were thoroughly investigated, with the aim to effectively explore their positive attributes for current building developments.

2. Research region

Yangshan lava area is located in the north of Hainan Island, which is refers to the southwest of Haikou volcanic lava area (19°45’33.6″N-19°58’48.95″N, 110°14’19.76″E~110°24’41.72″E), as shown in Figure 1. It covers an area of about 1000 km², with a population of more than 300,000. Shishan Town and Yongxing Town are the main hinterland of volcanic ancient villages in this area.

2.1. Geographic analysis

Hundreds of millions of years ago, volcanic eruption and underground lava eruption overflowed, forming high and low rolling hills in the northern part of Hainan Island. The
ground surface of this area is covered with volcanic rocks. Several dormant volcanoes erupted ten thousand years ago surrounding thousands of miles of wild trees and luxuriant vegetation in the area, which gave birth to the distinctive traditional volcanic-rock ancient villages. The distribution of villages and craters are shown in Figure 2, which formed the unique geological features of the landscape.

There are a number of volcanic communities distributed in Yangshan lava area, Haikou city. The volcanic-rock ancient villages are adjacent to the crater, and the geological distribution is mainly basalt. Due to the abundant volcanic rock materials, the construction materials of local traditional dwellings are mainly by volcanic rocks, which are the local materials, taking measures according to local conditions.

2.2. Climate data

Hainan island is situated at the low-latitude tropical northern edge. The island belongs to the hot summer and warm winter climate zone, according to China's National Standard of Climatic Regionalization for Architecture (GB50176-2016) (China National Standard (GB50176-2016) 2016). Yangshan lava area is located in the southwest of Haikou, a city in the north of Hainan Island, the climate data of Haikou is used as the typical climate data for climate analysis. In this region, the year is divided into hot and warm seasons in this region. As shown in Figure 3, in the hot season, the highest average temperature is about 28°C, with more precipitation; in the warm season (from December to February), the average temperature is about 18°C. The annual average temperature is 24.4°C, the mean outdoor air temperature of the hottest month (July) and the coldest month (January) is respectively 28.8°C and 18.0°C (Haikou Meteorological Information Sharing Service System 2005). There is no cold weather all the year, and the thermal comfort zone is rarely small. In other words, the climate in Haikou is characterized by high temperature and humidity throughout the year with abundant rainfall in summer, and frequent tropical storms during summer and autumn periods.

3. Climate-responsive strategies of volcanic-rock vernacular dwellings

3.1. Description of studied case

The field measurements were proceeded in Yangshan lava area. The studied cases are split into two different types. One is volcanic-rock dwelling built approximately one hundred years ago, which is the typical vernacular...
dwelling in the north of the Hainan Island. The other is modern dwelling constructed recent years, which is extensively built in the same district as a comparative case.

3.2. Settlement pattern and layout: adapting to geography and climate

The terrain of volcanic-rock settlement has a certain slope (Dinghai 2009). Since the surface of the Yangshan lava area is full of volcanic rocks, artificially ponds are excavated in low-lying areas (Dinghai 2013). Low-lying land and pond can alleviate the local hot and humid climate, which contribute to solve the problems of ventilation, cooling and drainage (Dinghai 2013). The axis-aligned settlement pattern is beneficial to get a cross wind pass through the building. During the day time, the land heats up faster than pond. So the wind blows from pond to the land. On the contrary, when the temperature is lowered at night, the wind flows from land to the pond.

As shown in Figure 4, Fengtang Village has an artificial water pond with an area of more than 3000 m² on the east side. The village buildings are composed of volcanic houses and modern brick-concrete houses. According to the size of the family population and economic strength, the size of the built volcanic-rock dwellings also varies. For the population and economic strength of different family, the number and scale of the built volcanic-rock dwellings also varies. Some families own only 1–2 courtyards, and some can reach the number of 4–6, as shown in Figure 4. The houses constructed after the already-built houses will be distributed longitudinally along the axis of the already-built house, or will develop laterally along both sides of the completed houses, forming a multi-axis layout side by side. Therefore, the volcanic houses in the entire village are aligned in the center hall from the front to back, with the pond as the center, and a long series of repeating radial settlements facing the pond, arranged from east to west as a whole and compact, forming a courtyard space.

