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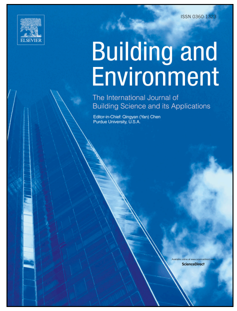

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Field study on adaptive thermal comfort in typical air conditioned classrooms

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Abstract: This study investigates adaptive thermal comfort in air conditioned classrooms in Hong Kong. A field survey was conducted in several typical classrooms at the City University of Hong Kong. This survey covered objective measurement of thermal environment parameters and subjective human thermal responses. A total of 982 student volunteers participated in the investigation. The results indicate that students in light clothing (0.42 clo) have adapted to the cooler classroom environments. The neutral temperature is very close to the preferred temperature of approximately 24°C. Based on the MTSV ranging between -0.5 and +0.5, the comfort range is between 21.56°C and 26.75°C. The lower limit is below that of the ASHRAE standard. Of the predicted mean vote (PMV) and the University of California, Berkeley (UCB) model, the UCB model predictions agree better with the mean thermal sensation vote (MTSV). Also, the respective fit regression models of the MTSV versus each of the following: operative temperature (T_{op}), PMV, and UCB were obtained. This study provides a better understanding of acceptable classroom temperatures.

Keywords: Classroom; Air conditioned; Thermal adaptation; Thermal sensation; Prediction models

1. Introduction

Adaptation is defined as "the gradual lessening of the human response to repeated environmental stimulation" [1], and mainly consists of three processes: physiological adaptation (adjusting body temperature, sweating, etc.), psychological adaptation (expectation and preference) and behavioral adaptation (adjusting clothes, operating windows, using fans, etc.)[2]. Different from the PMV model, adaptive comfort model emphasizes the effect of human, i.e. the interaction between human and the ambience, which can extend comfort range [3]. This explains why people have moderate sensation in an extreme thermal environment.

In many previous investigations, the adaptive thermal comfort was analyzed and the adaptive models were developed based on the data from naturally ventilated (NV) buildings in different climatic zones [4-8]. They were supposed to be applied to NV buildings. To date, only limited studies explore adaptation in the mechanically conditioned environments. As emphasized by Schweiker et al. [4], more studies were quite needed. de Dear et al. [6] analyzed the discrepancy between the predicted mean vote (PMV) and Actual Mean Vote (AMV) in the air conditioned environment and found only behavioral adaptation. The study of Humphrey [7] believed that deviation results from physical, physiological and psychological factors. To explore adaptation in air conditional environment, Yang et al. [8] undertook a series of experiments in a well-controlled chamber and found that occupants who had resided long time in regions with hot and humid climate in summer perceived hot (or extreme) condition as less extreme due to psychological adaptation. Also, the psychological adaptation can neutralize occupants' actual thermal sensation. Brager and de Dear [3] also agreed with this opinion, while Liu et al. [9] insisted that physiological adaptation exerted more influence than the other two processes after conducting series of field trials both in China and U.K.

In a typical office space, the steady-state thermal sensation would be correlated with the PMV against the operative temperature or the effective temperature. A neutral temperature can be obtained at the intercept of a linear regression line with the temperature axis [10, 11]. This is the perceived temperature by an occupant in a space that offers a "neutral feeling of thermal sensation" and the occupant votes neither the "warm" nor "cool" side. A semantic differential scale of evaluation on thermal sensation has been widely adopted in many thermal comfort studies, with the results adopted in developing design criteria have been widely used in many air-conditioned office buildings in Hong Kong [12].

Recently, the Hong Kong government promotes 25.5 °C for AC office environment in general. Besides encouraging the occupants to dress in lighter clothing, an AC design tactic is to increase air movement to allow high room temperature setting in summer [13-16]. The preceding analysis, particularly in Hong Kong, revealed that most of the investigations focus on the office buildings. However, the energy consumption of educational buildings, as one of kind of general building, has dramatically increased. However, while most of the earlier studies were mainly carried out in offices, few studies are on educational buildings. Similarly, a host of thermal comfort investigations considered natural ventilation with less consideration for mechanically conditioned classrooms. Nevertheless, in Hong Kong, nearly all the classrooms are ventilated by HVAC systems with low-temperature set-points [17, 18]. Therefore, it is imperative to carry out field surveys of characteristic adaptive thermal comfort in AC classrooms for better insight into the temperature set-points for thermal comfort, which is beneficial for the optimization control of Heating Ventilation and Air Conditioning (HVAC) systems.

This paper, therefore, investigates occupants' adaptation to the air conditioned university classrooms in Hong Kong. A field survey was carried out in the mechanically conditioned classroom in Hong Kong from August to October in 2015, which is located in Southern China and characterized by the hot and humid climate in the summer. In this study, the environmental parameters, including air temperature, relative humidity, air velocity, and mean radiant temperature were measured. Also, the study conducted subjective survey wherein occupants were asked to answer thermal comfort questionnaires. Based on the survey data, two thermal comfort models, the UCB [19] and PMV [20] models, were validated. Finally, the neutral temperature and thermal comfort range in Hong Kong classrooms were obtained and analyzed to provide a suitable reference for evaluating the thermal environment and optimizing the control of HVAC systems for Hong Kong classrooms.

2. Methodology

2.1 Hong Kong climate

Hong Kong is located at latitude 22°18'N and longitude 114°10'E, according to the climatological method of classification, the weather of Hong Kong is classified as "Humid Subtropical Climate." [21]The spring season is short, and the change of light fog is high. In summer, i.e., between May and September, the weather is mainly hot and humid with showers or occasional thunderstorms. The region witnesses decrease in relative humidity between October and December. Figure 1 shows the mean monthly variation of temperature and relative humidity in Hong Kong. As shown, nearly all of the average monthly relative humidity exceeded 70%. In summer, all the three mean months' temperature is higher than 28 °C. Therefore, the diurnal and year round temperature profiles render the opportunities for adaptive comfort tempertaure (ACT) control instead of operating the air-conditioning systems to meet the usual single set-point of either 23 °C for high grade buildings, 24 °C for average buildings or 25 °C for government buildings [17].

2.2 The surveyed buildings

The study involved field surveys that were conducted in Hong Kong, in Southern China. The study was comprised of two major parts. The first part was an objective measurement, including onsite indoor thermal environment monitoring. For the second part, occupants provided their subjective answers to the thermal comfort questionnaires. The onsite investigations procedure was similar to that of previous field studies [22, 23]. The measurement points were set base on the ASHRAE 55-2013 [24] and ISO standard 7730 [25]. All the data and survey results were analyzed using SPSS 17.0 with a significant level of 0.05.

