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Field study of thermal comfort in non-air-conditioned buildings in a tropical island climate

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ABSTRACT

The unique geographical location of Hainan makes its climate characteristics different from inland areas in China. The thermal comfort of Hainan also owes its uniqueness to its tropical island climate. In the past decades, there have been very few studies on thermal comfort of the residents in tropical island areas in China. A thermal environment test for different types of buildings in Hainan and a thermal comfort field investigation of 1944 subjects were conducted over a period of about two months. The results of the survey data show that a high humidity environment did not have a significant impact on human comfort. The neutral temperature for the residents in tropical island areas was 26.1 °C, and the acceptable temperature range of thermal comfort was from 23.1 °C to 29.1 °C. Residents living in tropical island areas showed higher heat resistance capacity, but lower cold tolerance than predicted. The neutral temperature for females (26.3 °C) was higher than for males (25.8 °C). Additionally, females were more sensitive to air temperature than males. The research conclusions can play a guiding role in the thermal environment design of green buildings in Hainan Province.

1. Introduction

It is generally understood that a good and comfortable thermal environment is not only conducive to people's health, but also helps people work at high efficiency. A higher requirement of indoor thermal comfort implies that our buildings consume more energy. While energy consumption and carbon emissions are two of the most serious issues in the world today (Valipour, 2012a; Yannopoulos et al., 2015; Khasraghi et al., 2015; Valipour, 2012b; Valipour et al., 2015), we need to find a balance between energy consumption and thermal comfort. An in-depth study of thermal comfort characteristics and requirements can contribute to a conducive thermal environment and building energy efficiency.

Thermal comfort is defined as “that condition of mind which expresses satisfaction with the thermal environment”, by ISO (ISO 7730, 1994). Based on the thermal comfort of the climate chamber, Fanger proposed the human thermal comfort theory and thermal equilibrium equation (Fanger, 1970a). Fanger and Gagge thought thermal comfort was equivalent to the thermal sensation in a thermal neutral state. The air humidity must be neither too high nor too low, and the air flow rate should be maintained at a relatively low level (Fanger, 1970b; Gagge, 1977). Fanger's equation is widely used in the research on thermal comfort, but the deficiencies in this equation began to appear in the literature gradually (Taleghani et al., 2013). In Humpherys's study, the predictive value of predicted mean vote (PMV) was not equal to actual mean votes (Humphreys and Sayigh, 1992). Malama tried to explain those disparities (Malama, 1997). de Dear and Brager found that the PMV was more suitable for predicting the votes of conditioned buildings, and it was not accurate for naturally ventilated buildings (deDear and Brager, 2002). Many scholars began to recognize this. In order to seek more accurate results and draw thermal comfort maps, the studies of field thermal comfort were conducted in each region.

The comfort surveys were divided into five climatic regions; Asit Kumar Mishra summarized the characteristics of thermal comfort in different climatic zones (Kottek et al., 2006; Mishra and Ramgopal, 2013). In this division, Hainan belongs to tropical moist climates. In the same climatic zone, the results of Indraganti's (Indraganti, 2010; Indraganti et al., 2013) study on Indian apartments showed that the thermal neutral temperature of offices at Chennai and Hyderabad was 29.3 °C, whereas the thermal comfort temperatures were 27.6 °C and 28.1 °C, respectively. Mishra's (Mishra and Ramgopal, 2015) study found that the EN15251 standard's adaptive comfort equation was more suitable for India.

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Djamila (Harimi et al., 2015; Djamila et al., 2013) used many methods to calculate the thermal neutral temperature of Malaysia, and the result was 30 °C.

Hainan belongs to the hot summer and warm winter area, according to China's architectural climate zoning. Within the same partition, Ng (Ng and Cheng, 2012) in his studies found that the neutral physiological equivalent temperature was around 28 °C in the summer of Hong Kong; Jie's (Han et al., 2007) survey showed that the thermal neutral temperature of three central cities in southern China was 28.6 °C; Xi Tianyu's survey of young students in Guangzhou showed that the neutral SET* was 24 °C (Xi et al., 2012). The unique geographical position of Hainan made its climate characteristics different from those of the abovementioned locations. Hainan is the smallest and southernmost province of China, belonging to the hot summer and warm winter climate zones, and its climate is different from that of inland regions. Hainan is the only tropical island Marine climate of China, and it has a unique tropical monsoon climate. Summers are hot and winters warm.