The newly built modern dwellings are scattered in different parts of the village. The orientation and arrangement of modern dwellings designed by villagers themselves without any regular pattern, and they are constructed according to the individual preferences of themselves. Although the residents of modern houses retain some rural traditions, the lifestyle is close to that of modern life. The spaces of modern houses include living room, bedroom, kitchen, and bathroom. The family is composed of a small unit of the family population. Generally, it consists of 1–2 generations of 3–6 people per family. Modern dwellings are built without logical relationship with the surrounding already-built buildings. The settlement pattern and layout are completely different from the traditional volcanic-rock dwelling.

3.3. Spatial design of the volcanic-rock dwelling: diverse space configuration for natural ventilation and air circulation

Figure 5 shows that the indoor space of the volcanic-rock dwelling is composed of the living room (central hall) and four bedrooms, two on each side. The living
The living room is a variable and changeable space in the building. During daytime, the front and rear doors of living room are open for people to stay in or walk through, and the windows above the doors approach to the roof and are hollowed out all the time. At this time, the space becomes a semi-open space, which is a type of space with a semi-enclosed wall or roof, also called "gray" space or "buffer" space in architectural design. The residents have higher neutral temperatures in semi-open spaces than indoor spaces (Rijal, Yoshida, and Umemiya 2010). The wind passes through the living room during the daytime, for the doors and windows are all open, and the maximum velocity of the airflow in the living room can reach 0.42 m/s on the test day. When they fall asleep at night, the front and rear doors are closed, and then the living room changes into closed indoor space but keep air flowing. Night ventilation is the most effective strategy for passive cooling in vernacular dwellings during the hot summer period (Michael, Demosthenous, and Philokyprou 2017). The airflow enters the living room through the leak window above the door, which can reduce the indoor temperature at night. The bedrooms are located on both sides of the living room, with wooden walls between two bedrooms. The wooden partition wall is open overhead so that air can flow smoothly from one bedroom to the other. Some wooden walls between the living room and bedrooms also have a group of holes above so that the air can flow from living room to bedrooms.

Outdoor space Courtyards, patios and gardens are the main components of outdoor space in volcanic-rock houses. Some courtyards are enclosed by the stone wall. Most of them are surrounded by the main house and auxiliary houses, and there is a walkway between them for wind easily passing through. The space scale of the courtyard is uniform and stable, for the ratio of distance to height is between 0.8 and 1.2 (Yoshinobu-ashihara 2017).

In the modern dwellings, the indoor spaces are divided into separate space without any holes on the wall. The room layout is irregular. Semi-outdoor spaces mostly split into two types: one is an outside veranda, which was set at the entrance; the other is a balcony, which is usually set at the second floor. The depth varied from 1.2 m to 1.8 m. There are rarely courtyards or patios in the modern dwellings.

3.4. Double-layer building structure: adapting to high density of typhoon weather and rainy climate

The structure of volcanic-rock dwellings makes full use of the compressive properties of stone and the tensile properties of wood to form a unique structure constructed by the outer volcanic stone walls and the inner wooden frames, as shown in Figure 6.

Due to the large amount of volcanic rocks in this area, the external walls of the volcanic-rock dwellings are completely taken from the local materials, and the thickness of the wall is approximately 400 mm. The walls rely on stones built up one by one, without any adhesive, and keep stable. In order to strengthen the wall and resist the typhoon, the volcanic stone is built with horizontal and vertical overlapping masonry at the corners of the wall. The thermal conductivity of the stone wall is 0.326 W/(m·k), which has a good thermal insulation performance. The stone walls also have good rain and moisture-resistant properties.
resistance (Xiong 2011). Therefore, even if the eaves are short, it will not affect the performance of the wall.

The inside wooden frame is the other main load-bearing support system. The diameter of the column of the wood-frame structure is approximately 200–400 mm. There is a layer of stone about 200 mm high at the bottom of the wooden frame. This kind of structural wood and stone helps to enhance the stability of the main structure, and the stone pillar foundation plays an important role in moisture and corrosion resistance. The wooden walls on both sides of the living room adopt beam-lifted frame construction, which is one of China’s three major traditional wooden structural forms (Dunzhen 2019). The wooden beams and columns are connected by mortise and tenon, which is cut out of different forms of notches. The wooden structure is exposed for convenient maintenance.