This field investigation was conducted in several typical classroom mock-ups with the central air-conditioning system at the City University of Hong Kong. The classroom was located in a fully enclosed environmental chamber served by ceiling diffusers for general cooling and dehumidification, which were controlled by a central cooling system. Because most previous studies were conducted with mixing ventilation, the room air distribution employed was mixing ventilation for easy comparison. Figure 2 presents the setup of a typical classroom. The subjects were seated conducting typical academic tasks without talking. The classroom was kept in steady conditions during the survey which lasted for over half an hour.

2.2 Measurement and questionnaire

In this study, the measured physical parameters include the air temperature, globe temperature, and air velocity. In term of the ASHRAE 55-2013 [24] and ISO7730 [25] requirements for seated occupants, thermal parameters were measured and recorded at 0.6 m height. Mean radiant temperature (T_{mrt}), and the operative temperature was calculated according to ISO Standard 7726-2002 [26].

The mean radiant temperature (T_{mrt}) for forced convection was calculated from the measured T_g, V_a, T_a, globe emissivity (ε_g, assumed to be 0.95) and diameter (D, approximately 150 mm) [24-26]:

$$T_{mrt} = \{(T_g + 273)^4 + \left[\frac{(1.1\times10^8\times V_a^{0.6})}{(\varepsilon_g\times D^{0.4})}\right] \times (T_g - T_a)\}^{1/4} - 273 \quad (1)$$

The operative temperature (T_{op}), which considers the impact of air temperature, mean radiation temperature and air velocity on thermal comfort, was calculated by the following equation [24]:

$$T_{op} = (T_a + T_{mrt})/2 \quad (2)$$

Two kinds of instruments, omnidirectional hot-wire anemometers and ultrasonic anemometer, were employed to measure the thermal parameters. They were proved to be capable of accurately and efficiently measuring indoor thermal parameters [27]. The range and accuracy of the instrument were shown in Table 1.

The clothing insulation cannot be measured for most routing engineering applications. The ASHRAE Handbook affords a list clothing insulation of individual garments commonly worn. The insulation of an ensemble is estimated from the individual values using a summation formula [26] as follows:

$$I_{cl} = 0.835\sum_i I_{clu,i} + 0.161 \quad (3)$$

While $I_{clu,i}$ is the effective insulation of garment i, and I_{cl}, as before, is the insulation for the entire ensemble. A simpler and nearly accurate summation formula [28] as follows:

$$I_{cl} = \sum_i I_{clu,i} \quad (4)$$

The ASHRAE Handbook [24] gives insulation with acceptable accuracy for typical indoor clothing. Thus, based on survey clothing information data, the clothing insulation value was estimated using Equation (4).

All measurements were taken in steady states. Every field survey lasted 40 minutes. The test procedure consists of two parts. In the first part, every subject was required to stay in a transition room for learning the information to understand the questionnaires for 10 minutes. And then, the subjects were required to enter and stayed in the typical classroom to conduct the experiment, for lasting 30 minutes. After the first 20 minutes in the typical classroom, the subjects started to answer the questionnaire. Thus, the whole procedure lasted near about 40 minutes, depending on how fast a subject filled the questionnaire. During the field survey, the subjects were told to bring their own reading material or choose any reading materials provided by the research staff during the test (Figure 1). The thermal environmental parameters were recorded after the instruments attained steady values. Then the subjects were asked to complete the questionnaires. Because little variations existed in the microclimatic parameters during the experiments, the average values were used for analysis. The questionnaires were mainly comprised of two parts. The first part mainly asked for the subjects' anthropometric information such as age, gender, weight, height, and type of clothes. In the second part, standard questions about thermal sensation in response to the room condition were asked. The subjects were asked to provide their responses to the thermal environment in accordance with the ASHRAE thermal sensation scale (-3 = cold, -2 = cool, -1 = slightly cool, 0 = neutral, 1 = slightly warm, 2 = warm, 3 = hot). Also, thermal preference was asked in the questionnaire to enhance the accuracy of responses in the evaluation of thermal environment. A three–point scale method (preferring cooler, no change, or warmer) was adopted. The subjects were required to make only one choice from the scale for each of the questions.

2.3 Subjects

A total of 946 healthy undergraduate students were recruited in this survey. Table 2 provides the anthropometric information of the subjects. The subjects, who were all born in and grew up in Hong Kong, have been studying in the surveyed building for more than one year. This implied that the subjects had adapted to the indoor thermal environment in Hong Kong.

2.4 Thermal comfort models

2.4.1 PMV

As the most common thermal sensation model used, the PMV was derived from steady-state heat balance of a human body [20]. Based on experimental data, the equation for the PMV was reported as follows:

$$\mathrm{PMV} = (0.303e^{-0.036M}+0.028)\times[(M-W)-3.05\times10^{-3}\{5733-6.99(M-W)-P_a\}-0.42\{(M-W)-58.15\}-1.7\times10^{-5}M(5867-P_a)-0.0014M(34-t_a)-3.96\times10^{-8}f_{cl}[(t_{cl}+273)^4-(t_r+273)^4]-f_{cl}h_c(t_{cl}-t_a)] \quad (5)$$

Where, M is the energy output from body (W/m^2); W is the using energy of body (W/m^2); Pa is the partial vapor pressure in the air; t_a is the air temperature (°C); f_{cl} is the proportion of dressed and undressed part of body; t_r is the mean radiant temperature (°C); t_{cl} is the clothing surface temperature (°C); and h_c is the thermal convection (W/m^2.k);

The PMV model can predict a mean judgment of the thermal environment from a broad cross-section of people by the seven-point comfort scale.

2.4.2 UC-Berkeley model

Due to some observed limitations of the PMV comfort model, successive research resulted in comprehensive thermal sensation and comfort model for a broad range of environments efforts [19, 29, 30]. The model was developed based on vast experimental data in the controlled environmental chamber at the University of California-Berkeley, upon which the model name (UC-Berkeley) was derived. The model contained local sensation and comfort for each body segment as well as the whole body sensation and comfort. The local thermal sensation model for individual body parts was derived by regression of skin and core temperatures against thermal sensation votes of human subjects and comprised two sections: a static portion and a dynamic portion [31, 32].

The UCB model predicts local thermal sensation with four inputs: local skin temperature, mean skin temperature representing the whole body thermal state and time derivatives of skin and core temperature representing the response to transient conditions. Also, the whole body sensation has two forms [31, 32] – ‘No-opposite sensation’ and ‘opposite-sensation’ – that depends on whether there is any body part that feels significantly opposite to the other regions. Hence, the UCB model includes all the major effects that have been observed in human responses to thermal environments. The structure and the regression coefficients of the model are all available, and it is the first model that addresses human responses to simultaneous asymmetrical and transient thermal conditions.

