

Improvement of Ventilation and Thermal Comfort Using the Atrium Design for Traditional Folk Houses-Fujian Earthen Building

Ying-Ming Su

Abstract—Fujian earthen building which was known as a classic for ecological buildings was listed on the world heritage in 2008 (UNESCO) in China. Its design strategy can be applied to modern architecture planning and design. This study chose two different cases (Round Atrium: Er-Yi Building, Double Round Atrium: Zhen-Chen Building) of earthen building in Fu-Jian to compare the ventilation effects of different atrium forms. We adopt field measurements and computational fluid dynamics (CFD) simulation of temperature, humidity, and wind environment to identify the relationship between external environment and atrium about comfort and to confirm the relationship about atrium H/W (height/width). Results indicate that, through the atrium convection effect, it makes the natural wind guides to each space surrounded and keeps indoor comfort. It illustrates that the smaller the ratio of the H/W which is the relationship between the height and the width of an atrium is, the greater the wind speed generated within the street valley. Moreover, the wind speed is very close to the reference wind speed. This field measurement verifies that the value of H/W has great influence of solar radiation heat and sunshine shadows. The ventilation efficiency is: Er-Yi Building ($H/W = 0.2778$) > Zhen-Chen Building ($H/W = 0.3670$). Comparing the cases with the same shape but with different H/W, through the different size of patios, airflow revolves in the atriums and can be brought into each interior space. The atrium settings meet the need of building ventilation, and can adjust the humidity and temperature within the buildings. It also creates good ventilation effect.

Keywords—Traditional folk houses, Atrium, Earthen building, Ventilation, Building microclimate, PET.

I. INTRODUCTION

FUJIAN Earthen buildings are traditional large-scale residential buildings, scattered in the southeast of China. Due to their long history and unique design, Fujian Earthen building structures have been listed as the 'World Heritage Site' by the United Nations Educational, Scientific and Cultural Organization (UNESCO) in 2008. Earthen buildings are not only appreciated for their aesthetic appeal, but provide valuable insight through which vernacular buildings should be designed. Recent study shows that the total primary energy consumption per household for earthen building was much lower than the average rural houses in the area [1]. Besides, earthen buildings enjoy better thermal comfort even without using any air conditioner [1].

Vernacular architecture is influenced by long-term culture and weather, therefore usually vernacular architecture is the

best nature solution to a specific location in which it exists. It is challenging to package vernacular architecture traditions and quantitative design knowledge to modern building designers. Researches indicated that the atrium is a common architectural feature in both modern and historic naturally ventilated buildings [2]-[4].

Lots of researches had developed design strategies for atriums. Atrium can act as a buffer thermal zone which can provide passive solar gains, increase availability of daylight into the adjacent space, assist ventilation, reduce air-conditioning equipment, and save the building energy and enhance the quality of the indoor environment which makes use of the building's thermal mass and is applicable in many climates [5]-[9].

Atria were primarily adopted in vernacular buildings in parts of Asia, the Middle East, South America, and the Mediterranean countries [10]-[12]. Nguyen et al. suggest that a new research methodology (in-site survey and building simulations) which is adapted to the natural and social context of subtropical was proposed and applied [13].

This paper aims to study the ventilation effects of two earthen buildings, Er-Yi Building and Zhen-Cheng building, in Fujian. We focus on the role played by the atrium, which is a significant architectural feature for traditional earthen building. Physical attributes of both internal and external environment are monitored on site for each of the two buildings. As has been noticed by previous researches, atrium produces different effects in different seasons.

We conduct separate field studies both in summer and in winter. As a complement, a CFD simulation is implemented to recreate thermal conditions of two buildings in both seasons. To evaluate the field measurement results, CFD simulation is run with cases of the shape but different H/W ratio. The rest of the paper is organized as follows, Section II explains field measurements, CFD simulation setting; Section III shows results and discussion; Section IV is the conclusion. The traditional round earthen building was proven to have superior performances in natural ventilation [14]. This study focuses on promoting natural ventilation effect at atrium, with the air velocity as the most important factor of environmental comfort. Results show that indoor comfort is preserved by the convection effect of the atrium. This study could recognize the advantages of vernacular dwelling [15].

II. METHODOLOGY

This study measured physical environmental of comfort

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factors including air velocity, average air temperature, and relative humidity at the outdoor space by Testo 480 instrument. The study was investigated with photos, site survey, and record data. The goal of this study is to analyze the ventilation effectiveness by CFD-based performance simulation generated from ANSYS FLUENT software and to investigate the microclimate conducted by field measurements in a Chinese traditional vernacular house. Subsequently, the results of measurements were compared with a dynamic thermal and a CFD simulation in order to determine the microclimate and thermal comfort of the typical (Earthen building) vernacular house over the period of an entire summer and winter. Lin et al. (2014) [16] mentioned that different cities layout influenced wind velocity under constant building face width, building height, and street block width. Results indicate block width, passage width (H/D), height variation of buildings (PR) are the important parameters of the outdoor ventilation.

A. Introduction of Two Earthen Buildings

Fujian province lies in the southeast of China (23°20'-28°22' N; 115°50'-120°40' E). It is close to the northern tropic, with mild weather and abundant precipitation. Fujian is influenced under the subtropical monsoon climate, with average temperature ranging from 15.3-21.9 °C. The basic information of two earthen building cases including location, wind rose, monthly average temperature and humidity is shown in Fig. 1 (Central Weather Bureau of China (1981 -2010)).