The modern houses generally adopt brick and concrete structure. This type of building has the disadvantages of poor seismic performance, wet operation, etc., but for the reason of convenient material and low cost, it is widely used in low-rise civil buildings in villages.

3.5. Building material and envelope: heat insulation and shading avoiding excessive solar radiation

The envelope of traditional dwellings employing local and natural materials are used to alleviate inconvenient transportation and economic constraints before (Jiaping, Liang, and Shijun 2019). These materials include volcanic stone, dried wood and clay tile. Volcanic stone is the main materials of external walls and floors. Compared with the material bricks and concrete used in the modern houses, the volcanic stone take advantage of thermal conductivity, hard texture, moisture-proof, noise reduction, refrain from glare. etc. The interior wall and beam used local pine-apple wood material which possess performance of hard, natural antisepsis, stable and durable. Thermal properties of materials were shown in Table 1. The envelope of the roof consists of purlines, rafters and clay tiles. Purlines and rafters also use the wood material, while Clay tiles are made of mud, clam shell debris, sand, soil, etc. Unlike traditional dwellings in other areas, the tiles spread over rafters instead of board, as shown in Figure 6. The main reason for this is the indoor air can flow outside through the space among tiles (Xiong 2011). The two adjacent tiles overlap to form the thickness of two layers for good heat insulation performance on the top of the building. Near the cornice, volcanic slates are pressed to prevent the roof from overturning when typhoon strikes. All the windows and doors are made of wood. The window of bedroom is composed of two layers without glazing. The outer is a hollow one and the inner is a wooden board. The windows on both sides and the hollow partition wall above the middle ensure natural ventilation in the bedroom (Guanyu and Jing 2019).

4. Test method

4.1. Description of tested building

In this paper, a volcanic-rock dwelling and a recently built modern dwelling in a same village named Fengtang village are chosen for detailed comparison to achieve the object of climatic-responsive strategies research. The village is located in the center of Yangshan lava area is quite representative, as shown in Figures 1 and 4.

Feng’s houses are traditional volcanic-rock dwellings in Fengtang Village, Yangshan lava area. The
Table 1. Description of the case study: volcanic-rock dwelling and modern dwelling.

| General overview | Location | Climate region |
|------------------|----------|----------------|
| Completed year   | 1900s    | The hot summer and warm winter area in Hainan Island |
| Climate region   | 2015     |                |

**Volcanic-rock dwelling**

- **Location**: Fengtang village, Haikou (shown in Figure 1)
- **General overview**: Completed year 1900s
- **Climate region**: The hot summer and warm winter area in Hainan Island

**Modern dwelling**

- **Completed year**: 2015

**Site Layout pattern**

**Appearance**

**Aerial view of model**

(Continued)
|                | Volcanic-rock dwelling | Modern dwelling |
|----------------|------------------------|----------------|
| **Space**      | Semi-open space        | Semi-open space |
| **Living room/Center hall** (depends on center doors opening and closing) | **Inner space arrangement** | Symmetric layout of bedrooms on both sides of the living room |
| **Construction** | Beam-lifting timber frame, and volcanic-rock wall bearing structure | Building construction Beam-lifting timber frame, and volcanic-rock wall bearing structure |
| **Wall Exterior wall** | Volcanic stone | Brick and Concrete Structure |
| **Wall Exterior wall Material** | Brick and Concrete Structure | Brick and Concrete Structure |
| **Wall Exterior wall Thickness** | Brick 240 mm; cement mortar 15 mm | Brick 240 mm; cement mortar 15 mm; plaster |
| **Wall Exterior wall Thermal conductivity [W/m · K]** | 0.326 | 0.76 |
| **Interior wall Material** | Wood | Brick wall with cement mortar |
| **Interior wall Thickness** | W1:40 mm; W2: 25 mm, hollow above 2.4 m | Brick 240 mm; cement mortar 15 mm; plaster |
| **Roof Type** | Pitched roof | Flat roof |
| **Roof Material** | Wood and clay tile | Reinforced concrete |
| **Dimension** | Wooden purline: diameter of 150 mm; wooden rafter: 80 mm width, 10 mm thickness; plate tile: 200 mm width, 10 mm thickness, double-layer; tube tile: 130 mm length, 90 mm width; 7 mm thickness | 120 mm thickness |
| **Door Material** | Wood | Aluminum alloy single-layer glass |
| **Door Size** | 1.4 m width, 2.4 m height with 200 mm high volcanic stone threshold and hollowed upper part to the roof | 1.5 m width, 2.7 m height |
| **Window Material** | Wood | Aluminum alloy single-layer glass window |
| **Window Size** | 300 mm*300 mm | 1500 mm*1600 mm |
| **Window Form** | Two layers: outside grille, inside board | Sliding window |
| **Floor Indoor floor material** | Volcanic stone with cement mortar | Cement mortar with ceramic tile surface |
| **Floor Outdoor floor material** | Volcanic stone | Cement mortar |
entire courtyard of the Feng’s houses consists of five main buildings, and the tested house is the second one, with auxiliary house arranged on the side, as shown in Figure 4. It is a typical volcanic-rock dwelling built more than one hundred years ago. It extends along the terrain, facing the low ground and water, as shown in Table 1.

