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Thermal perceptions, general adaptation methods and occupant's idea about the trade-off between thermal comfort and energy saving in hot–humid regions

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ABSTRACT

A field study conducted in workplaces and residences in Taiwan is carried out to clarify two questions in detail: (1) do people in the tropical climate regions demonstrate a correlation between thermal sensation and thermal dissatisfaction the same as the PMV–PPD formula in the ISO 7730; and (2) does the difference in opportunities to choose from a variety of methods to achieve thermal comfort affects thermal perceptions of occupants? A new predicted formula of percentage of dissatisfied (PD) relating to mean thermal sensation votes (TSVs) is proposed for hot and humid regions. Besides an increase in minimum rate of dissatisfied from 5% to 9%, a shift of the TSV with minimum PD to the cool side of sensation scale is suggested by the new proposed formula. It also reveals that the limits of TSV corresponding to 80% acceptability for hot and humid regions are −1.45 and +0.65 rather than −0.85 and +0.85 suggested by ISO 7730. It is revealed in the findings that the effectiveness, availability and cost of a thermal adaptation method can affect the interviewees' thermal adaptation behaviour. According to the discussion of interviewees' idea about the trade-off between thermal comfort and energy saving, it is found that an energy-saving approach at the cost of sacrificing occupant's thermal comfort is difficult to set into action, but those ensure the occupant's comfort are more acceptable and can be easily popularized.

1. Introduction

After the adaptive model of thermal comfort became the spirit of changes to the current version of ASHRAE Standard 55 [1,2], more and more researchers (e.g., Zhang et al. [3], Han et al. [4], Wong and Khoo [5], Henry and Wong [6], Yang and Zhang [7]; Cheng and Ng [8], Rangsiraksa [9], Kwok [10], de Dear and Fountain [11], Chan et al. [12], and Hwang et al. [13]) have paid attention to the study on thermally comfortable environment in the hot and humid climate, both in air-conditioned spaces and naturally ventilated spaces. According to PMV–PPD formula [14], the predicted mean vote between the limits of ±0.85 corresponds to the point where 80% of the residents feel satisfied. In line with this criterion, all the former studies determined the acceptable conditions for 80% acceptability from a linear regressive model of thermal sensation and air temperature without investigating the applicability of PMV–PPD formula to hot and humid region. Humphreys and Nicol [15] had suggested that people who live in the tropical climate regions would prefer a cooler-than-neutral thermal condition.

The merit of the PMV–PPD formula, as shown in Eq. (1), is that it reveals a perfect symmetry with respect to thermal neutrality (PMV = 0). At PMV = 0, a minimum rate of dissatisfied of 5% exists.

$$PPD = 100 - 95.0 \times \exp\left[-0.03353 \times PMV^4 - 0.2179 \times PMV^2\right] \quad (1)$$

As more and more field studies have found that thermal neutrality does not correspond to the optimal condition, the application of PMV–PPD curve in cold or hot climates is under suspicion. The point is when Fanger developed the PMV–PPD model, the correlated percentages of dissatisfied was not obtained by direct inquiry but by definition. Satisfaction is synonyms to the three categories (slightly cool; neutral; slightly warm) in the middle of the seven-point scale, while cold dissatisfaction is synonyms to "cool" and "cold" categories, and warm dissatisfaction to "warm" and "hot" categories. Some studies [16,17] tried to

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amend the correlation between dissatisfaction percentage and thermal sensation by redefining dissatisfaction. For example, Mayer [16] conducted a field study in Germany and gave a new definition of uncomfortable cold sensation by accessing the votes for cold, cool and slightly cool for cold climates. A new correlation between PMV and PPD for cold climate regions was also suggested in Mayer's article.

As none of the amendments made for the correlation of PMV–PPD has been suggested for hot–humid climate, a question is very important and must be answered by thermal comfort researchers: do people in the tropical climate regions demonstrate a correlation between thermal sensation and thermal dissatisfaction the same as the PMV–PPD formula in the ISO 7730? This motivated us to conduct a comprehensive field survey on occupants' thermal sensation, preference and adaptation in workplaces and residences in Taiwan. Through comparisons on measured data of field survey and original data of Fanger's experiments [18], this study is expected to examine the applicability of PMV–PPD formula in hot and humid regions and further suggest a new correlation if the formula fails to apply.

In addition to a variety of adaptation methods, occupants in residences have more opportunities to choose the methods of adaptation to achieve thermal comfort depending on their needs and their preferences. On the contrary, the methods and opportunities are limited to a certain degree in the workplaces. For example, usually in offices the control of air temperature for individuals and an electrical fan for increasing air velocity are not provided, even the clothing level is not as free for adjustment as in private spaces. Does the difference in opportunities to choose from a variety of methods to achieve thermal comfort affects thermal perceptions of occupants? It is worth to discuss in detail.