Two Fujian Earthen buildings are included in this study, which are (a) Er-Yi Building (b) Zhen-Cheng Building (Fig. 2). All two buildings are large residential buildings with significant semi-enclosed atria. However, they differ in many aspects such as location, size, and type of atrium. The details of two earthen buildings and their atria are stated as follows:

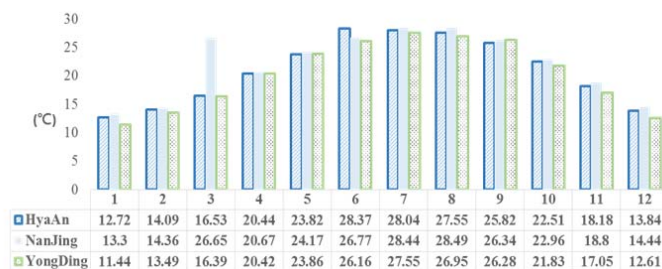
1. Er-Yi Building was built around 1740 in Dadi Village, Xiandu Zhen, Hua'an Xian, Zhangzhou Shi, Fujian province. It is a typical circular shape building, facing the Southwest direction. With the height of 16 m and diameter around 73.4 m, it in total occupies around 6600 m² [17].
2. Zhen-Cheng Building was established in 1912 and located in Hongkeng village, Hukeng zheng, Yongdingxian, Longyan Shi, Fujian Province. It is a double circular south-facing building, whose height is around 19 m and diameter is 57.2 m. It is as large as 5000 m² [17].

B. Field Measurement

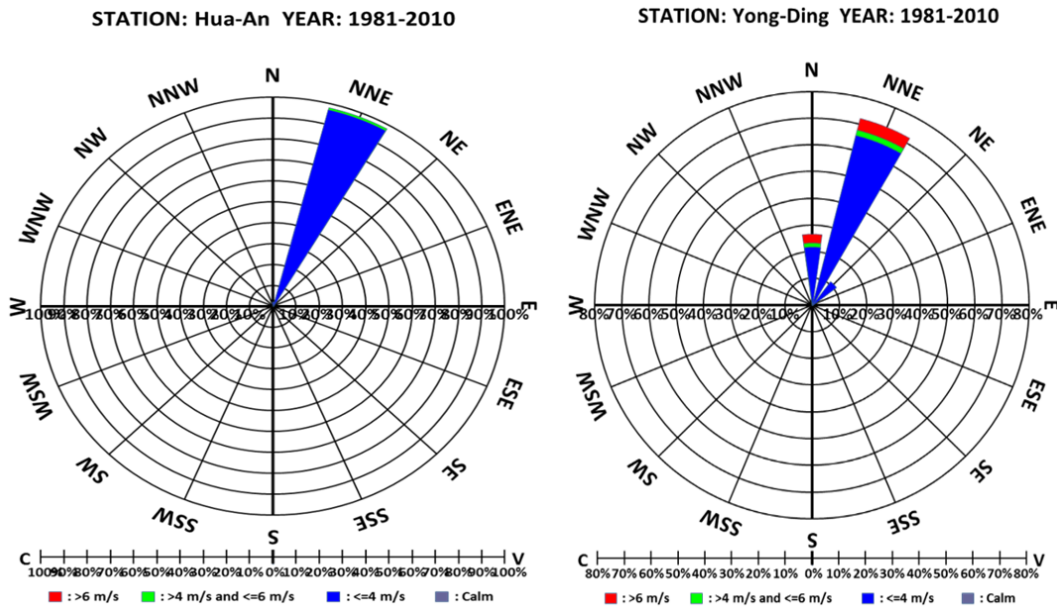
The field study includes measurements of both indoor and outdoor temperatures, wind velocity, and humidity in two different earthen buildings (Fig. 3). In summer of 2012, we measured Er-Yi Building on the 13th and 14th August, respectively. On the 20th and 21st Nov, the measurements of Zhen-Chen Building were taken and treated as winter cases. An automatic temperature logger and temperature and humidity logger, which recorded data every five minutes, were used. The equipment was placed above the ground at a height of 1.5 m at the measured points both indoors and outdoors. To avoid the effect of device movement causing airflow disorder, the measuring period lasted for ten minutes with the data recorded every one second for each measuring point. Moreover, the mean radiation temperature was recorded by a globe sensor whose diameter is approximately 150 mm with the minimum accuracy of 0.5 °C. Having all instruments installed on a tripod, the aforesaid probes were connected to a multi-parameter indoor climate meter (Testo 480) for accurate measurement of the flow velocity, temperature, and relative humidity (Table I). The data obtained above will be used to evaluate the high-rise building arcade in autumn wind environment.