The tested modern dwelling is a typical new rural house built and designed by farmers themselves, 54 meters away from the tested traditional volcanic-rock dwelling. It is a semi-detached townhouse with three units built in June 2015, living three consanguinity families, respectively. It faces south, two floors, constructed with brick and concrete, facing the main road of the village.

4.2. Data acquisition

In order to acquire the indoor thermal environment of two different types of houses, an in-situ survey and
measurement was carried out in the two buildings mentioned above. The test parameters of the volcanic-rock dwelling include air temperature, relative humidity, wind velocity, and the surface temperature of walls and windows; the test parameters of the modern dwelling include air temperature, relative humidity; and the test parameters of the outside environment include air temperature, relative humidity, air velocity and solar radiation intensity. All the tested rooms are in a natural operating condition without mechanical cooling (no active systems like A/C, fans, coolers, etc. were operated) during the period of investigation. The windows of modern housing and vernacular building are both opened during the measurement. The

Figure 9. Solar radiation in different planes.

Table 2. Parameters of test instruments.

| Test instrument               | Type                  | Test parameters       | Range              | Accuracy          |
|------------------------------|-----------------------|-----------------------|--------------------|-------------------|
| Thermometer and hydrometer   | HOBO (UX100-003)      | Air temperature       | −20°C to 70°C      | ±0.2 °C           |
|                              |                       | Relative humidity     | 15% to 95%RH       | ±3.5%RH           |
| Thermometer                  | RH-4HC                | Air temperature       | −30°C to 60°C      | ±0.2 °C           |
|                              |                       | Relative humidity     | 0 to 93%RH         | ±0.3%RH           |
| Thermometer                  | Testo 830-T2          | Wall and window surface temperature | −30°C to 400°C | ±1.5°C |
| Anemometer                   | CENTER-309            | Wind velocity         | −50°C to 280°C     | ±0.3 m/s          |
| Solar radiometer             | JTR 05                | Solar radiation       | 0−2000 W/m²        | ±2%               |

Figure 10. Comparisons of the air temperatures of volcanic-rock dwelling and modern dwelling over time.
instruments are arranged at height of 1.1 m from the finished floor as recommended by China National Standard (China National Standard (GB/T50785-2012) 2012) and ISO 7726 (International Organization for Standardization 1998). The test points of solar radiation intensity are arranged on the terrace and outdoor without shelter. The test period of the two dwellings is over 48 h for accurate assessment on typical summer days (from 28/07/2019 to 31/07/2019). The bedrooms and living rooms of the volcanic-rock dwelling and modern dwelling, which have the highest frequency of use in the daytime, are used to analyze the thermal comfort.

Figures 7 and 8 show the layout and test points, and Table 2 shows the parameters and models of the test instruments.

4.3. Evaluation criteria for thermal comfort

Current comfort standards (Rijal, Yoshida, and Umemiya 2010; International Organization for Standardization 2005) have developed adaptive thermal comfort models. Previous research considering adaptive thermal comfort to be related to outdoor temperature have proposed an adaptive comfort model for naturally ventilated buildings (Li et al. 2018; De Dear and Brager 2002).