3. Results

3.1 Indoor thermal parameters

The room air temperature and relative humidity were recorded and compared with the thermal comfort zone of ASHRAE 55-2013 [24]. Figure 3 shows the indoor thermal environmental conditions. In the investigated building, the air conditioning system is used to control the thermal environment in comfort zone according to the ASHRAE Standard 55-2013 [24]. However, the thermal environment was cooler as most of the points exceeding the thermal comfort zone for clothing insulation of 0.5 clo, concentratingin the zone for clothing insulation of 1.0 clo, which indicated that the thermal comfort in air-conditioned classrooms in Hong Kong was much cooler, rather than warmer. Previous studies also found that because of the training in the cooler indoor thermal environment, the subjects adapted and felt comfortable [17, 18]. Chan found that 60% of the workstations in Hong Kong air–conditioned offices were on the cool side [33]. Therefore, energy consumption could be reduced by setting higher room air temperatures.

3.2 Clothing insulation

Clothing is an important factor in achieving thermal comfort at a different temperature. The optimal temperature in an office space located away from the perimeter zone is mainly a function of the occupant’s clothing, of which the selection is influenced by the thermal environment [20]. Therefore, the clothing pattern of subjects has a high correlation with indoor and outdoor temperatures. Figure 4 showed the variation of the clothing insulation with the operative temperature. It was noted that most of the clothing insulations concentrated in the range between 0.3 and 0.6 clo. The mean clothing insulation is approximately 0.425 clo, which was similar to the results of some previous investigations [34, 35], the clothing insulation was maintained at a relatively stable level, approximately 0.45 clo. Also, from Figure 4, although subjects changed their clothing level to achieve comfort at different operative temperature, no significant correlation was found between the clothing insulation and operative temperature in air conditioning buildings. In this study, the subjects wore light clothes for adjsuting thermal comfort. The clothing insulation of most of the subjects was around 0.42 clo.

3.3 Thermal sensation vote

The mean thermal sensation votes (MTSV) are the subjects actual thermal sensations collected during field survey investigation. The predicted mean vote (PMV) [20] is a widely used model to predict human thermal comfort. Based on extensive chamber experiments, a newer thermal comfort model, UC-Berkeley (UCB) thermal comfort model, were developed and reported to predict the overall thermal sensation and local thermal sensation [19]. To examine whether these three indicators show good agreement, Figure 5 presents the comparisons among the PMV and UCB models, the MTSV and T_{op}. Simple linear regression analyses were performed on the PMV and UCB model predictions and MTSV values against T_{op}. The results, shown in Figure 5, indicate strong positive correlations between the two thermal comfort models and T_{op}. Their relationships were obtained as shown in Equations (6) to (8). The correlation coefficients of these indices were found as R^2 = 0.774, R^2 = 0.992, and R^2 = 0.89, respectively for MTSV, PMV, and UCB model. Therefore, it is reasonable to use T_{op} as the main indicator for analysis of the thermal sensation limit, which is applied in ASHRAE Standard 55-2013 [24] and ISO 7730 [25].

$$\mathrm{MTSV} = 0.198T_{op} - 4.789 \; (R^2 = 0.774) \tag{6}$$

$$\mathrm{PMV} = 0.371T_{op} - 9.765 \; (R^2 = 0.992) \tag{7}$$

$$\mathrm{UCB} = 0.186T_{op} - 4.663 \; (R^2 = 0.89) \tag{8}$$

In Figure 5, the results showed that there were significant deviations between the MTSV and PMV, especially at low T_{op}, which indicates that the PMV model underestimated the actual thermal sensation, similar to findings of several previous studies. However, when T_{op} was around 27 °C, the PMV model could predict the actual thermal sensation accurately. Comparing the deviation between the MTSV and UCB predictions, the difference is insignificant. Most of the scatters of the UCB data overlapped with the points of MTSV. Both regression lines are approximately parallel.

The slope of the UCB regression line is 0.186, close to that of MTSV of 0.198. Therefore, the prediction of UCB agreed well with the actual thermal sensation votes of the subjects.

Thermal neutral temperature is defined as the operative temperature that mostly corresponds to a mean thermal sensation vote of zero [5]. By using the linear regression models shown in Equations (6) to (8), the neutral T_{op} of the three thermal comfort models was computed and shown in Figure 5. They were found to be 24.14 °C, 25.02 °C, and 26.35 °C for MTSV, UCB, and PMV respectively. By comparing the discrepancies between the actual neutral T_{op} and the predictive one, it was found that the actual neutral temperature was much closer to that of the UC-Berkeley model with a deviation of about 0.8 °C, whereas the neutral T_{op} of PMV was much higher, by 2.21 °C, than that of the actual value. Therefore, the PMV model overestimates the neutral T_{op} of air-conditioning buildings in Hong Kong. On the contrary, the UC-Berkeley model predicts the neutral T_{op} well.

The acceptable temperature range was determined when MTSV varied between -0.5 to 0.5, corresponding to the acceptable conditions for about 90% of people as recommended by ASHRAE 55 [24].

Further, the relationship between MTSV and T_{op} for the classroom was used to derive comfort zone limits for 80% satisfaction. As defined in ASHRAE 55 [24], comfort zone refers to conditions falling within and including the PMV ranging from -0.5 to +0.5. In Figure 4, in the range from -0.5 to +0.5, the acceptable temperature ranges of MTSV, UCB, and PMV models are between 21.65 – 26.75 °C, 22.25 – 27.45 °C, and 25.0 – 27.45 °C, respectively. Similar to the results of the neutral T_{op}, the differences between the PMV and the other thermal indicators were large. The acceptable temperature range of the PMV was narrower than that of MTSV or of UCB. The subjects adapted the indoor thermal environment in Hong Kong due to training. The adaptation of thermal sensation has also been proved in many previous investigations [9, 36]. Thus, the acceptable T_{op} was obviously wider than that of the PMV. Also, the acceptable T_{op} range of MTSV was almost identical to the comfort temperature range suggested by the UC-Berkeley model.

3.4Thermal preference

It is not enough to describe an existing environment as comfortable or uncomfortable. Using regression of collected data, it is possible to obtain the temperature at which subjects are thermally neutral, hence to determine the neutral T_{op}. This investigation also considered the answers to the question of thermal preferences (cooler (-1), no change (0) and warmer (+1)) given by the subjects. Figure 6 shows that the percentage of the "warmer" choice decreases with rising of the T_{op}, while the percentage of the "cooler" choice increases with the elevation of the T_{op}. Based on the point of intersection, the preferred T_{op} was determined. It was found to be 24.58 °C, very close to the neutral T_{op} of 24.14 °C.

The adaptation to the climate on human thermal comfort has been previously proved, especially in tropical climate [36]. The influence of thermal experience on the occupants' expectations regarding the indoor conditions, which can be short-term, due to the prevailing weather, or long-term, relate to the general climate they are used to [37]. Based on the data, Figure 7 presents, variations of the percentage of "no change" with MTSV. The range of 80% of the subjects choosing "no change" in the surveyed indoor thermal environment was much narrower than the predictions of PMV-PPD [20]. The acceptable comfort range of MTSV was from -0.34 to 0.04, which indicated that the subjects preferred to stay in the cooler indoor environment.