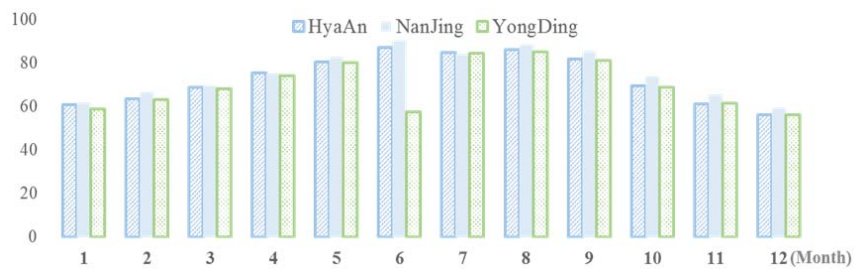
(a) Two earthen building Cases positional distribution



(b) Monthly average temperature



(c) Wind rose chart in all year of Hua-An and Yong-Ding area



(d) Monthly average humidity

Fig. 1 Basic information of two earthen building cases (a) location (b) monthly average temperature (c) wind rose chart in all year of Hua-An and Yong-Ding area (d) monthly average humidity by Central Weather Bureau of China (1981 -2010)

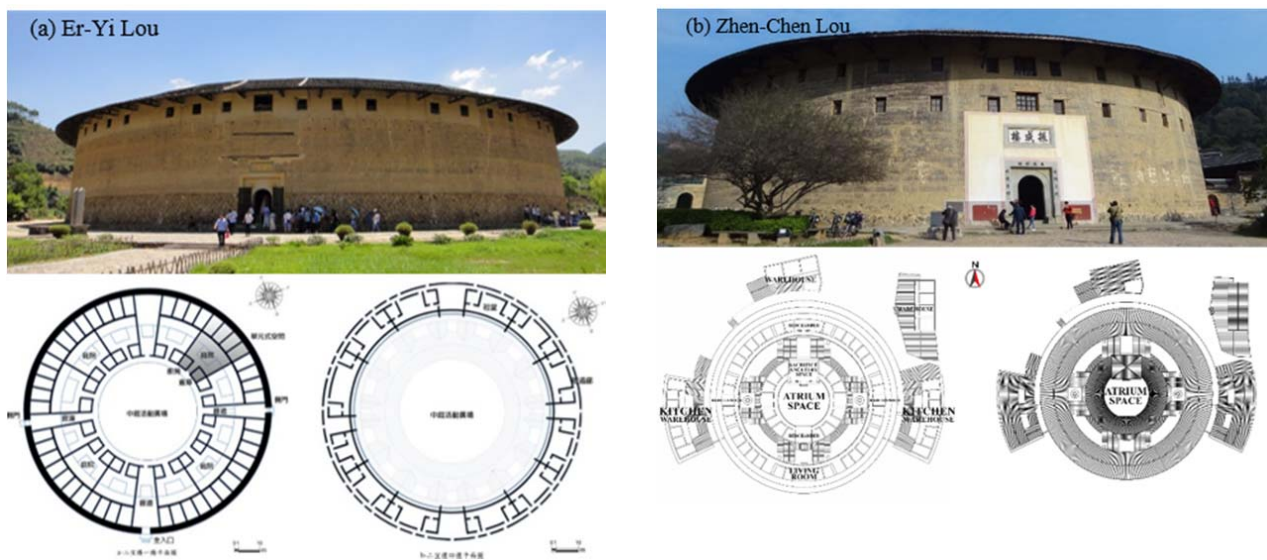


Fig. 2 Photos and floor plans of two cases: (a) Er-Yi Building, (b) Zhen-Chen Building

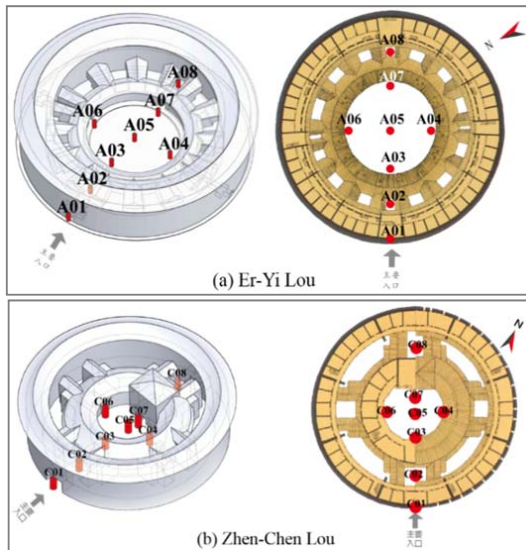


Fig. 3 Location of measuring points of earthen building

TABLE I
MEASUREMENT EQUIPMENT

Label	Intention	Measuring ranges	Error value
TESTO 0635	Air velocity	0~+10 M/S	$\pm(0.03\text{M/S}+5\%\text{OFMV})$
TESTO 0602	Mean radiation temperature	0~+10 M/S	$\pm(0.03\text{M/S}+5\%\text{OF MV})$
TESTO 0636	Relative humidity	-20~+70 °C, TO 100% RH	$\pm(0.1\% \text{ RH} + 0.7 \text{ OF MV})$

C. Computational Simulation

According to information of Central Weather Bureau of China (1981 -2010), we use average wind velocity and average temperature in summer and winter as the variables for CFD simulation. The solid model was then readily transported to the preprocessor of the CFD software ANSYS FLUENT ver.16 for constructing a numerical model using the grids generator module ANSYS ICEM. The inflow boundary in CFD calculations of the atmospheric boundary layer (ABL) flow was treated to simulate the related atmospheric processes. Calculations were performed using the ANSYS FLUENT software to examine the wind field structure characterized by the interaction of airflow with buildings. The computational approach was based on the steady-state three-dimensional conservation equations of mass, momentum, and energy for the incompressible turbulent flow with the governing equations.