The subjects in hot-humid area of China are more acclimated and tolerable with hot and humid environments and more uncomfortable and intolerable with cold environments while compared with those in temperate climates. Based on the research (Zhang et al. 2010) of naturally ventilated buildings in hot-humid area of China, the 80% acceptable thermal comfort range from 22.1°C to 28.7°C, which is the benchmark in the study.

5. Analysis of thermal conditions in summer

5.1. Solar radiation

Solar radiation was tested from 06:30 to 19:00 on the two days of 29/07/2019 and 30/07/2019, data were recorded manually every half an hour, including total radiation, scattered radiation, and different directions of the east, west, south, and north at the same time.

Sunny days occurred with clouds and thunderstorms are typical weathers of Haikou in summer. Figure 9 shows that the local solar radiation is significantly affected by changing weather conditions. There was a short-term heavy rain between 13:00 and 15:00 on the 29th and little rain at the time of 9:30 to 11:00 on the 30th; and there was a thick cloud cover at 12:00 pm and 14:30 pm on 30th. During this period, the total amount of solar radiation in the horizontal plane and vertical planes in all directions plummeted and changed significantly.

Compared with the average value of radiation in the vertical planes on different directions, about 100–140 W/m², the average value of the total radiation in the horizontal plane can reach 293 W/m², and the maximum value was 1128 W/m² at 11:30am on 29th. Due to the high solar altitude angle in summer and the low latitude of Hainan, the solar radiation intensity in the south vertical plane is not higher than other directions, so the four vertical planes of the building envelope should be balanced to consider the building insulation.

5.2. Air temperature

Figure 10 shows the indoor and outdoor air temperatures of the volcanic-rock dwelling and modern dwelling from 20:00 on 28/07/2019 to 11:00 on 31/07/2019. During the two days, the average outdoor temperature is 27.9°C. The period of low temperature appeared between 2:00 and 6:00 in the morning, and the lowest temperature is 25.1°C. The period of high temperature appears between 13:00 and 15:00, while the highest temperature is 34.0 °C. It is raining on the afternoon of July 29th from 13:00 to 15:00 and on July 30th from 9:30 to 11:00. The outdoor temperature drops drastically with the occurrence of rainfall, and the indoor temperature fluctuates accordingly.

Comparing the air temperature of the two types of dwellings, the results show that the average indoor air temperature of the 2nd floor bedroom in the modern dwelling is 31.3°C, which is the highest one in the tested rooms, and it is 2.4°C higher than the bedroom of volcanic-rock dwelling. The average air temperature of the 1st floor bedroom in the modern dwelling is

| Location       | 1st floor Living room | 1st floor Bedroom | 2nd floor Living room | 2nd floor Bedroom | Out-door |
|----------------|-----------------------|-------------------|------------------------|-------------------|----------|
| Max (°C)       | 32.3                  | 31.9              | 32.9                   | 34.0              |          |
| Min (°C)       | 28.4                  | 28.6              | 29.5                   | 25.1              |          |
| Average (°C)   | 29.8                  | 30.0              | 31.3                   | 27.9              |          |
| Fluctuation range (°C) | 3.4 | 3.4             | 3.4                    | 8.9               |          |

Table 3. Air temperature ranges at different locations.
Figure 11. Surface temperatures of the eastern exterior wall and the wooden window vs. time – volcanic-rock dwelling.

Figure 12. Wind velocity vs. time – volcanic-rock dwelling.

Table 4. Surface temperature and air temperature data at different locations of volcanic-rock dwellings.

| Location             | Test parameters              | Max (°C) | Min (°C) | Mean (°C) | Fluctuation range (°C) |
|----------------------|------------------------------|----------|----------|-----------|------------------------|
| Eastern volcanic-rock wall | Exterior surface temperature | 40.5     | 28       | 32.2      | 12.5                   |
|                      | Interior surface temperature | 35.7     | 28.3     | 31.5      | 7.4                    |
|                      | surface temperature D-value  | 6.7      | −1.5     | 0.6       | 8.2                    |
| Eastern wooden window | Exterior surface temperature | 37.7     | 27.3     | 30.4      | 10.4                   |
|                      | Interior surface temperature | 35.2     | 27.6     | 30.7      | 7.6                    |
|                      | surface temperature D-value  | 2.8      | −2.4     | −0.3      | 5.2                    |
| Bedroom              | Air temperature              | 31.6     | 27.0     | 28.9      | 4.6                    |
| Outdoor              | Air temperature              | 34.0     | 25.8     | 28.4      | 8.2                    |
30.0°C, 1.1°C higher than that of volcanic-rock dwelling, as shown in Table 3.

