Developing the methodology to investigate the thermal comfort of hot-humid climate under different ventilation modes

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Abstract. This study presents the development of an adaptive thermal comfort model for the hot and humid climate in Taiwan. We conducted field surveys in several offices and classrooms at National Taiwan University through a portable system which used Raspberry Pi, a small single-board computer, as processors to connect environmental sensors and as questionnaire user interface platform. This allowed us to collect indoor environmental data and investigate subjects’ responses simultaneously. The advantage of the portable system is to expand the pools of data collection. The field surveys can be set up and conducted in different classrooms or offices efficiently. In total, this study collected 257 samples. The thermal comfort profiles of two different ventilation strategies (i.e., air-conditioning (AC) and natural ventilation (NV)) were analysed. The results indicate that the actual percentage of dissatisfaction (APD) has the same trend as the predicted percentage of dissatisfaction by Fanger (PPD). However, when the predicted mean vote (PMV) is in the range of -0.5 to 0.5, the APD is approximately 20% higher than the PPD. The study also found that PMV underestimates subjects’ thermal sensation in both ventilation strategies.

1. Introduction

Environmental quality has a significant impact on people's health, productivity, and psychology. Moreover, a pleasant indoor thermal environment not only offers comfortable thermal sensations to occupants but also affects the cooling or heating demand. ASHRAE [1] defined thermal comfort as a "condition of mind, which expresses satisfaction with the thermal environment and is assessed by subjective evaluation." The most commonly used methods for estimating indoor thermal comfort is Fanger's Predicted Mean Vote model (PMV model) [2].

The PMV model developed by Fanger [2] was meant to estimate the "average" thermal sensation that a group of people would report when occupying a given space. This model combines multiple environmental parameters (air temperature, air velocity, relative humidity, and radiant temperature) and two individual parameters (metabolic rate and clothing level) to predict an occupant's thermal sensation, and the data is collected in a controlled climate chamber. Fanger also developed another equation to correlate the PMV to the Predicted Percentage of Dissatisfied (PPD), which indicates the predicted percentage of people that feel dissatisfied in the PMV comfort index. However, studies have found that the thermal comfort in buildings involves not only environmental and individual parameters but also involves physiological, psychological, social, cultural aspects of the occupants and even geographical location [3]. Researchers have been using adaptive approaches to improve the number of satisfied people [4].
People have a natural tendency to adapt to surrounding environmental changes by adjusting their expectations and preferences [5]. Yang et al. [6] examined the application of PMV in a hot-humid climate region and identified that occupants who lived long-term in hot-humid climate tend to identify warm conditions in PMV prediction as neutral environments. A field study conducted in Hong Kong by Fang et al. [7] indicated that the PMV model underestimated the human thermal sensation when the operative temperature was lower than 27 °C. Barbadilla-Martin et al. [8] investigated adaptive thermal comfort in the southwestern area of Spain, and the results showed that the neutral condition there was higher than the PMV model’s predicted condition. In other words, they viewed PMV’s warm condition as neutral. However, due to the equipment limitations, most of the surveys were conducted in a confined chamber instead of the places where occupants have their every-day activities. Apart from this, Taiwan has not yet established enough data samples in the aspect of adaptive thermal comfort.

We have studied several options such as a movable weather station cart, fully equipped data acquisition and sensor systems, and low-cost microprocessor systems. The solution was to combine low-cost microprocessors with high accuracy sensors. In recent years, the usage of low-cost embedded systems has become a popular way of prototyping and data collecting. Raspberry Pi as an embedded system is a credit-card sized and low-cost computer integrated with an operating system and graphical user interface. Li et al. [9] used a Raspberry Pi equipped with temperature and motion sensors to send the presence and temperature data to the database. Aftab et al. [10] designed and implemented an occupancy-predictive HVAC control automation system by using Raspberry Pi 3. Tang et al. [11] developed a prototype smart home intelligent control architecture, and the Raspberry Pi acts as the controller to communicate between the mobile application and the luminaires. With these in mind, we chose to use Raspberry Pi as the base hardware to connect with different sensors and made the whole device portable.