III. RESULTS AND DISCUSSION

A. Measurement and Verification

Due to air flow into Er-Yi Building (circular earthen building) in summer times, entrance to condense to form a higher wind speed (1.9m/s), the average velocity was 0.66 m/s. The temperature variation of Er-Yi Building was small which between 35 and 37 °C. The humidity of atrium of Er-Yi Building maintained between 44 and 49%.

Zhen-Chen Building has stable wind velocity between 0.31~0.49 m/s in winter time. Zhen-Chen Building also had

more stable temperature (17~20.3 °C during daytime, 13~14.5 °C during nighttime). The results indicated atrium could maintain the velocity in earthen building by field measurement (0.28~0.85 m/s in summer times, 0.2~0.38 m/s in winter times). Floor and wall surfaces absorb solar heat to maintain the temperature of atrium in winter (19~11 °C). Humidity and temperature were all in comfortable range.

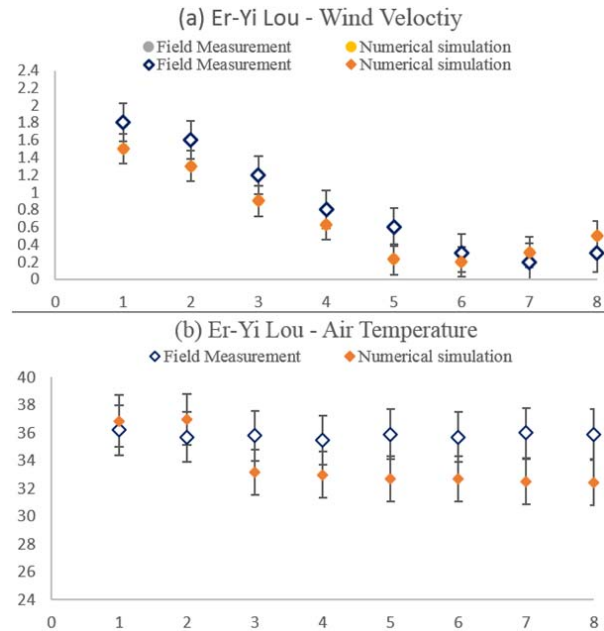
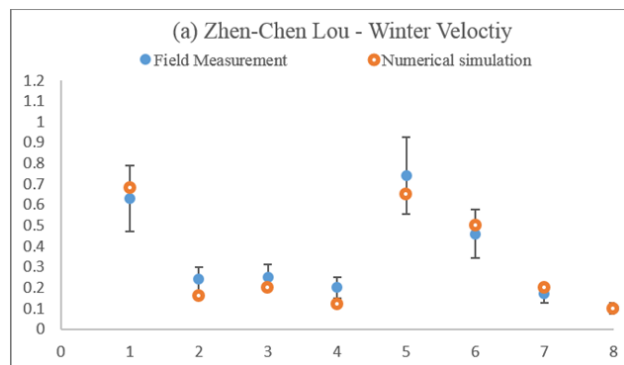


Fig. 4 Comparison of field measurement and CFD simulation data of Er-Yi Building (a) wind velocity (b) temperature

We compare the results of micro-climate of atrium by CFD simulation and field measurement. The results are consistent in CDF simulation and field measurement within standard difference error (Figs. 4 and 5). It proved that we could predict the wind velocity and temperature variation of atrium reasonably by CFD. According to weather information, we use average wind velocity and average temperature in summer and winter as the variables for CFD simulation.



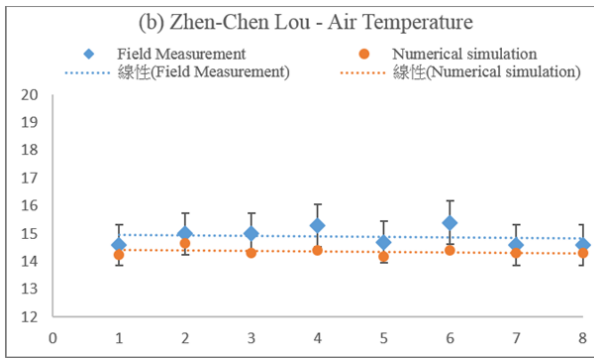


Fig. 5 Comparison of field measurement and CFD simulation data of Zhen Chen Building (a) wind velocity (b) temperature results

