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Evaluation of thermal sensation among customers: Results from field investigations in underground malls during summer in Nanjing, China

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ABSTRACT

Previous studies on thermal sensation have mainly focused on offices and residential buildings, but rarely on underground malls. In this paper, field studies on thermal environment in six underground malls were conducted in Nanjing, China, particularly from customer's perspective. The results showed that when indoor operative temperature (T_{op}) was more than 26 °C, the customers' mean thermal sensation votes (TSV) were lower than PMV. It indicated that they may perceive the warmth to be less dramatic than PMV predicted in underground malls. When T_{op} was below 24 °C, a higher percentage of customers desired a warmer indoor environment. Customers' thermal acceptability (TA) decreased significantly when relative humidity (*RH*) increased from 65% to 75% ($p < 0.01$), and significant changes of TA were recorded when air velocity increased from 0.2 m/s to 0.4 m/s under *RH* ranging from 70% to 80%. The customers' duration time (DT) in malls were different, the mean TSV of customers with DT less than 1 h was significantly different from other customers' TSV ($p < 0.01$). Among customers, those who had spent less than an hour in underground mall perceived the thermal environment to be cooler. In addition, the customers' TSV under outdoor-indoor temperature drop in entrance regions in two underground malls was compared. It showed that setting the transitional space with non-air-conditioned system or at a slightly higher temperature would improve the customers' thermal sensation and save energy.

1. Introduction

Underground construction is perceived to be environmental friendly and sustainable, as it provides more protection from climatic influences by constant surrounding soil temperature [1], thus ensuring pleasant thermal comfort with less energy [2,3]. With the speeding up of Chinese urbanization process, the contradiction between urban land demand and supply had increased significantly. More and more underground structures appeared, and were used as crowed shopping malls, etc. Nanjing is one of the typical Chinese metropolises in Hot Summer and Cold Winter climate zones, with a population of more than 8 million. Many underground malls have been or will be constructed in this city. The rapid development of underground malls brings problems regarding thermal environment and energy consumption.

Many field studies for thermal comfort have been conducted in different climate regions [4–7] and involves a variety of building types such as office buildings [8], residential buildings [9–11], educational buildings [12–14] and museums [15,16]. During these studies, how air temperature, air velocity, relative humility, globe temperature impact on occupant's thermal comfort was analyzed. Recently, M. Luo [17] explored the relationship between occupants' anticipated control of their thermal environment and the thermal sensation. How the occupants' weight [18], gender [19,20] and age [21,22] impact their thermal sensation was also discussed. However, most of these studies considered aboveground buildings, and few studies focused on underground constructions, especially for underground malls.

Recently, with an increasing number of underground structures appearing, the thermal environment and indoor air quality [23–25] of underground space has received much attention. Jieun Han et al. [26] proposed a wider comfort range for underground railway in Seoul based on field studies. In China, S. Hu et al. [27] performed a field test of thermal environment parameters and obtained subjective information via questionnaires in underground railway trains in different cities. Y. Li [28] explored the occupant's thermal comfort in different underground constructions in different areas in China. However, the thermal environment and people's behaviours in a subway are usually different from the conditions in malls, despite both cases being underground.

Chow and Fung [29] studied 84 shopping malls and discovered

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occupants felt comfortable at mean temperature of 20–24 °C, relative humidity of 50–65% and wind speed of 0.2–0.4 m/s. Compared with the department store, C. Chun et al. [30] found that the acceptable range of temperature was wide for underground shopping malls. Lam et al. [31] examined the thermal conditions of 10 shopping malls and detected temperatures were 1–2 °C lower than 25.5 °C in summer. Recently, with setting the air conditioning thermostat at 25.5 °C, Tin Fai Kwok et al. [32] presented a thermal sensation profile of visitors in Hong Kong's shopping mall. However, most of these studies were conducted in above-ground malls rather than underground malls.

Nanjing belongs to the Hot Summer and Cold Winter climate zone in China. The *RH* in underground malls was higher, even reaching to 90% [33,34]. The study by Zhang et al. [35] and Shi et al. [36] indicated that subjects' thermal responses in hot-humid areas to humidity differed from those of people in other climates. He Y et al. [37] studied occupants' adaptation to both temperature and humidity in air conditioned dormitories of university in Changsha in hot-humid climate. Li et al. [38] studied the human responses to high *RH* and CO_2 concentration in underground confined spaces. Jin et al. [39] showed that the impact of humidity on human responses was significant when the *RH* was above 70%. Whether higher *RH* leads to different impacts on customers' thermal acceptability and TSV is not completely clear in underground malls.