The objective of this study is to present how we investigate Taiwan’s thermal sensations by portable data collecting system, to develop an adaptive thermal comfort model for the hot-humid climate in Taiwan, and to compare the results with past studies. With the developed portable system, we can collect more samples in different daily-life conditions. The thermal comfort profiles of two different ventilation strategies (i.e., air-conditioning (AC) and natural ventilation (NV)) were analyzed. Based on the data collected, we developed an adaptive thermal comfort model that can be easily used by other applications in the future.

2. Methodology
In this research, we intended to develop a portable and light-weighted system which can collect occupants’ feedback and simultaneous indoor environment and store them in the database systematically. We used Raspberry Pi as the processor to connect the environmental sensors, the user interface, and the database. The hardware part of the system composed of Raspberry Pi, thermometer, hygrometer, black-bulb thermometer, anemometer, and a 7” touchscreen display as shown in figure 1 and the software part was installed in Raspberry Pi processor and a cloud server.

We had three different environmental sensors installed and connected to Raspberry Pi. First, we used DHT22 (as shown in figure 1 (b)) for measuring temperature and relative humidity, which combined a capacitive humidity sensor and a thermistor to sense the dry bulb temperature and relative humidity of surrounding air. The analog signal was then converted into the digital signal through the internal chip and then spit out to the data pin. For measuring air velocity, we used F200 [12] (as shown in figure 1 (d)) from Digital Controls, which was a high-performance sensor with a digital interface (UART or I2C), and can be connected to microprocessors easily, and its measurement range is 0.15 m/s to 10 m/s (30 fpm to 2000 fpm) which was suitable for our case. Since Raspberry Pi can provide power to both F200 and DHT22, the device was space-efficient, and the socket requirement of the overall system was reduced. For measuring globe temperature, we had thermometer TRH-300 covered with a customized metal black-globe, which is 8cm in diameter. The black-globe temperature sensed by the thermometer is a balance between the heat gain and loss caused by radiation and convection [13]. Equation (1) was
then used to convert the black-globe temperature to the mean radiant temperature used in PMV equations.

\[
T_{mrt} = \left[ \left( T_g + 273.15 \right) + \frac{h_{cg}}{\varepsilon \times D^{0.4}} \times \left( T_g - T_a \right) \right]^{0.5} - 273.15
\]

where \( h_{cg} \) : globe’s mean convection coefficient (Black globe=1.1×10^8×v_{a0.6}), \( v_a \) : wind velocity [m/s], \( \varepsilon \) : emissivity of sphere (=0.95), \( D \) : diameter of the sphere [mm], \( T_g \) : globe temperature [°C], \( T_a \) : air temperature [°C].

We mounted a 7” touchscreen display as part of the user interface, which only required a ribbon cable that connected to the DSI port on Raspberry Pi. The screen displayed the questionnaire and occupants’ response and the indoor environment at that moment would be sent directly back to the database on the cloud when the occupants clicked “submit.” The questionnaires had two parts. The first part was to collect for the subjects’ information such as age, gender, type of clothes, and metabolic rate. In the second part, subjects were asked to provide their response to the thermal environment in accordance with the scale “-3 = cold, -2 = slightly cool, -1 = cool, 0 = neutral, 1 = slightly warm, 2 = warm, 3 = hot.” Thermal preference was also asked for in the questionnaires to enhance the accuracy of the responses, and a three-point scale method was adopted (prefer warmer, prefer cooler, no change). During the survey, the researcher would explain the contents and process of the questionnaire and invited the students or workers who were willing to come to the system to fill out the questionnaire. The system was usually set up and located in the back part of the classroom or a typical seat in an office. The questionnaire process has been approved by the National Taiwan University’s review board (NTU-REC 201905HS016).