B. CFD Results

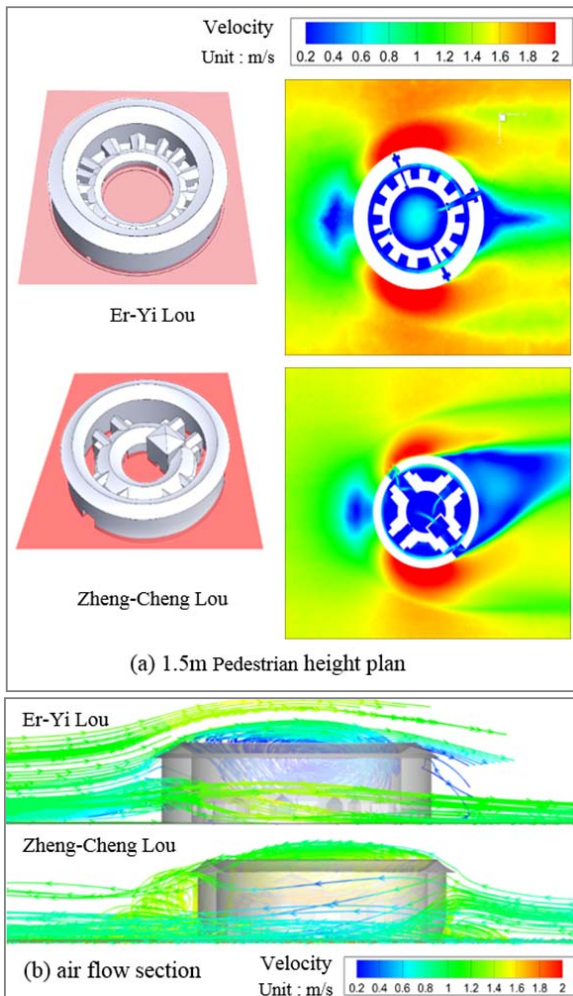


Fig. 6 The predicted velocity magnitude contours of wind around earthen building in summer (a) the height of 1.5m floor plan (b) air flow section

The atrium ratio (H/W) of Er-Yi Building is 0.2288 less than that of Zhen-Chen Building ($H/W=0.4909$). The average maximum spot velocity in summer is 22.37 m/s. Air vortices of

atrium compared to the wake effect of building were obvious (Fig. 6 (a)).

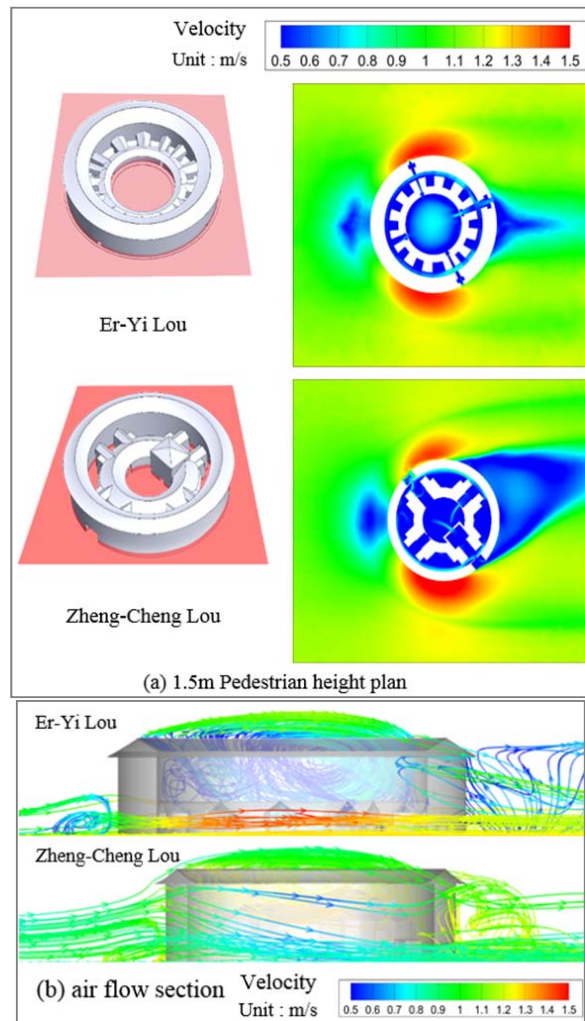


Fig. 7 The predicted velocity magnitude contours of wind around earthen building in winter (a) the height of 1.5 m floor plan (b) air flow section

The skin temperature will cause heat transfer and change with the external environment when the skin is exposed to the external environment. As air velocity can make skin temperature drop more rapidly, it will be closer to the air temperature. For humans, the comfort of low-temperature environment influenced by the temperature difference and the wind speed are closely related. Therefore, the breeze into the room not only can take away the surface heat of the human, but can remove indoor pollutants due to the increase of ventilation rate at indoor air.

Results indicated that average velocity in summer was 1.14% higher than that of winter. The variations of velocity in summer (0.2~0.8m/s) are higher than those in winter (0.2~0.5 m/s). Atrium is both air inlet and air outlet. Figs. 6 (b) and 7 (b) indicated that wind pass through the atrium by atmospheric pressure, and then blew to various space from opening to side

yard to achieve the natural ventilation effect.

C. ACH

ASHRAE Standard 62-89 is the most popular standard of interior ventilation and air conditioner worldwide conducted by American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). ASHRAE ventilation for is acceptable for indoor air quality (62.1-2013). Table II shows the ACH values of earthen buildings with atrium and without atrium. The results indicated that the ACH values with atrium were all higher than those of without atrium up to 97~99%. It proved that atrium could improve the ventilation.

$$ACH = \frac{Q}{\text{Volume}} (\text{m}^3), \text{ACH: number / hr or h}^{-1}, Q: \text{Volume}$$

flow rate (m^3/hr).