When customers enter underground malls, a significant individual difference is that their duration time (DT) is different. Different DT may have different impact on thermal sensation. G. Liu [40] discussed the relationship between length of waiting time and thermal comfort of passengers at a high-speed railway station. When customers enter or exit malls, the customers would experience great temperature drop because of the temperature difference between the indoor and outdoor. A.K. Mishra et al. [41] found that the visitors' TSV had a significant relationship with the outdoor temperature when the visitor remained inside for 20 min or less in a museum. The results of Luo M and Zhu. Y's work on exploring the influence of thermal experience on occupants' thermal adaptation showed that both outdoor and indoor thermal exposures can influence occupants' thermal adaptation [42,43].

So far, few investigations have reported on thermal environment and customers' dynamic thermal sensation in malls, especially in underground malls. Performing research on customers' thermal sensation can provide information that are helpful for improving underground mall thermal design, moreover, it can improve attractiveness of underground shopping malls and saving the energy consumption.

Accordingly, field studies on customers' thermal sensation in 6 underground malls in Nanjing, China were conducted during summer in 2015 and 2016. The aims of the study are as follows: a) comparing actual TSV from questionnaires with PMV to obtain the actual customers' thermal perceptions in underground malls; b) explore how *RH* impact on the customers' thermal sensation; c) find out the relationship between customers' thermal sensation and customers' duration time in underground malls; d) estimate the customers' TSV variation under outdoor-indoor temperature drop in the entrance region.

2. Methodology

2.1. The malls

Field surveys were conducted from June 1st to September 30th in 2015 and 2016 in six local underground malls as shown in Fig. 1. Mostly, the survey period within a day was 10:00 through 18:00. The 6 underground malls were selected with similar building functionalities in Nanjing, which is located in the JiangSu province in Hot Summer & Cold Winter climate zone of China. All the selected malls were categorized as large-scale department store buildings with more than 3000 m^2 floor area and a very similar open plan layout of the retail space.

The information of the floors, air-conditioning systems and measured points are summarized in Table 1.

All the malls have two separate air-conditioning systems for underground and aboveground floors. The overall system was designed for maintaining indoor conditions at the set air temperature and *RH*, shown in Table 1. However, due to poor management, the indoor temperature and *RH* fluctuate greatly. During summer, all the air-conditioning systems run from 9:00 to 21:00. In order to make specific contrast, investigations also have been performed in some areas in aboveground shopping malls. However, the investigated customers were completely separate in underground malls and aboveground malls.

2.2. Field investigations procedure

The customers were asked outside the malls if they would agree to take part in the survey, and then, the investigations began. First, the investigated customers were asked to read a guide on how to complete the questionnaire, and the staff also provided a brief introduction to the survey. Each volunteer customer conducted the survey through completing a paper questionnaire or using an online questionnaire filling system on WeChat (Scan QR-Code), which is an interaction platform on customers' smartphones. In China, almost all of people have WeChat on their phones. Through the WeChat, the survey tablets were used for data recording instead of paper questionnaires and all records were sent to an online database instantaneously.

The survey consisted of both objective measurements and subjective questionnaire. During the investigation, thermal environment parameters were measured by portable instruments. To explore the influence of thermal experience on customers' thermal perception and analyse how the customers' duration time impact on their TSV, the customers were tracked in underground malls, with the thermal parameters recorded every 5 min, and the questionnaires were requested to be completed at different intervals in different locations. The survey scheme was shown in Fig. 2. In the first 30 min, the questionnaires were requested to be filled every 5 min; afterwards, the time interval was 15 min.

2.3. Objective measurements

The thermal parameters including internal air temperature (T_a), mean radiation temperature (T_R), relative humidity (*RH*), air velocity (v) and concentrations of CO_2 were measured. The instrument range and accuracy are shown in Table 2.

The operative temperature T_{op} could be calculated according to the conditions introduced in ASHRAE Standard55 [44]. Because the investigations occurred simultaneously in different malls, multiple instruments were involved, including LSI thermal comfort device, AM-101 PMV and PPD indices meter, hot wire anemometer, self-recording thermometer and hygrometer and self-recording globe thermometer, as shown in Fig. 3. The measurement points were set in different merchandise sections of the buildings, such as the clothing, cosmetics, catering, and leather products sections. Because customers were moving around, it was deemed suitable to position the instruments at head level to minimize their disturbance to customers.

2.4. Subjective questionnaire

The field questionnaire was designed based on the Thermal Environment Survey of Standard 55 [45]. The questionnaire consists of two main parts: I) Basic information: the name, height, weight and age and the clothing and level of activity of customers and II) Thermal comfort: the thermal sensation, thermal preference, humid sensation, thermal acceptance and acceptance of air movement of customers. The main contents of subjective questionnaire are included in Fig. 4.

Because of the need to fill in the questionnaire many times, it was commonly found that people were reluctant to fill in a lengthy questionnaire because of the time required; as a result, the data quality could be much compromised. The main survey tablets used for data

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