Once the subject submitted his/her questionnaire, programs in Raspberry Pi would trigger the sensors to capture the indoor environmental data at that moment (air temperature, relative humidity, mean radiant temperature, air velocity). The collected responses and environmental data would then be submitted to a cloud database (MySQL) through Wi-Fi or 4G service. Figure 2 presents the overall system structure.

**Figure 1.** Raspberry Pi system (a) TRH-300: black-bulb thermometer; (b) DHT22: thermometer and hygrometer; (c) 7” touchscreen display; (d) F200: anemometer.

**Figure 2.** System Structure.

3. Results
Thermal comfort surveys were conducted between March to May in 2019 at ten different types of classrooms and office at National Taiwan University. A total of 257 questionnaires were collected, including 174 in AC mode and 83 in NV mode. During the survey period, the outdoor mean temperature was 24.17°C, ranging from 15.0-30.8°C, and the mean relative humidity was 72.38%, ranging from 50.1%-83.3%.
3.1. Indoor environmental conditions during the survey

Table 1 shows the summary of indoor environmental data and subjects’ variables collected during the experiments in different ventilation strategies. In NV mode, the indoor air temperature was slightly higher than ones on AC mode; but they both fall inside the typical thermal comfort range, which shows that occupants tend to actively maintain the indoor environment within a comfortable range if possible. The interior relative humidity was also quite similar between two ventilation strategies, around 72.5%. Compared with previous studies [4, 8], the relative humidity in Taiwan was much higher than that in other climate zones, which might be a significant reason why our comfort profile seems different from others. For the mean air velocity, 0.12m/s and 0.08m/s were obtained in AC mode and NV mode, respectively. Most of the time, the air velocity was close to 0.

Clothing had a substantial impact on thermal comfort. Previous research has found that the clothing level of subjects had a high correlation with outdoor air temperature [14]. Figure 3 showed the scatter plots between clothing level and outdoor air temperature, while there was significant variation between occupants within the same outdoor temperature range, the coefficient of correlation is -0.47. The overall trend fit previous research’s description - when the outdoor air temperature increased, the clothing level decreased. The average metabolic rate was 1.21, and the corresponding physical activities were sitting, writing, and typing, which fit the typical everyday activities on the campus.

| Table 1. Indoor environmental and personal variables. |
|------------------------------------------------------|
| **Ventilation Mode**                                 |
| **Variables** | **AC** | **S.D.** | **Max.** | **Min.** | **NV** | **S.D.** | **Max.** | **Min.** |
| Td(°C)       | 23.67  | 1.67     | 26.5     | 18.4     | 24.24  | 1.44     | 26.8     | 21.6     |
| RH(%)        | 72.06  | 6.48     | 83.3     | 50.1     | 73.05  | 3.99     | 81.7     | 67.5     |
| Vd(m/s)      | 0.12   | 0.37     | 2.02     | 0        | 0.08   | 0.25     | 1.51     | 0        |
| Clo          | 0.67   | 0.23     | 1.37     | 0.37     | 0.65   | 0.24     | 1.49     | 0.37     |
| Met          | 1.22   | 0.18     | 2        | 1        | 1.18   | 0.18     | 1.7      | 0.7      |

3.2. PMV and TSV

The scatter plots of the thermal sensation vote (TSV) derived from the study and PMV calculated based on Fanger’s model, as shown in Figure 4, indicating that the correlation between PMV and TSV in both AC and NC mode were positive and the neutral values of PMV and TSV were also similar. However, it also showed that in Taiwan no matter under AC condition or NV condition, people's thermal sensation was more sensitive than that of a typical PMV scale.