TABLE II
COMPARISON OF ACH VALUES OF EARTHEN BUILDINGS

(a) without atrium	Without Atrium (h^{-1})	Opening area (m^2)	Aperture Ratio (%)	
Er-Yi Building	4.07756	2312.408	0.561	
Zheng-Chen Building	4.64951	1155.119	0.469	
(b) with atrium	Volume flow rate Q (m^3/h)		Volume (m^3)	ACH (h^{-1})
	Air Intake	From Atrium		
Er-Yi Building	104868	9989603.856	46293.000	218.056
Zheng-Chen Building	114890.4	4990114.08	25451.551	200.577

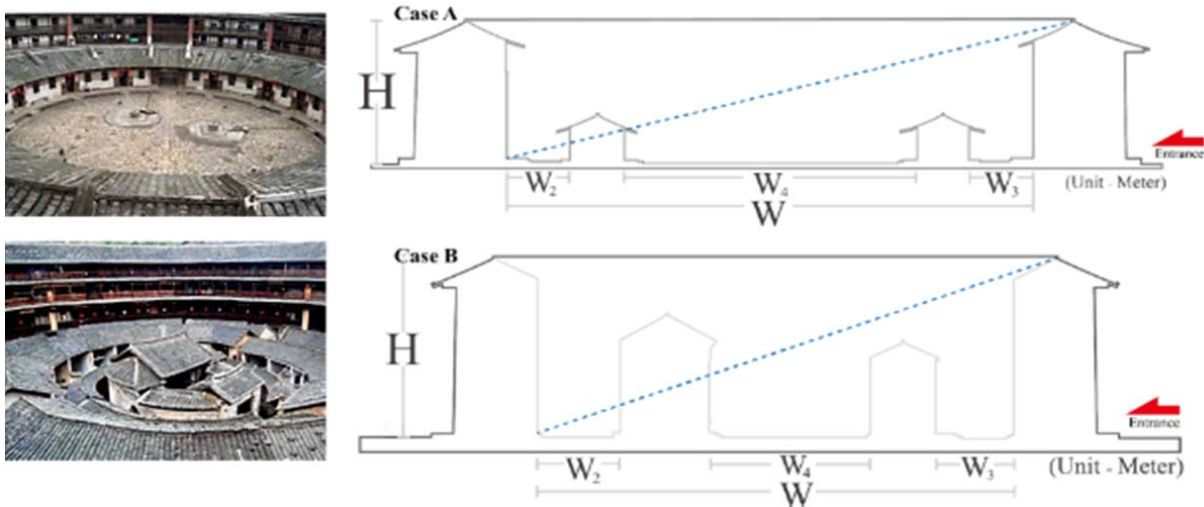


Fig. 8 Atrium sectional space and live photo: (a) Er-Yi Building (b) Zheng-Chen Building

D. Air Temperature 1.5m Height Plane

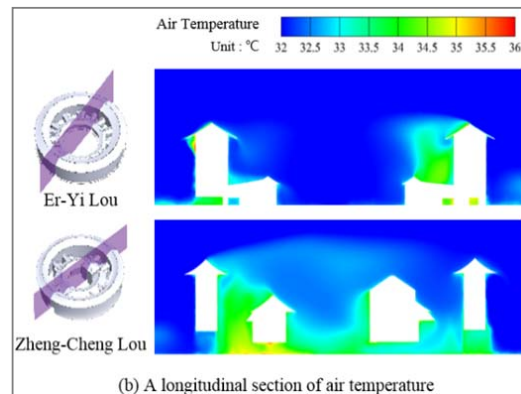
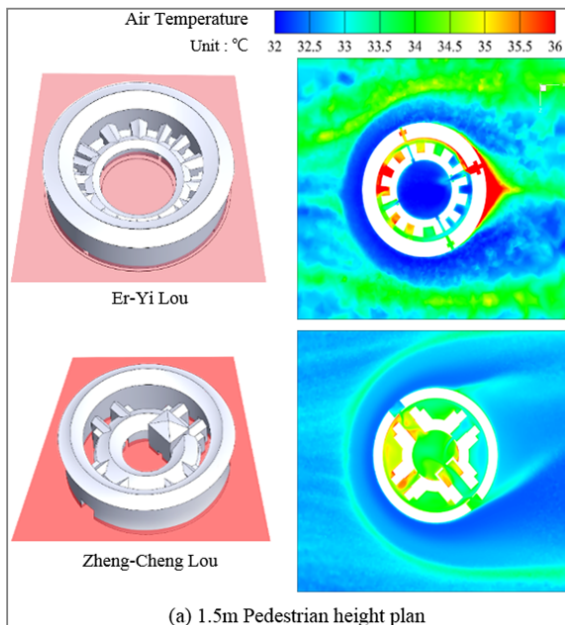


Fig. 9 CFD simulation temperature analysis of atria in summer (a) Air temperature 1.5 m height plane (b) A longitudinal section of air temperature

Atrium temperatures compared to the other spaces of the atrium were more stable between 32.45 and 32.98 °C of Er-Yi Building in summer. Compared to the temperature of entrance (36.86~36.96°C), the temperature of atrium was dropped about 11.76 ~13.59% (Fig. 9). Atrium temperatures compared to the other spaces of the atrium were more stable between 31.6 and

31.84 °C of Zhen-Chen Building. The average error among every measured point was about 0.76% (0.24 °C). The temperature of atrium was dropped about 1.55~2.12% than that of entrance. Air vortex effect can increase the speed of removing the heat in atrium.

The variation temperature of atrium (16.24~17.23 °C) was more stable compared to that of outdoor (14.24~24°C) of Er-Yi Building in winter. The temperature difference was about 2.13~2.86% in winter. The air vortex effect (maximum wind velocity 16.06 m/s, average wind velocity 1.87 m/s) can regulate the temperature about 0.24 °C (1.41%) in atrium (Fig. 10). The temperature difference between atrium and interior space of building was about 2.13~2.86%. The diameter of Zhen-Chen Building is smaller than that of Er-Yi Building. The temperature of atrium was about 15.31~15.35 °C, and temperature difference was about 0.26%. The temperature of interior space was more stable and warmer compared to that of outdoor. Fig. 11 shows the temperature of measuring points of two earthen buildings.

