Original Article

Indoor and Built Environment

Indoor Built Environ 2007;16;1:1–11 Accepted January 12, 2007

Thermal Comfort Investigation of Naturally Ventilated Classrooms in a Subtropical Region

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Key Words
Thermal comfort · Classroom · Field measurement · Questionnaire · Subtropics.

Abstract
A field study of student thermal comfort was conducted in the Chinese subtropics. Thermal comfort affects people's physical and psychological health. The study was performed in Hunan University in China from March 24 to April 23 in 2005. Two teaching buildings were selected as study sites. Thermal comfort was measured in naturally ventilated classrooms with ceiling fans. A total of 25 classrooms were surveyed and each classroom was visited two or three times and 1273 students responded to the questionnaire. Thermal comfort variables were measured at the same time: students answered a survey on their perception/sensation of the indoor climate. Objective data analysis showed that most respondents found thermal satisfaction during the sampling month, even though the indoor air temperature and relative humidity varied greatly, with average values at 20°C and 71%, respectively. The thermal neutral temperature calculated by Thermal Sensation Vote (TSV) was at about 21.5°C and the slope of the regression line relating TSV with operative temperature was 0.0448/°C, which is quite different from that found in other similar thermal comfort studies. This difference is attributed to the different climate and adaptation and tolerance of students, who were the study subjects. There was a relatively large gap between studied TSV and Predicted Mean Vote (PMV). An extended PMV model that incorporated two common forms of adaptation – reducing activity pace and expectation – was also considered, but the discrepancy between predicted and studied thermal sensations did not reduce noticeably, especially at the lower temperatures.

Introduction

Thermal comfort is the condition that relates to satisfaction with the thermal environment. A comfortable thermal environment makes people healthy both physically and psychologically. An environment that makes occupants feel too cold or too hot could cause a decrease in work efficiency. In consequence, a large number of thermal comfort studies have been performed around the world. Webb [1] carried out some observations of thermal comfort in the

DOI: 10.1177/1420326X07076792
Accessible online at http://ibe.sagepub.com

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equatorial climate and introduced an 'Equatorial Thermal Index, ETI' in 1959; de Dear and Auliciems investigated thermal environment in Darwin, Brisbane and Melbourne and found that neutral temperatures (ET*, the temperatures at which the majority of people felt neither too warm or too cold.) were 24.2, 23.8 and 22.6°C, respectively [2]. Thermal responses in both naturally ventilated and air-conditioned offices in Thailand were carried out by Busch, who found the ET* to be 28.5 and 24.5°C, respectively [3]. A field investigation was carried out both in winter and summer in San Francisco by Shiller, where the ET* were 22.0 and 22.6°C, respectively, the lowest predicted percent of dissatisfied (LPPD) value was 12% and 80% of the subjects found their thermal environment acceptable in the temperature range of 20.5–24.0°C [4]. Donnini *et al.* found ET* of 22.8 and 24.1°C in Montreal, in winter and summer, respectively, and an LPPD of 12% with an acceptable temperature range for 80% of the residents of 21.5–25.5°C in winter and 20.7–24.7°C in summer [5].

Many standards have been established to prescribe thermal comfort in the indoor environment. The two most frequently used are: ASHRAE Standard 55 [6] and ISO7730 [7]. The latest version of the ASHRAE Standard is ASHRAE 55–2004 'Thermal Environmental Conditions for Human Occupancy', which provides a simple method of compliance for commonly-designed space types, a calculation method that applies to a broader range of space types and a new adaptive method for naturally ventilated spaces in certain climate areas. The ISO7730 standard relates to human physiology and heat transfer, and is mainly based on the research of P.O. Fanger, named 'Moderate thermal environments – determination of the PMV and PPD indices and specification of the conditions for thermal comfort'.

Thermal conditions in classrooms must be considered carefully because of the high occupant density and the negative influence that an unsatisfactory thermal environment may have on learning and performance. Kwok studied this concern in Hawaii and Japan, respectively, in 1998 and 2003 [8,9]; Wong undertook a thermal comfort study in a secondary school with natural ventilation [10] and Hwang conducted field experiments in 10 naturally ventilated and 26 air-conditioned campus classrooms in Taiwan [11]. In China, most classrooms have traditionally relied on a combination of cross-ventilation and mechanical ventilation by fans to achieve thermal comfort. Research into thermal comfort started relatively late in China, and most studies were concentrated on residential and office environments [12–14]. It is therefore, necessary and interesting to carry out investigations on thermal comfort in classrooms and the adequacy of mechanical ventilation provided by fans.