3.5Adaptation thermal comfort model

From the preceding analysis, the PMV model needs certain modifications to predict the actual thermal sensation. Thus, Bin method with a width of 0.5 °C T_{op} was applied to the MTSV, PMV, and UCB. For each Bin MTSV, PMV and UCB values were predicted, and the scatter points were shown in Figure 8. Through fitted regression, the simple models of MTSV with PMV, and MTSV with UCB were determined. The models were as shown in Equations (9) and (10). :

$$\text{MTSV} = 1.05\ \text{UCB} + 0.185\ (R^2 = 0.916) \tag{9}$$

$$\text{MTSV} = 0.131\ \text{PMV}^2 + 0.667\text{PMV} + 0.382\ (R^2 = 0.966) \tag{10}$$

The regression models drawn from data across all sample subjects were statistically significant. The fitting quality was guaranteed by the determination of R^2, for which the value of R^2 = 0.983. Especially, there is a strong positive linear relationship between

MTSV and UCB model value. Figure 8 shows that the regression line of the PMV model was much higher than that of the UCB model. The comparison between the two fitted lines indicated that the UCB model accurately predicts the actual thermal sensations.

4. Discussion

4.1The neutral temperature and preferred temperature

Room air conditioning (AC) systems influence indoor temperature. As room AC system consumes significant amounts of energy, higher indoor temperature set-point remains an energy savings opportunity. However, such elevated indoor temperature should not exceed the upper limit of the comfort range [38]. A previous study [39] have shown that an increased indoor temperature set-point of about 1~2 °C in summer can save about 6-10% of the electric energy. Therefore, it is necessary to determine the neutral and/or preferred temperature by building users.

The thermal neutral temperature corresponds to the temperature at which subjects vote neutral thermal sensations. Regression analysis was applied to determine the thermal neutral temperature from the thermal sensation data. All subjects were divided into two groups according to their preference for "warmer" or "cooler." Based on the previous investigations, the neutral temperatures in different locations were summarized in Table 3. As could be seen from Table 3, neutral temperatures are measured by several kinds of temperature metrics, including T_{op}, T_a, Effective temperature (ET^*), and T_g. Comparing different kinds of temperature, T_{op} is mostly applied in the evaluation of thermal neutrality. In some popular standards [24, 25], the operative temperature T_{op}, as a thermal comfort index, is widely used to evaluate thermal comfort. Therefore, the present study investigated the effects of the neutral operative temperature. Previous studies reported that the respective minimal and maximal neutral operative temperature were 21.4 °C and 30.4 °C respectively. However, most of the neutral operative temperatures concentrated in the range between 24°C and 27°C. In the current study, the reported neutral operative temperature of 24.14 °C, goes in tandem with some previous investigations reported widely across tropical and subtropical climates in the world [40-50]. The primary reason probably is the climate of Hong Kong is similar.

Also, to confirm comfort temperature, the preferred temperature was also analyzed in some previous investigations [22, 39, 43, 47, 49]. Comparison between the preferred temperature and neutral temperature revealed insignificant differences. Most of the differences were higher by 0.5 °C. In this study, the preferred temperature is higher than the neutral temperature by 0.44 °C, resulting in a value of 24.58 °C. Hence, the preferred temperature can be used as one of the indices to evaluate the human preference for thermal environment. Also, the neutral temperature of the classroom is lower than that of residential buildings due to the clothing insulation. In the residential buildings, occupants can adjust their clothing level to achieve comfort. However, the clothing insulation of students in the classroom cannot be conveniently changed, thereby leading to the lower neutral temperature.

According to the “adaptive theory”, people are not passive receivers of their thermal environment but alter or adapt to their environment to suit themselves by adjusting their thermal comfort [37]. Therefore, the comfort range as one of the most indices is required. When compared to the ASHRAE comfort range (23.0-27.0 °C), the comfort range (21.65 - 26.75 °C) for subjects in this study, is wider, which indicates the Hong Kong students' preference for cooler indoor thermal environment. The upper limit is similar to the ASHRAE comfort range. Thus, it can be concluded that the comfort criteria of ASHRAE Standard 55 can be used to decide the set point in hot and humid climates. Many researches also reached similar conclusions as shown in Table 3. However, there are significant differences among different comfort ranges in different places due to thermal adaptation. To evaluate indoor thermal environment correctly, the comfort ranges of each climate zone needs to be specifically modified.

As living standards rise, at present, the increasing number of air conditioners will be a significant threat to the goal of the Paris Climate Accord. The lifting indoor set-point temperature in air-conditioned buildings is helpful to energy conservation. In classroom, the neutral temperature is 24.14 °C. It located in the comfort range between 21.56 and 26.75 °C. To provide preferred or comfortable thermal environment, the temperature set-point can be selected at 24 °C. However, to reduce energy consumption of the HVAC system, the indoor set-point temperature in air-conditioned classrooms, can be regulated at 26 °C or even higher in Hong Kong.

4.2 Thermal comfort models

Under the adaptive approach to modeling thermal comfort, thermal perception is affected by circumstances beyond the physics of the body's heat-balance, such as climatic setting, social conditioning, economic considerations and other contextual factors. Three modes of adaptation are: (1) behavioral adjustments (personal, environmental, technological, or cultural), (2) physiological (genetic adaptation or acclimatization), and (3) psychological (habituation or expectation). In order to simplify the thermal comfort model [2], T_{op} is applied in thermal comfort model to evaluate the thermal environment. Current comfort standards, such as ASHRAE Standard 55 [24] and ISO 7730 [25], determine the design values of T_{op} in indoor spaces based on the PMV-PPD models. Thus, many studies have demonstrated the relationship between PMV and T_{op}, as summarized in Table 4. The linear relationship between the PMV and T_{op} is strong. Most of the R^2 exceeded 0.7. The maximal R^2 is higher than 0.98, similar to this study R^2 = 0.93. Also, the MTSV, as the actual thermal evaluation, were extensively applied in field survey investigation. Many previous studies concluded that there was a strong linear relationship between MTSV and T_{op}. The statistical results indicated most of R^2 also exceed 0.7. However, from Table 4, the slopes of the regression models were different by geographical locations and types of buildings. Hong Kong is located in a hot and humid climate zone. In the classroom buildings, the students are trained in the cooler indoor thermal environment due to lower set-point temperature, which leads to the difference of the regression model to be significant. Based on the analysis of different thermal comfort models, the predictions of the UCB thermal comfort model are in good agreement with the MTSV. For an accurate evaluation of the thermal environment, the relationships between the MTSV, UCB, and PMV were also summarized in Table 4. The fitted linear relationship between the MTSV and UCB is significant with a high R^2 of 0.916. The relationship between the MTSV and PMV is a quadratic function with a R^2 of 0.966. Thus, this study reported using three methods to evaluate the indoor thermal environment of Hong Kong classrooms. Based on the variations of the T_{op}, UCB, and PMV, the MTSV prediction models could be obtained.