In a previous study, Humphreys and Nicol [15] comprehensively explored the difference between PMV and TSV and found PMV prone to overestimate subject’s warmth sensation in a warm environment. Nevertheless, our results showed that PMV underestimated a subject’s thermal sensation in both ventilation strategies. On the other hand, we can also find that PMV was more reliable in AC mode than NC mode, which was consistent with previous studies. We were collecting more data for further analysis at this moment. We then developed an adaptive thermal comfort model by linear regression, as shown in equation (2) and (3). These models can be easily used for further applications.

\[ aPMV = 0.45 \times PMV + 0.053 \] (Air-conditioning) (2)

\[ aPMV = 0.18 \times PMV + 0.147 \] (Natural ventilation) (3)

3.3. PPD and APD

To calculate the actual percentage of dissatisfied (APD), the interval of PMV was set to 0.5, and APD was equal to the sample size divided by the number of dissatisfied people (we categorized people “prefer warmer” and “prefer cooler” as dissatisfied people in this calculation). By comparing the PPD and APD in Figure 5, we can find that the trend of APD was not far off from the trend of PPD. However, when the PMV index was in the range of -0.5 to 0.5, the APD was approximately 20% higher than the PPD, and the minimum APD was 21%, which was much higher than Fanger's minimum of 5%. Also, since...
the weather in Taiwan from March to May was not hot enough, only small amounts of samples with PMV higher than 1.5 have been collected for detailed analysis. More comprehensive data was required for further development.

4. Discussions

Most of the questionnaires collected in this study were from the spring period of Taiwan, and the weather is moderate. Therefore, most of the TSV is between -1 and 1. While the daily-life sensation was precious to capture a whole spectrum of thermal sensations, as people tend to keep themselves in a comfortable environment, it was necessary to conduct some experiments in a controlled environment for collecting samples of the extreme spectrum. Besides, the extension of the experimental period is another way to obtain more data at different thermal conditions and is planned.

Figure 6 shows the scatter plot of TSV and PMV from data collected in ASHRAE’s Thermal Comfort Database II’s [16]. Samples from Asia and hot-and humid were chosen for comparison. However, the samples in the database do not cover the entire spectrum (it only provides hot conditions data for NV and moderate conditions for AC). We mixed all the samples. The slope of the ASHRAE data’s TSV and PMV regression is similar to our AC conditions, but the neutral condition was higher than our results and indicated that people in those studies preferred slightly warmer condition.

The average relative humidity values in our study (72.4%) were also much higher than the average RH of samples collected from ASHRAE database (57.4%). Therefore, we suspect that relative humidity might be an essential environmental factor that affects the overall thermal comfort profile of Taiwan. However, the PMV model’s original study and data in ASHRAE database do not fully cover the
spectrum of a higher range of relative humidity. Consequently, this may be one of the reasons that the TSV in Taiwan’s comfort profile, especially natural ventilated condition, was very different compared to other studies.

Besides, Shortwave solar radiation landing on occupants may cause thermal discomfort [17]. However, Fanger's PMV index did not mention shortwave radiation. Therefore, the impact of solar radiation might be a reason causing discrepancies of results collecting spaces from the everyday condition and results collecting from climate chamber.

5. Conclusions

Compared to previous field studies, the portable and light device system developed in this study can help researchers collect a massive amount of samples systematically and efficiently.

In this study, we investigated the thermal comfort profiles of occupants under two different ventilation strategies (i.e., air-conditioning [AC] and natural ventilation [NV]), and the difference between PMV and TSV for the hot-humid climate. In total, 257 questionnaires were collected. The comparison between PPD and APD index indicated that APD has the same trend as the PPD index. However, when the PMV index was in the range of -0.5 to 0.5, the APD was approximately 20% higher than the PPD. The study also found that the PMV underestimated subjects’ thermal sensations in both ventilation strategies, which was inconsistent with previous studies, especially for the natural ventilated condition. Further studies are required to verify the possible cause.

Since our survey was conducted from March to May, future work should cover another season in Taiwan, to obtain a more accurate and more comprehensive thermal comfort data. It is also necessary to modify the PMV equations and to consider the shortwave solar radiation in thermal comfort calculation process in order to improve the thermal sensation prediction.

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