The main objectives of this study were as follows:

1 to generate a general profile of thermal environment in naturally ventilated classrooms in Hunan Province, China;
2 to Investigate occupants' perception of the level of thermal comfort in classrooms;
3 to find out the characteristics of thermal conditions in classrooms and students' thermal perceptions in comparison with previous studies and relevant standards.
4 to compare our data with thermal sensation models.

Methodology

Site Description and Climate Background

The investigation was carried out in classrooms of two teaching buildings, named TB1 and TB2, on a campus of Hunan University in Changsha, Hunan Province (Figure 1). TB1 was the busiest teaching building on this campus and it was located close to a main road. TB2 was located in a cleaner and quieter environment. More information on each sample site is listed in Table 1.

Fig. 1. General view of investigated university and ambient environment.

Table 1. Structural information for the selected teaching buildings

Site No.	TB1	TB2
Structure of external wall	Reinforced concrete & Heavy sheet glass	Reinforced concrete
Volume of classroom (m^3)	406.7	460.7
Floor area (m^2)	101.7	121.2
Max. number of occupants	100	120
Ventilation style	Natural ventilation + Ceiling fans	

Changsha is located in south central China, bordered by mountains to the west, south and east and by the Xiangjiang River to the north. The climate in Hunan is continental subtropical monsoon humid climate. The province has long summers with extreme heat and humid weather conditions. The field study was carried out in spring between March 24 and April 23 in 2005. There are two main characteristics of the spring climate in Hunan: the temperature may increase greatly and rapidly and it is the rainy season. During the field study month the outdoor air temperature ranged from 10.0–29.3°C with an average value of 17.7°C, and the relative humidity in the atmosphere was very high with an outdoor relative humidity (RH%) around 70%, at times rising to a max value of 100%.

Data Collection

In this investigation, both objective physical measurements and subjective assessments were performed. The following six physical parameters affecting human thermal comfort were measured: Air temperature (T_a), relative humidity (RH), air velocity (V), average radiant temperature (T_r), metabolic rate (M) and cloth insulation (I_{cl}). The first two parameters were measured by a psychrometer (Model DHM2, Tianjin Meteorological Instrument Works) and the air velocity by a thermal-anemometer (Model CDF-2A, Beijing Detector Instrument Ltd.) directly; the mean radiant temperature was estimated from the globe temperature, using a 150 mm diameter black globe thermometer. The objective physical measurements were carried out at five points in each classroom and at each sampling point each parameter was measured three times over a 30-min period. The average value of each measured variable was used for subsequent analysis.

Having measured the environmental parameters, the two personal parameters – metabolic rate and cloth insulation – were estimated in accordance with ASHRAE standard 55-1992 [15]. The standard provides a checklist of typical activities and their corresponding metabolic rates. For this study, the metabolic rate was taken to be 1.2 met (1 met = 58.15 W/m^2), which represents the value for sedentary activities, chosen because the process of responding to a questionnaire may last more than 15 min during which the respondents were seated and responding to the questionnaire. Respondents were asked to write out what they were wearing at the time of the field study by means of a clothing checklist that was included in the questionnaire. Individual clothing articles in the survey responses were converted into their respective thermal clothing insulation in units of clo (1 clo = 0.155 m^2/K/W) according to ASHRAE standard 55-1992. The clo is a measure of thermal resistance and includes the insulation provided by any layer of trapped air between the skin and clothing and insulation value of clothing itself. The overall clothing insulation for each subject's entire clothing ensemble was calculated using the equation $I_{cl} = 0.82 \Sigma I_{cli}$.