5. Conclusion

An appropriate indoor air temperature setting for air conditioned classrooms is crucial for students' comfort and for energy efficiency. In this study, a field survey was conducted in typical classroom setups at the City University of Hong Kong. Responses of 982 students to their perceived thermal environment in air conditioned classrooms were collected along with the indoor temperatures. Based on analysis of the survey data, major findings of this investigation are as follows:

(1) The indoor thermal environment of typical classrooms is found to be cooler by measurement. The students donned light clothing of 0.42 clo in the classroom environment due to adaptation.

(2) There is an insignificant difference between the neutral temperature and preferred temperature, which were found to be 24.14°C and 24.58°C respectively. Both temperatures fall within the comfort range of 21.56°C - 26.75°C. Hence, to provide a preferable and comfortable thermal environment and to reduce energy consumption of HVAC systems, a set-point temperature of 26°C is recommended.

(3) Comparing the PMV and UCB models, the predictions of the UCB model were in good agreement with the MTSV values. The PMV model underestimated the human thermal sensation when T_{op} was lower than 27°C.

(4) There were strong linear relationships between the MTSV and each of the following: T_{op}, PMV and UCB with high R^2 values.

The adaptive model is important for evaluation of the indoor thermal environment in NV buildings. However, the differences between the thermal comfort in NV buildings and that in air conditioned buildings are significant. Therefore, the findings of this investigation are only applicable to air conditioned buildings. Also, the Hong Kong climate is classified as "humid subtropical", which is different from those in the other climatic zones. Hence, the characteristic of the adaptive thermal comfort could be specific only to this climatic zone.

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Table

Table 1 the information of instruments

Instruments	Measured parameters	Measurement range	Accuracy
LUMASENSE transducer MM0038	Indoor velocity	0-10 m/s	5% of readings+0.05m/s
LUMASENSE transducer MM0034	Indoor temperature		±0.2 °C
LUMASENSE transducer MM0037	Indoor humidity		±0.5 °C
FLUKE 561 Thermometer	Surface temperature	-40 - 550°C	Greater one of ±1 °C and ±1% of readings

Table 2 Anthropometric information of the subjects

Gender	Age	Height H (cm)	Weight W (kg)	Body Surface Area (m2)	Ponderal index
Male	21.2 (0.8*)	173.1 (4.8)	64.7 (9.2)	1.77 (0.06)	2.32 (0.1)
Female	21.4 (0.9)	158.2 (3.8)	51.2 (5.6)	1.50 (0.04)	2.34 (0.06)
Male+Female	21.3 (0.85)	165.4 (7.9)	58.2 (8.8)	1.64 (0.08)	2.34 (0.08)

*Standard Deviation

The body surface area was determined by the DuBois area, $A = 0.202W^{0.424}H^{0.725}$ [27]

Ponderal index = $W^{1/3}/ H$.

Table 3 the comparing the different locations investigations

Study	Location	Climate	Buildings	Sample size	Neutral temperature (˚C)	Preferred temperature (˚C)	Comfort range (˚C)	Acceptable percentage (%)	Thermal sensation
Busch (1990) [40]	Bangkok	Tropical savanna	Office	1100	25 (T_{op})	-	-	-	-
de Dear et al. (1991) [22]	Singapore	Tropical rainforest	Residential and office	235	24.2 (T_{op})	-	23.6- 25.1(T_{op})	95%	-
Kwok (1998) [41]	Hawaii	Tropical	Classroom	1363	21.4 (T_{op})	23.0 (T_{op})	-	-	-
Karyono (2000) [39]	Jakarta	tropical monsoon	Office	459	26.7 (T_{op})	-	23.5- 29.9 (T_{op})	80%	(-1,+1,)
Mui et al. (2003) [18]	Hong Kong	Humid subtropical	office	-	23.7 (T_{op})	-	20.8- 25 (T_{op})	80%	-
Yamtraipat et al. (2005) [42]	Thailand	Tropical	office	755	25.4 (T_a)	-	25 -26.2 (T_a)	80%	(-1, +1)
Hwang et al. (2006) [43]	Taiwan	Marine tropic al	Classroom	932	24.7 (ET*)	25.6 (ET*)	21.1-29.8 (ET*)	80%	-
Mui et al. (2007) [17]	Hong Kong	Humid subtropical	Office	128	23.6 (T_{op})	-	-	-	-
Yang and Zhang (2008) [39]	Changsha, Wuhan, Shanghai, Jiujiang and Nanjing	Humid subtropical	Residential	100	27.7 (T_{op})	27.3 (T_{op})	25.1-30.3 (T_{op})	80%	(-0.85,+0.85)
Torres et al. (2012)[44]	Colima	Tropical	Office	414	24.2 (T_a)	-	22.6 – 25.8 (T_a)	-	(-1, +1)

Indraganti et al. (2014)[45]	South Indian states of Andhra Pradesh and Tamil Nadu	Hot and humid	Office	1168	26.4 (T_g)	-	-	-	-
Hussin et al. (2015)[46]	Kepala Batas	Classified tropical	Mosque	330	30.4 (T_{op})	-	27.0-31.4 (T_{op})	90%	(-0.5, 0.5)
de Dear et al. (2015)[47]	Australian	Temperate, subtropical and semi-arid climate zones	Classroom	1326	22.4 (T_{op})	22.2 (T_{op})	19.5-26.6 (T_{op})	-	(-0.85,+0.85)
Natarajan et al. (2015)[48]	Bogota	Subtropical highland	Office	37	23.0 (T_{op})	-	-	-	-
He et al.(2016)[49]	Changsha	Humid subtropical	Dormitory room	-	26.08 25.02; 25.61; (T_{op})	26.16; 25.38 ;25.91; (T_{op})	23.85 -28.30; 23.24 - 26.80; 23.71-27.43; (T_{op})	90%	(-0.5, +0.5)
Present study	Hong Kong	Humid subtropical	Classroom	946	24.14 (T_{op})	24.58 (T_{op})	21.65 - 26.75		(-0.5,+0.5)

Table 4 the thermal comfort models in previous investigations

Study	Location	Building	PMV-T	MTSV-T
Karyono et al. (2000)[39]	Jakarta	Office	-	MTSV=0.31T_{op} - 8.38 (R^2=0.42)
Hwang et al. (2006)[43]	Taiwan	classroom	PMV = 0.2805 ET* - 7.717(R^2=0.9128)	MTSV=0.1413ET*-3.762 (R^2=0.8857)
Hwang et al. (2007)[50]	Taiwan	Office	PMV=0.274*Top - 6.732 (R^2=0.985)	MTSV=0.215T_{op} - 8.068 (R^2=0.805)