It is clear that the maximum and minimum of indoor air temperature appears approximately one hour later than that of the outdoor. It is observed that, when the minimum temperature recorded in the bedrooms of modern dwelling on 2nd floor is 0.9°C higher than the 1st floor and 2.5°C higher than the traditional one, the maximum temperature of the 2nd floor bedroom in modern dwelling can reach to 32.9°C, higher than traditional by about 1.3°C, and 4.2°C higher than the upper limit of the 80% acceptable temperatures. As shown in green shaded area, there are 10 h with temperatures below 28.7°C from 23:30 to 9:30 the next day in the traditional volcanic-rock dwelling, which is within the range of thermal comfort on the second and third day. Comparing the traditional dwelling, the time below 28.7°C of the rooms on the 1st floor of modern dwelling is only 1 h around the time of sunrise, while the bedroom on the 2nd floor completely beyond the 80% acceptable thermal comfort range. Overall, the thermal environment in the volcanic-rock dwelling is better than modern dwelling.

Indoor temperature fluctuations are affected by changes of outdoor temperature. The diurnal variations of outdoor, living room and bedroom air temperature corresponding to volcanic-rock dwelling and modern dwelling are also shown in Figure 10. From this figure, it can also be observed that the fluctuation range of the bedroom on the 1st floor of modern dwelling is identical with the bedroom of 2nd floor, which is lower compared to that of outdoor and the rooms in volcanic-rock dwelling diurnal variation. The fluctuation range of outdoor air temperature is up to 8.9°C, while the volcanic-rock dwelling bedroom is 4.6°C, and the living room of volcanic-rock dwelling is 5.5°C.

5.3. Surface temperature of the wall and window

Figure 11 shows the variations in the surface temperature of the volcanic-rock eastern wall and wooden window and the outdoor air temperature from 20:00 on 28/07/2019 to 11:00 on 31/07/2019. The interior and exterior test points of the window and wall on the east side of bedroom are shown on the Figure 7(a) without shelter during the test period. Table 4 presents the surface temperatures of the volcanic-rock wall and wooden windows and the air temperatures of bedroom and outdoor.

Due to the change of the solar radiation and air temperature, the exterior surface temperature of volcanic-rock wall reached a maximum of 40.5°C, while the exterior surface temperature of wooden window reached a maximum of 37.7°C during 12:00–12:30 at noon. The temperature of the interior surface temperature of the wall and window reached the maximum of 35.7°C and 35.2°C, respectively, at 13:00, lower than the exterior one. It shows that the surface temperature variation regularly with time is related to the change in solar radiation and air temperature.

![Figure 13](image)

**Figure 13.** Correlation between outdoor air temperature and indoor air temperature across tested rooms.
of outdoor thermal environment. In addition, the peak time of the interior surface is delayed by about 1 h compared to the exterior surface.

The exterior surface temperatures of the wall and window fluctuate by over 10°C due to the changes of the outdoor air temperature. Compared with the exterior surface temperature of the bedroom volcanic-rock wall and wooden window, those of the inner surface temperature have very limited variations, which is 7.4°C and 7.6°C respectively, less than the externals. The surface temperature D-value (difference between exterior surface temperature and interior surface temperature at the same time) of volcanic-rock wall reached the maximum of 6.7°C, while that of wooden window get to 2.8°C. It is indicated that the volcanic-rock wall and wooden window has good thermal inertia and thus great significance for maintaining a relatively stable indoor air temperature. This result also indicates that both volcanic-rock wall and wooden window are suitable as the exterior envelop of dwellings. Because they can resist the heat transfer from the outside and keep a stable indoor thermal environment.