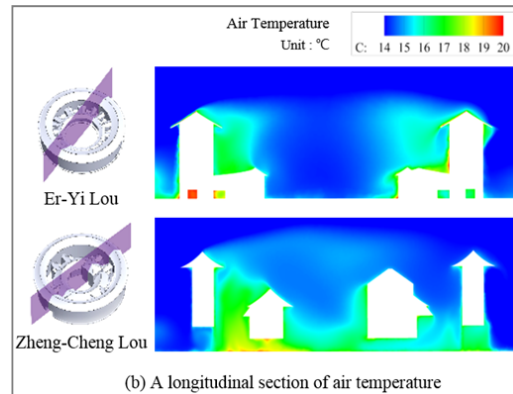


Fig. 10 CFD simulation temperature analysis of atria in winter (a) Air temperature 1.5 m height plane (b) A longitudinal section of air temperature

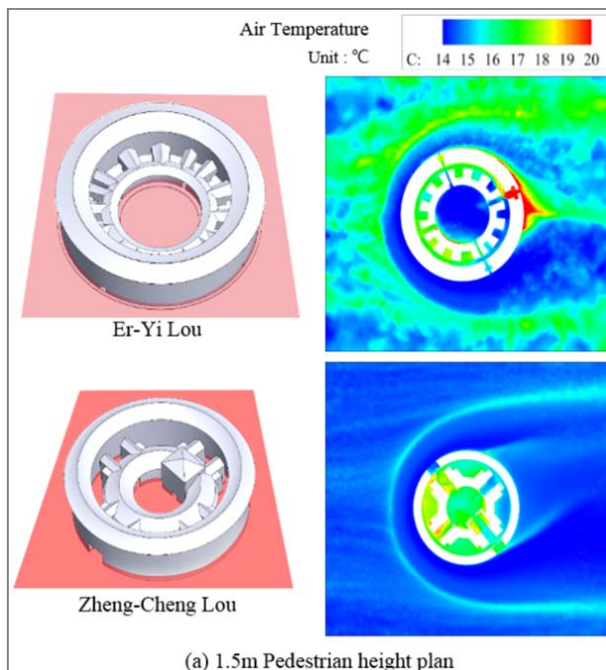
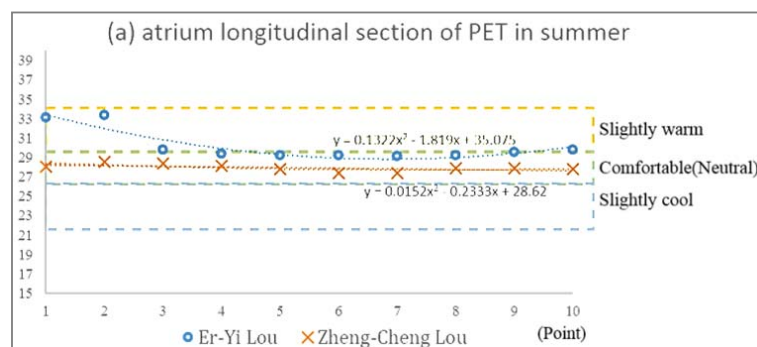


Fig. 11 Temperature of measuring points of two earthen buildings (a) Summer (b) Winter

E. Physiological Equivalent Temperature (PET)

The international evaluation standards of thermal environment and thermal comfort contain WBGT, MRT, ET, ET*, To, PMV and etc. This study analyzed thermal comfort degree by physiological equivalent temperature (PET).