Yang and Zhang (2008)[39]	Nanjing; Shanghai; Wuhan; Changsha Jiujiang	Office	-	$MTSV=0.32T_{op} - 9.12$ ($R^2=0.57$)
Ricciardi et al. (2012)[51]	Italy	Office	PMV=0.3879 Top - 8.8784 ($R^2=0.48$)	-
Hussin et al. (2015)[46]	Malaysia	mosque	PMV=0.394Top - 10.2 ($R^2=0.96$)	$MTSV=0.097T_{op} - 2.9$ ($R^2=0.29$)
Natarajan et al.(2015)[48]	Bogota	Office	PMV=0.2617Top - 5.9523($R^2=0.7456$)	$MTSV=0.454T_{op} - 10.47$ ($R^2=0.4819$)
de Dear et al. (2015)[47]	Australia	Office	-	$MTSV=0.12T_{op} - 2.78$ ($R^2=0.76$)
Luo et al. (2015)[35]	Shenzhen	Office	PMV=0.356Top - 9.154	$MTSV=0.203T_{op} - 5.077$
He et al. (2016)[49]	Changsha	Dormitory	-	(1)$MTSV= 0.225T_{op} - 5.867$ ($R^2=0.927$) (2)$MTSV=0.282T_{op} - 7.055$ ($R^2= 0.798$) (3)$MTSV=0.269T_{op} - 9.879$ ($R^2=0.818$)
At Present	Hong Kong	Classroom	$PMV=0.371T_{op} – 9.765$ ($R^2=0.992$) $UC\text{-}B=0.186T_{op} – 4.663$ ($R^2=0.89$)	$MTSV=0.198T_{op}– 4.789$ ($R^2=0.774$) MTSV=1.05 UCB + 0.185($R^2= 0.916$) $MTSV=0.131\ PMV^2 + 0.667PMV + 0.382$ ($R^2=0.966$)