In addition, the temperature of the inner and outer walls changes regularly during the day and night. Figure 11 shows that during the period from 7:00 to 19:00 of the daytime, the temperature of the exterior wall and window is higher than that of the inner wall and window. The envelopes prevent from external heat entering the room. On the contrary, the building dissipates heat at night from 19:00 to 7:00 the next day. The

**Figure 14.** Comparison of thermal comfort time-volcanic (V) and modern (M) dwellings.

**Figure 15.** PMV of traditional volcanic dwelling and modern dwellings.

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temperature of the exterior wall and window is lower than that of the inner wall and window.

### 5.4. Wind velocity

Natural ventilation has an important role in buildings to create thermally comfortable environment by regulating indoor air parameters, such as air temperature, RH and air speed (Chen 2009). It takes a positive contribution for cooling in the vernacular architecture (Michael, Demosthenous, and Philokyprou 2017). Figure 12 shows that the wind velocity was tested at different locations of the volcanic-rock dwelling, including the outdoor courtyard, living room (semi-open space at daytime) and bedroom. According to the data showed on Figure 12, the air speed of living room was greatly higher compared to the courtyard and bedroom. The mean value of air speed in living room is 0.25 m/s, while that of courtyard is 0.16 m/s. The air speed in the bedroom is very weak, which is less than 0.10 m/s on average. There is only one small window about 0.1 m² on the eastern wall of the bedroom because of previous defensive needs. The small size window takes disadvantages to cross ventilation. On the contrary, the front and rear doors are open at daytime and aligned on the axis, the wind can easily pass through the living room and courtyard. Cooling effect of night ventilation is larger than those of the other ventilation strategies during the day and night according to the study carried out by Kubota et al. (Kubota, Toe Hooi Chyee, and Ahmad 2009) in which they reported that in a hot humid climate, night cooling in the vernacular architecture effectively reduces indoor operative temperature and improves thermal comfort, but the majority of occupants tend to apply not night ventilation but daytime ventilation mainly due to insects, security risks and rain (Ank-Tuan et al. 2011). Actually, occupants appreciate air movement, even when it is not necessary for cooling action.

In the modern dwelling, we can feel the wind in the living room on the first floor, but there is not enough wind to enter the rooms on the first- and second-floor bedrooms.

### 6. Discussion

#### 6.1. Discussion on results

Figure 10 shows that the traditional volcanic-rock dwelling in comparison with the modern dwelling, maintains a low diurnal variation of the indoor temperature. Although the external walls and windows of volcanic-rock dwelling are covered by narrow eaves, the modern building is protected by a balcony as a shading and thermal buffer space. The volcanic-rock dwelling still keeps a stable indoor thermal performance. Figure 13 shows that the indoor air temperature ($T_i$) of all tested rooms is directly affected by outdoor air temperature ($T_o$). In general, the living room in volcanic-rock dwelling has the highest gradient but lowest constant compared with other tested rooms. This proves that the living room played a role of semi-open space was more significant influence from $T_o$. Also, it reveals that the high thermal insulation property of the envelope of the volcanic-rock building, which can control the heat from sun through conduction and radiation along with appropriate ventilation and provide a comfortable indoor environment in hot-humid climate.

In the living room, the front and rear windows and doors of the volcanic-rock dwelling keep open at daytime, and there is a combination of well-ventilated wooden partition walls. The most important design characteristic of the partition walls and windows are that they consist of empty lattices without glass to ensure that the heat in the indoor spaces can easily dissipate at night. The space design of bedrooms uses incomplete height to the top of the wooden partition wall, which can increase the air circulation between the adjacent bedrooms. Bedroom windows are small to reduce heat radiation into the bedroom, but also limiting indoor ventilation and illumination.

#### 6.2. Thermal comfort analysis

##### 6.2.1. Thermal comfort time

During the 63 hours of testing, the length of thermal comfort temperature below in different rooms are different. According to Lufeng Zhang (Zhang et al. 2010), the 80% acceptable thermal comfort range from 22.1°C to 28.7°C. Figure 14 makes statistics on the length of thermal comfort time. As shown in Figure 14, living room and bedroom in volcanic rock dwelling can achieve more than 22 hours than modern dwelling during the test time.