An assessment of thermal comfort in the classrooms was based on the responses to a questionnaire survey (Table 2), which was administered simultaneously with the physical measurements in each class. A total of 1273 students in 25 different classrooms answered the questionnaire for the survey. The respondents were college students about 20 years old. Each student required about 15 min to respond to the questionnaire, the contents of which can broadly be classified in four parts: 1) basic information on respondents, including age, gender and so on; 2) clothing checklist; 3) respondents' thermal sensation, which was defined using the ASHRAE Thermal Sensation Scale, a continuous seven-point scale (−3 cold, −2 cool, −1 slightly cool, 0 neutral, +1 slightly warm, +2 warm, +3 hot), and according to the seven-point thermal sensation scale, we also created a seven-point relative humidity sensation scale and a velocity sensation scale and 4) thermal preference responses (want to be warmer, keep constant, want to be cooler).

Results

Indoor Climate

The statistical summary of the indoor climate variables measured during the classroom visits are given in Table 3. Mean air and radiant temperatures were within 20.9 and 22.5°C, respectively. The relative humidity fell within the range of 40.2 to 90.6%. Mean air velocities were quite low they averaged 0.11 m/s and ranged from 0.01–0.60 m/s during the measurement. Air temperature and relative humidity are more constant indoors than the outdoors, and in general indoor temperatures are higher and relative humidity levels are lower than corresponding outdoor levels.

Clothing Insulation

The clothing insulation value was in a wide range between 0.65 and 1.93 clo. The low value is slightly greater than the value of 0.5 clo assumed for the summer season in the ASHRAE Standard 55-1992; the observed value of 1.93 clo is over twice as high as the 0.9 clo assumed for the winter season in the standard. The sample linear regression between clothing insulation and indoor air temperature has a high coefficient of determination, R^2 = 0.7018, indicating that increasing indoor air temperature results in decreasing insulation through clothing, (Figure 2).

Table 2. Questionnaire on the thermal environment and thermal comfort on the campus of Hunan University

Sex:	Age:	Inhabit time:
Clothing situation of yours at this moment (Please tick off the clothes in the corresponding place)		
Long sleeve- shirt/T-shirt (thick, thin)		☐
Short sleeve- shirt/T-shirt		☐
Sleeveless shirt/T-shirt		☐
Sweater (thick, thin)		☐
Woolen vest (thick, thin)		☐
Coat (thick, thin)		☐
cotton - padded coat (thick, thin)		☐
down coat (thick, thin)		☐
outer wear trousers (thick, thin)		☐
cotton-padded trousers		☐
woolen trousers		☐
short skirt (thick, thin)		☐
one-piece dress		☐
sport shoes		☐
leather shoes		☐
sandals		☐
hat		☐
scarf		☐

1. How do you feel about the temperature in the classroom at this moment?
   A. cold B. cool C. slightly cool D. neutral E. slightly warm F. warm G. hot
2. How do you feel at this moment in terms of humidity?
   A. much too dry B. too dry C. slightly dry D. just right E. slightly humid F. too humid G. much too humid
3. How do you feel about the air flow at this moment?
   A. much too still B. too still C. slightly still D. just right E. slightly breezy F. too breezy G. much too breezy
4. Do you feel comfortable now?
   A. very uncomfortable B. uncomfortable C. a little uncomfortable D. just right E. a little comfortable F. comfortable G. very comfortable
5. How do you rate the overall acceptability of the thermal environment at this moment?
   A. acceptable B. not acceptable
6. What is the temperature state that you expect ?
   A. cooler B. no change C. warmer

Thermal Responses

Figure 3 shows the distribution of thermal sensation votes, most of which range from −1 (slightly cool) to 1 (slightly warm), and 78% of the respondents perceive thermal sensation as neutral. In this study the portion of respondents accepting their thermal conditions was larger than the corresponding portion of other studies investigating natural ventilation in Asia [9–11,16]. This further indicates that during the one-month investigation, when indoor and outdoor temperatures and relative humidity varied considerably, most of the occupants adjusted to the climatic variation and remained satisfied with the indoor thermal environment during spring, in Hunan.