Figures

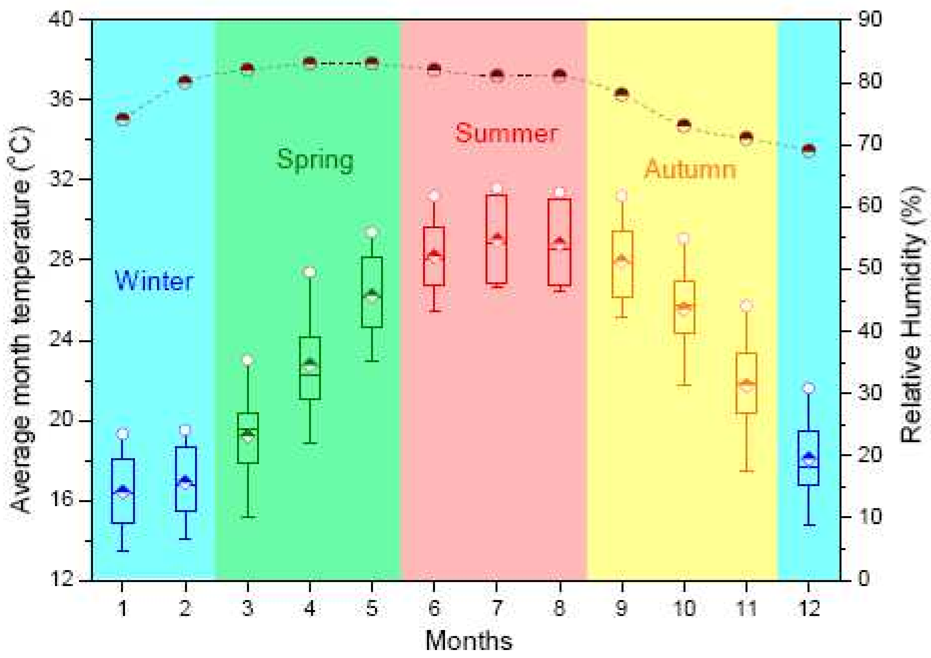

Fig. 1 Mean monthly variation of temperature and relative humidity in Hong Kong

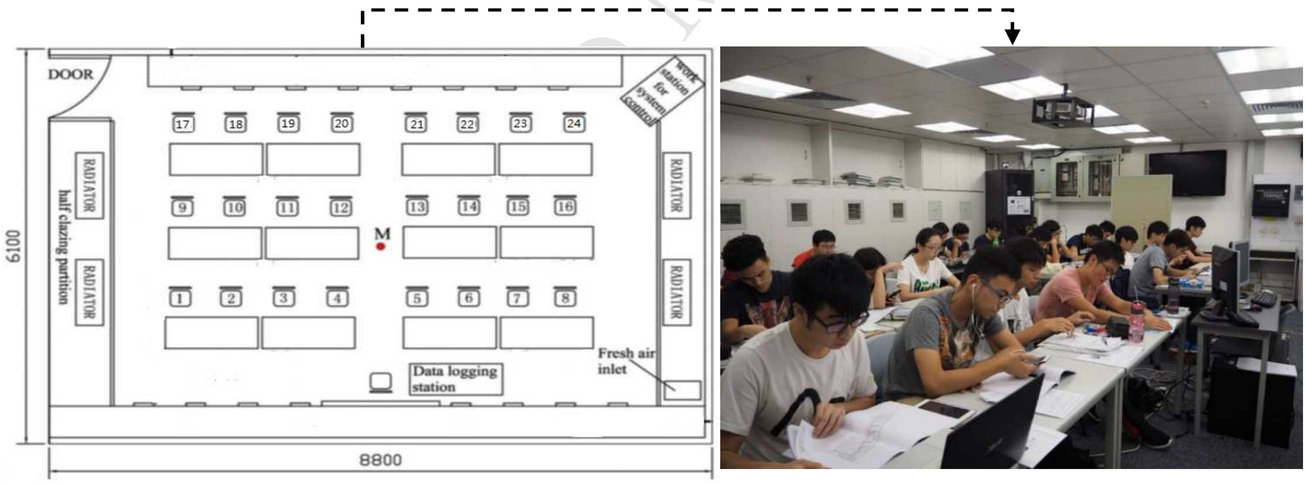

Fig. 2 Picture and layout of classroom

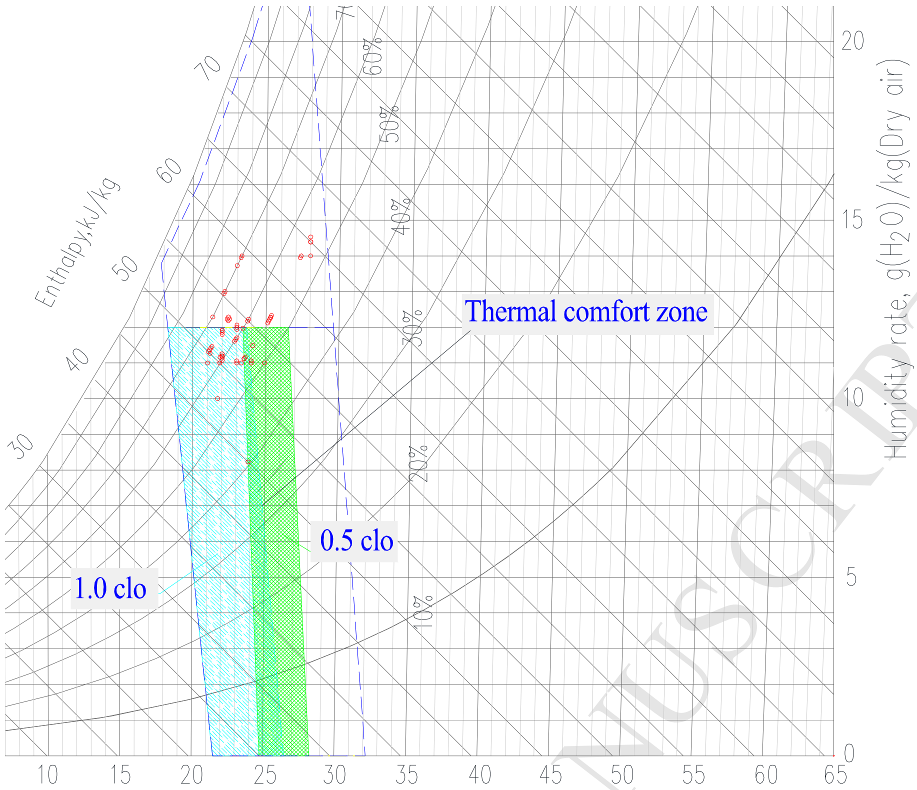

Fig. 3 Thermal environment status

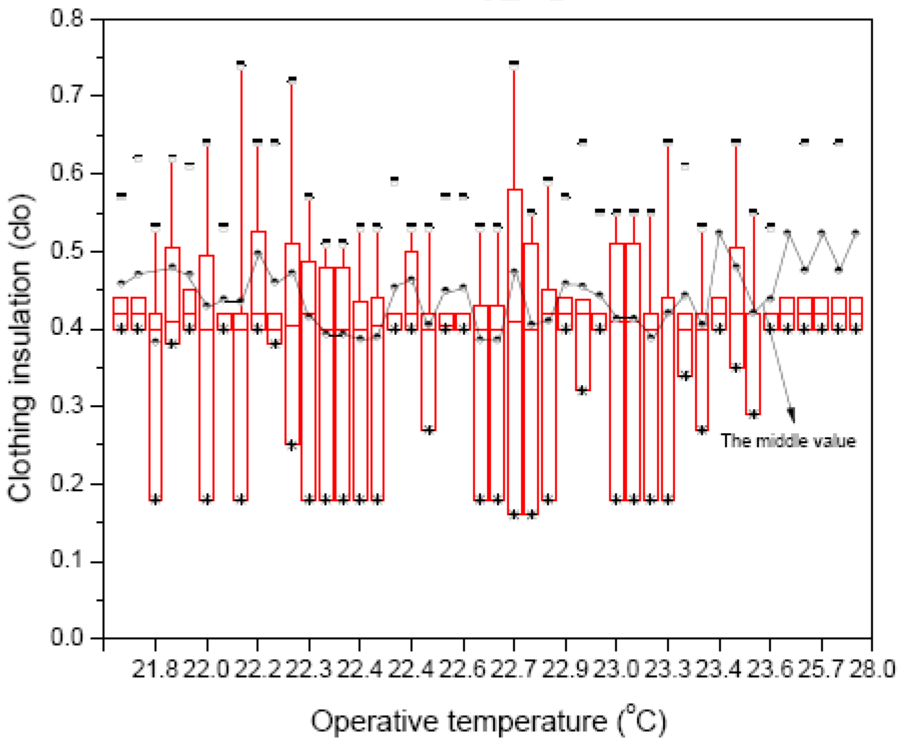

Fig. 4 Variation of clothing insulation with operative temperature

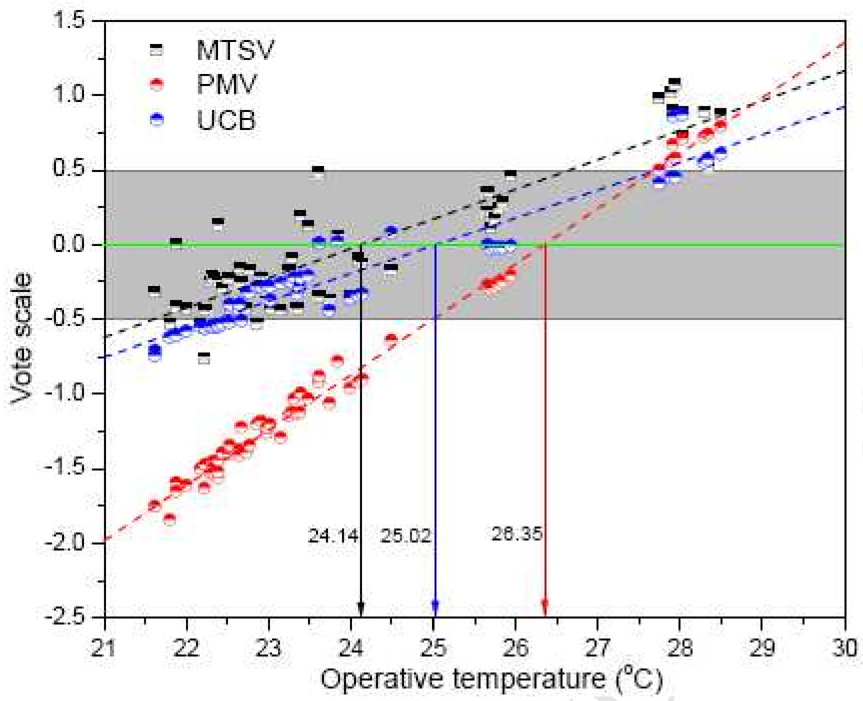

Fig. 5 Vote scale with operative temperature

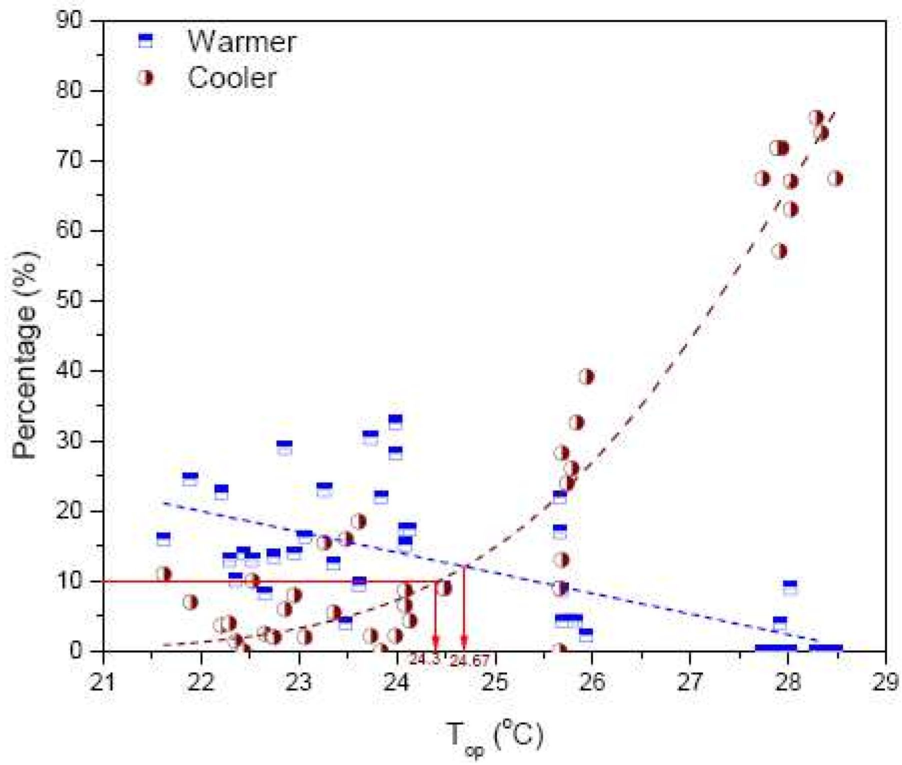

Fig. 6 Variation of thermal prefer percentage with operative temperature