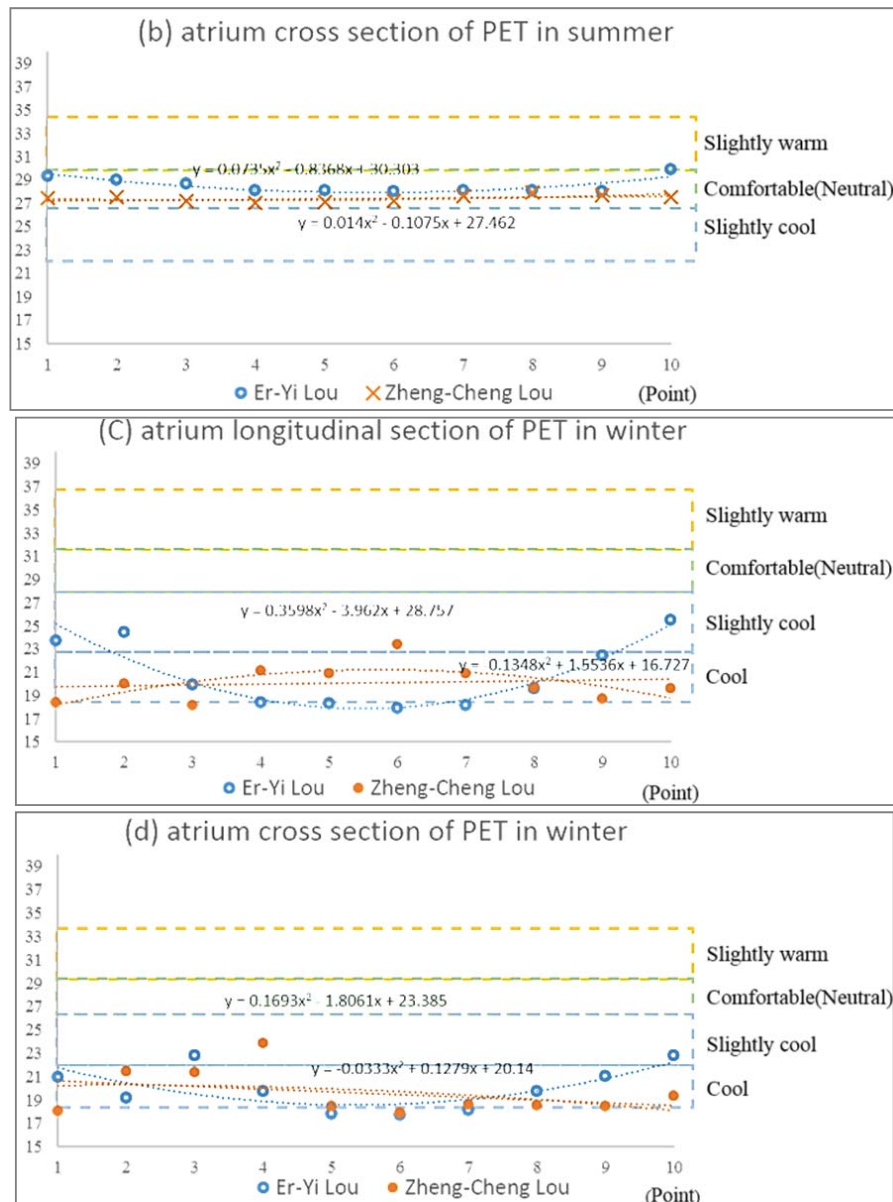


Fig. 12 (a) atrium longitudinal section of PET in summer (d) atrium cross section of PET in summer (c) atrium longitudinal section of PET in winter (d) atrium cross section of PET in winter

There are six main factors of PET index including air temperature (T_a), relative humidity (RH), radiation temperature, air velocity (V) and cloth (clo), activity (W). Setting of parameters such as height, weight, age, metabolic rate and amount of clothing was referred to researches of Matzarakis and Rutz (2005) [17] and Matzarakis (2007) [18] as normal outdoor activity of middle age male (height 175 cm, weight 75 kg, 35 years old, 175W metabolic rates, clothing 0.9clo). Ghaffarianhoseini et al. (2015) [9] evaluated the impact factors of atrium comfort in Kuala Lumpur including opening direction, H/W ratio, surface reflectance and greening through simulation and calculation by ENVI-met PET. Results proved that the importance of building type affected the comfort of

human body, and adaptability to the area. Lai et al. [19] evaluated the relationship of block characteristics and human comfort by SET and PET comfort assessment. Results showed that there is a close relationship between block setting and thermal comfort, also can affect the block shape or the building form.

Measurement data were calculated by RayMan1.2 and equation $y = 0.297x^2 - 19.428x + 346.69$, $R^2 = 0.8866$ PET (Fig. 12). PET data of atrium of earthen buildings were all located in "Slightly cool- Slightly warm" zone in summer and "Cool- Comfortable (Natural)" zone in winter which fit comfortable range. It confirms that atrium can regulate the interior micro-climate of building.

IV. CONCLUSION

The results indicated that wind velocity of atrium was lower than that of outdoor both by CFD simulation and field measurement. Such ventilation system caused draught to reduce temperature naturally. The H/W ratio of Er-Yi Building (0.2288) compared to the H/W ratio of Zhen-Chen Building (0.4909) is smaller. The velocity of Er-Yi Building was 1.94 times higher than that of Zhen-Chen Building.

Results indicated that atrium did increase the indoor ventilation effectiveness both by field measurement and CFD simulations. To compare the ACH value with and without atrium of earthen building, it showed that the air exchange rate with atrium was higher than that of without atrium up to 97%~99%.

The air inlet area is more important than the outlet area for ventilation effect of atrium. Enlarging the inlet area can improve the nature ventilation effectively. The temperature difference between interior and exterior of building can affect air exchange ventilation.

Results showed that the wind speed at the Atrium was between 0.3 m/s and 0.8 m/s for comfort range. CFD simulation and field survey results showed that wind environment in atrium space is obviously lower than exterior wind field. Atrium is proven to have a more stable wind environment and to retain a certain amount of ventilation.

Sun increased the atrium temperature sharply, and atrium forms a good cross ventilation system in order to achieve the objective of natural cooling.

The comfort of Er-Yi Building (H/W=0.2778) atrium is better than that of Zhen-Chen Building (H/W=0.4909). The value of H/W was concerned with solar radiation heat and sunshine shadows. The results of CFD show that the airflow in circular wind field is much more stable than in square wind field. So, when width differs in atrium, hot air is generated by the temperature difference between upper and lower layers, and atrium opening becomes a major wind channel.

PET data of atrium of earthen buildings were all located in "Slightly cool- Slightly warm" zone in summer (25–33°C) and "Cool- Comfortable (Natural)" zone in winter (18–27°C), which fit comfortable range. The Atrium of traditional Chinese earthen building can maintain the thermal comfort of humans in an acceptable comfort range and can regulate the microclimate inside the building effectively (wind speed, temperature and humidity) in high temperature and humid subtropical environment.

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