Additionally, understanding occupants' most preferred method of adaptation may help to understand the implementation result of some low-cost or zero-cost methods, as advocated by the energy related department of Taiwan government in order to reduce energy consumption in the use of A/C systems. It is also hoped that the results of this study will contribute to this goal.

2. Field experiments design

The two major approaches used to access thermal comfort are field experiments and laboratory chamber experiments. The former method is adopted in this study. Field experiments are respectively carried out in residences and workplaces. The surveyed sites scatter around Taiwan and are equipped with either HVAC systems or household air-conditioners. During the field experiments, none of the interviewees is asked to turn on, turn off, or adjust room temperature settings of the A/C system; the use of which is solely based on the users' demand. Analysis on the data gathered reveals that all the visited workplaces had their air-conditioning systems in operation during the field surveys, while a certain number of air-conditioners in residences visited are turned off. The utilisation of not only the A/C system but also other equipments, such as electrical fans, windows and so on, remains in same condition to the point before the interviews began.

The interviewees either work in the offices or live in the residences visited. The examiner arrived at the visited sites upon previously arranged time. After the measurement instruments are set up and a brief introduction to the experiment procedures is given, the interviewees resume their routine activities and were asked to fill in a questionnaire after 20 min time. Contained in the survey sheet are the interviewee's demographic information, most preferred method of adaptation when they sensed thermal discomfort, and votes for thermal sensation, thermal acceptability, and thermal preference with regard to the current condition. The thermal sensation vote is based on the ASHRAE seven-point sensation scale. Thermal acceptability vote aims to understand if the interviewee considers the current environment condition as acceptable. If the thermal condition is unacceptable, a further question is asked to see whether the discomfort is due to coolness or warmness. Thermal preference vote employs McIntyre's scale of preference, namely: "I wish for a warmer or cooler thermal condition or no change".

As the interviews proceed, the observation instruments continuously record the thermal conditions of the surrounding environment. The environmental parameters measured are air temperature, humidity, air velocity and global temperature. All the accessed environmental parameters will be converted into one single indexing parameter: new effective temperature, ET^*, which had been used in many other studies. The new effective temperature is the temperature at 50% relative humidity that yields the same total heat loss from the skin as for the actual environment. In the following data analyses, it also serves as an indicator of thermal environment condition. While the instruments record the surrounding environmental conditions, the examiner observed and kept track of the interviewee's clothing level as well as the utilisation of environment control equipments, such as air-conditioner, electrical fan, or windows.

3. Thermal perceptions

3.1. Regression analysis, neutral temperature and comfortable zone

In order to facilitate the comparison with ISO 7730 standard, which is mainly developed from data gathered in Fanger's laboratory chamber experiments, data processing in our field experiments have reached fully compliance to Fanger's approach [18]. In the approach of Fanger, to eliminate the influence of individual subjectivities, interviewees' responses were grouped into different temperature intervals with an increment of 1.1 °C (2 °F) represented by the mean temperature of each interval. In this way, all the measured data, with a total number of 968 gathered in workplaces and 707 in residences, were grouped by the corresponding air temperature (ET^*) into the closest temperature interval, followed by the calculation of the average votes for thermal sensation, thermal preference and thermal acceptability for each temperature interval. Both homes and workplaces have more than 40 samples under each temperature interval. As A/C systems in all visited workplaces were in operation, the measured air temperatures fell into the temperature range between 22.0 and 30.0 °C. With the use of a variety of environmental control equipments in the visited residences, the measured air temperatures scatter in a broader range (between 20.0 and 32.0 °C) than those measured in workplaces.

A simple method frequently used in thermal comfort studies for the calculation of neutral temperature is to access the relationship between thermal sensation and indoor climate. A linear regression analysis is employed to understand the relation between thermal sensation and indoor climate, as expressed in terms of ET^*. Due to the differences in subjects' clothing levels and activities conducted, as well as the availability of opportunities to control the surrounding indoor climate, the data collected from both types of sites were analyzed separately. Table 1 shows the obtained regression curves for both sites. The accessed linear regression models for both cases are statistically significant with a R^2 value of 0.982 and 0.907, respectively. The neutral temperature is defined as the temperature in which the occupants feel neither warm nor cool. In practice, the neutral temperature can be obtained by applying a TSV value of 0 to the accessed regression equations. The neutral temperatures, as illustrated in Table 1, are 26.1 and 25.8 °C for residences and workplaces, respectively. The neutral temperature for residences was slightly higher than that for workplaces by