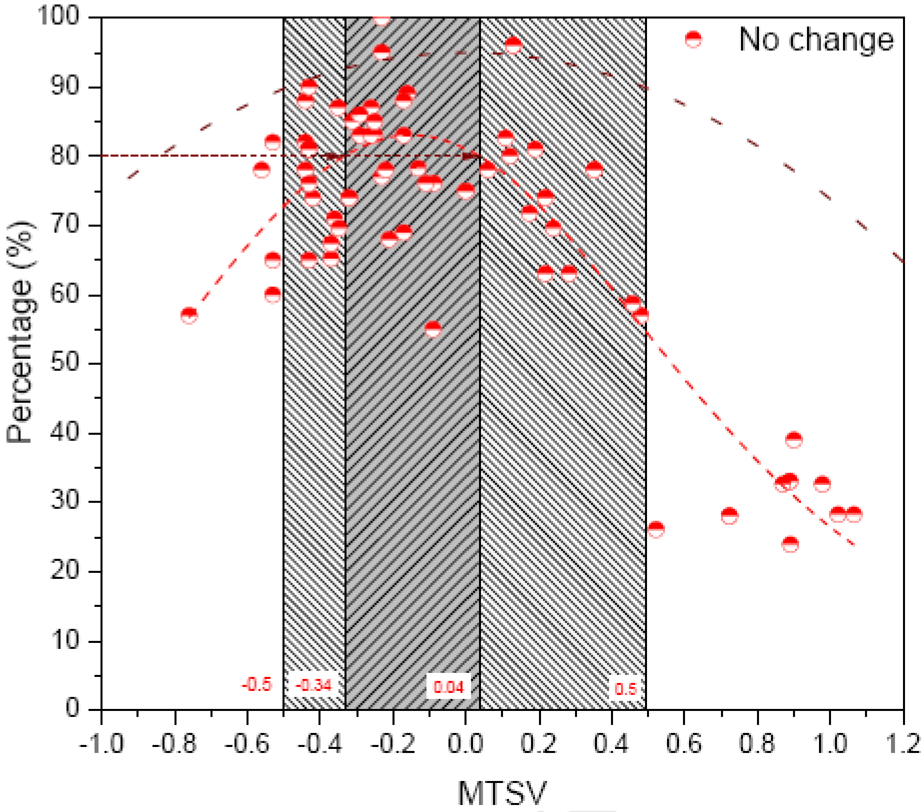

Fig. 7 Acceptable comfort range of MTSV

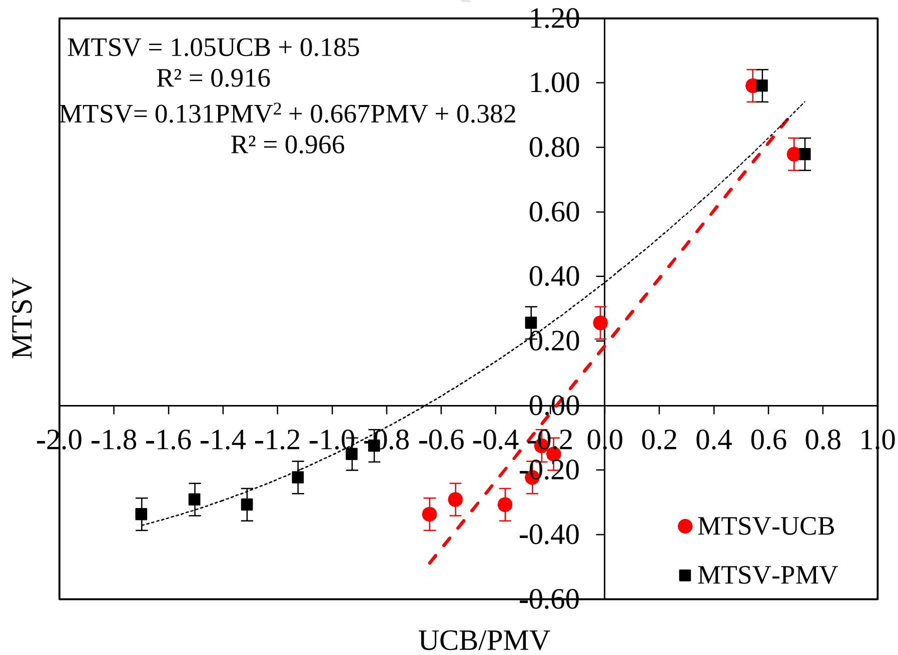

Fig. 8 Relationships between MTSV versus UCB or PMV

Highlights

- A field survey was conducted in several typical classrooms in Hong Kong.
- The students in light clothing (0.42 clo) had adapted to the cooler classroom environments.
- The neutral temperature is close to the preferred temperature of approximately 24°C.
- The regression models of the MTSV, respectively fitted versus T_{op}, PMV, and UCB, were obtained.