A large number of field studies have been performed around the world (Xia et al. (1999); Cena and de Dear (Cena and de Dear, 2001); Wang et al. (2003); Nicol (2004)). The results of such field studies indicate that the agreement between the expression of thermal comfort proposed by ASHRAE 55-1992 and ISO 7730 and the sensations people actually experience is not quite satisfactory. There have been a few field studies on occupants' comfort and residential thermal environment (Wang et al. (2003)). A large number of thermal comfort studies have been carried out in the climate chamber rather than in actual working locations (Giaconia et al., 2015; Pala and Oz, 2015). However, laboratory subjects are not in their familiar surroundings, nor do they engage in their usual work activities during the period of testing.

To the best of our knowledge, studies need to be carried out in tropical and cold climatic zones (Dahlan and Gital, 2016; Califano et al., 2017). There are few studies relating to occupants' comfort and residential thermal environment, dealing with the tropics of Hainan Province. Thus, the purpose of this study was to conduct a field study on comfort and residential thermal environment in a typical hot-humid climate of China. This research involved prediction and evaluation of thermal neutral temperature for naturally ventilated residential buildings in the hot-humid environment in Hainan.

This thermal comfort study of Hainan was comprised of three aspects:

1) Analyzing thermal neutral temperature, acceptable thermal comfort temperature range, and desired temperature for residents.
2) Further analyzing the characteristics of thermal comfort by comparing the measured results with thermal comfort evaluation index.
3) Analyzing gender differences in thermal comfort. This research highlights the importance of creating a comfortable indoor environment, while reducing building energy consumption as much as possible, and also provides guidance for building energy efficiency.

2. Method

2.1. Test of thermal environment parameters

Thermal comfort equation shows that the human feeling of thermal comfort is affected by many factors. In general, these factors can be divided into two categories: objective environmental factor and individual subjective factor. Consequently, the experimental testing methods adopted in this paper were also divided into two types; one is the test of objective thermal environment parameters, and the other is a field questionnaire survey of thermal comfort. Based on the survey results, two evaluation indices were introduced to analyze the experimental results. One widely used at present is the Operation Temperature (T_o) (ASHRAE 55, 2010); the other is the Predicted Mean Vote & Predicted Percentage of Dissatisfied (PMV-PPD), recognized by the International Organization for Standardization (ISO)since the early 80s (Fanger, 1970b; ISO 7730, 1994).

Objective environmental factors mainly include air temperature, air humidity, air flow velocity and mean radiant temperature. The outdoor thermal environment parameters collected in this experiment were air temperature and relative humidity; indoor thermal environment parameters collected were air temperature, relative humidity, black-bulb temperature, and air velocity.

The HOBO data loggers were used to test the outdoor thermal environment parameters (temperature and humidity), and the data were collected every 10 min. The HOBO data loggers were placed away from direct sunlight to avoid any impact from solar radiation and rainfall.

In strict accordance with the relevant provisions of the ASHRAE 55-2010, the position and height of the measuring point were determined through the field tests of indoor thermal environment. All subjects maintained a sitting position while filling the questionnaires, and the heights of measuring points were set at 0.1, 0.6 and 1.1 m. Table 1 presents the corresponding positions marked by the height of each measuring point in ASHRAE. Table 2 shows the testing positions of various environmental parameters in the field test. When measuring black-bulb temperature, the height of the measuring point for a person in sitting position should be set at 0.6 m, and 1.0 m for a person in standing position.

Handheld instruments were used for measurement of onsite thermal environment, and all the heights were measured by a ruler. In order to ensure consistency between the environmental parameters and the subjective feelings of the subjects, the thermal environment testing and questionnaire investigation proceeded at the same time.

The instruments used in this experiment are shown in Table 3.

2.2. Questionnaire

Individual factors included thermal resistance of clothing, metabolism, psychological factors, and health conditions. A questionnaire was used to collecting subjective feelings. Subjects were given time to complete the questionnaire, and they were required to fill out the questionnaire according to their own subjective

Table 1
Testing height and corresponding positions of indoor environment parameters.

State of the sample	Ankle	Waist	Head
Sitting position	0.1 m	0.6 m	1.1 m
Standing position	0.1 m	1.0 m	1.6 m

Table 2
Test position of indoor environment parameters.

Indoor environment parameters	Ankle	Waist	Head
Indoor air temperature	✓	✓	✓
Indoor relative humidity	✓	✓	✓
Indoor black-bulb temperature		✓	
Indoor air velocity	✓	✓	✓

Note:"✓" means environmental parameters were measured at corresponding positions.