##### 6.2.2. PMV-PPD analysis

PMV-PPD analysis based on Franger’s theory (Fanger 1970), which include factors of air temperature, humidity, wind speed, radiant temperature, metabolic rate, clothing. It is known that given clothing value and metabolic rate range, the environmental thermal conditions are tested; therefore, the result of PMV values can be calculated. The results are revealed in Figure 15.

In the bedroom of traditional volcanic-rock dwelling, the PMV values ranges from −0.8 to 1.2, while in modern dwelling ranges from 0.7 to 3. The PMV value of the living room of volcanic-rock dwelling is found to be lower compared to bedroom except for the hot period in the day time from 12:00 to 16:00, which can be treated as a semi-open space when the door keeps open.

#### 6.3. Development of dwelling in the future

Generally, there are small windows or no windows in the bedroom of volcanic-rock buildings, and indoor illumination is too low to meet the lighting standards
in China (China National Standard (GB 50034-2013) 2013). Secondly, there are number of holes – some volcanic-rock walls. The holes among rocks causes interference in the sight of life, which are not conducive to ensuring privacy. If it is raining accompanied with strong winds, rainwater would enter interior room and have a great influence on indoor living conditions. Thirdly, for lack of bathing rooms and kitchen in the main house, it makes an important influence on the daily use in hot-humid weather. Finally, the land of volcanic-rock villages is covered by volcanic rocks, which is not conducive to water storage and there are fewer rivers. Water-saving technologies such as rainwater recycling can be considered with the development of modern dwellings in the future.

Although the present study confirms the climate-responsive strategies of vernacular dwellings in Haikou and indicates that volcanic-rock dwellings can offer a comfortable thermal environment for occupants, it is limited to the field measurements of two buildings. The field data were collected for a period of two days only. It is necessary to extend further study of the design of modern dwelling with the comprehensive consideration of inheritance and innovation the volcanic-rock dwellings for comfort thermal performance. Additionally, there is promising potential for the synchronous optimization of volcanic-rock dwelling to solve many problems, such as indoor illumination, various function, economical and practical, and should be improved in future research. Therefore, future study will include how to optimize the traditional volcanic-rock dwellings under the demand of modern lifestyles in the space renovation and how to inherit the climate-responsive strategies into the design of modern dwellings in this region through computer simulation while considering natural environments and the regional culture.

7. Conclusion

Based on field measurement and data processing, it is systematically investigated in the present study by comparing two completely different dwellings with representativeness in a same village of Haikou. The following conclusions can be drawn:

(1) Thermal environment in the volcanic-rock dwelling is better than modern dwelling. The average indoor air temperature of the 2nd floor bedroom in the modern dwelling is 2.4°C higher than the bedroom of volcanic-rock dwelling. The average air temperature of the 1st floor bedroom in the modern dwelling is 1.1°C higher than that of volcanic-rock dwelling. There are 10 h (23:30–9:30 the next day) with temperatures below 28.7°C in the traditional volcanic-rock dwelling, which is within the range of thermal comfort on the second and third day, while the bedroom on the 2nd floor completely beyond the 80% acceptable thermal comfort range.

(2) The envelope of volcanic-rock dwelling has good thermal inertia and thus great significance for maintaining a relatively stable indoor air temperature. Temperature difference between exterior and interior of volcanic-rock wall and wooden window can reach a maximum of 6.7°C and 2.8°C, respectively.

(3) In the traditional vernacular house, the air speed in the bedroom is very weak, which is less than 0.10 m/s. But the mean value of air speed in the living room can reach 0.25 m/s. It indicates that the front and rear doors of living room are both open and the larger scale is conducive to natural ventilation.

(4) Traditional dwellings gradually formed passive and natural control system for climate during centuries of trial and error. Obviously, the design of modern dwellings did not inherit the climate-responsive methods and wisdom of traditional volcanic-rock dwellings. The test results show that, under the free running without air-conditioning in summer in modern country dwellings, for the occupants, a satisfactory indoor thermal environment has not been achieved. At the same time, in rural areas, residents are constrained by economic conditions when building a house, and it is difficult for them to use active high-tech technology to obtain thermal comfort in rural areas. Modern dwellings are designed and built without local low-tech and climate-responsive strategies.

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