Table 3. Summary of indoor climate

	Ta (°C)	*Tg* (°C)	*Tr* (°C)	*To* (°C)	RH (%)	*V* (m/s)
Mean.	20.9	21.8	22.5	21.7	71.2	0.11
Max.	29.4	29.8	30.9	29.9	90.6	0.60
Min.	16.0	17.0	17.3	16.9	40.2	0.01
S.D.	3.09	3.24	3.58	3.24	0.11	0.13

We formulated a 7-point humidity sensation scale named 'Humidity Perception Vote (HPV)' (−3 much too dry, −2 too dry, −1 slightly dry, 0 just right, 1 slightly humid, 2 too humid, 3 much too humid) similar to the ASHRAE Thermal Sensation Scale. Although the relative humidity exceeded the upper limit of the range prescribed by ASHREAE Standard 55-1992 23% of the time, there were more than 96% respondents satisfied with the indoor humidity, nearly all votes centred within −1 and 1, (Figure 4). This conclusion demonstrates that occupants were not too sensitive to humidity variation and perceived their condition to be comfortable, independent of the humidity level. This result also confirms Toftum's [17] conclusion that the effect of variation of humidity on thermal comfort may be very small in a certain range, but it becomes apparent at high temperatures.

Figure 5 shows the draft perception vote (DPV) results, a vote −3 indicated that the air is perceived stagnant or

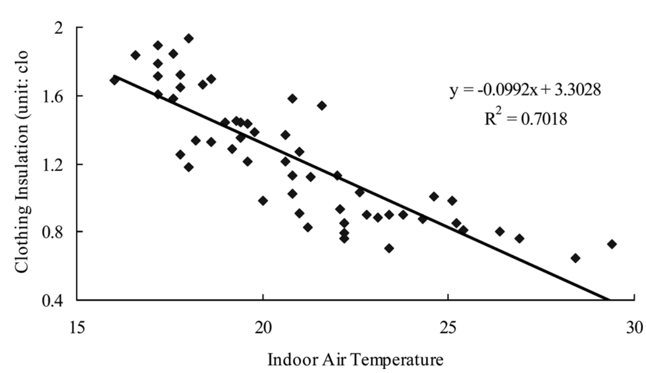

Fig. 2. Occupants' clothing insulation distribution according to indoor air temperature.

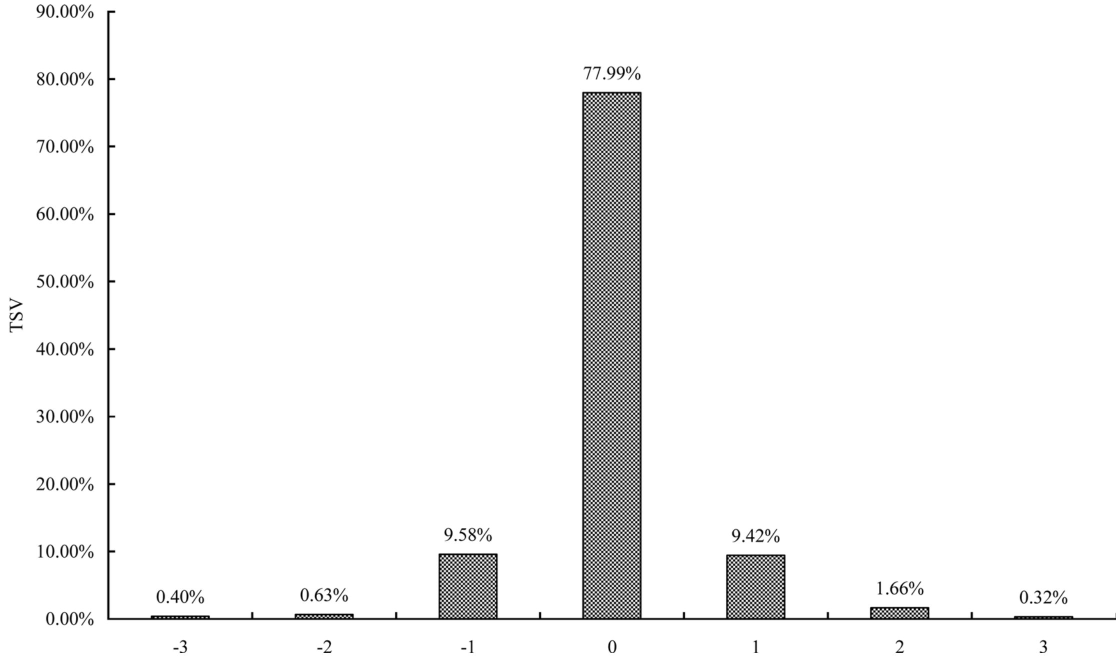

Fig. 3. Indoor Thermal Sensation Vote (TSV) results.

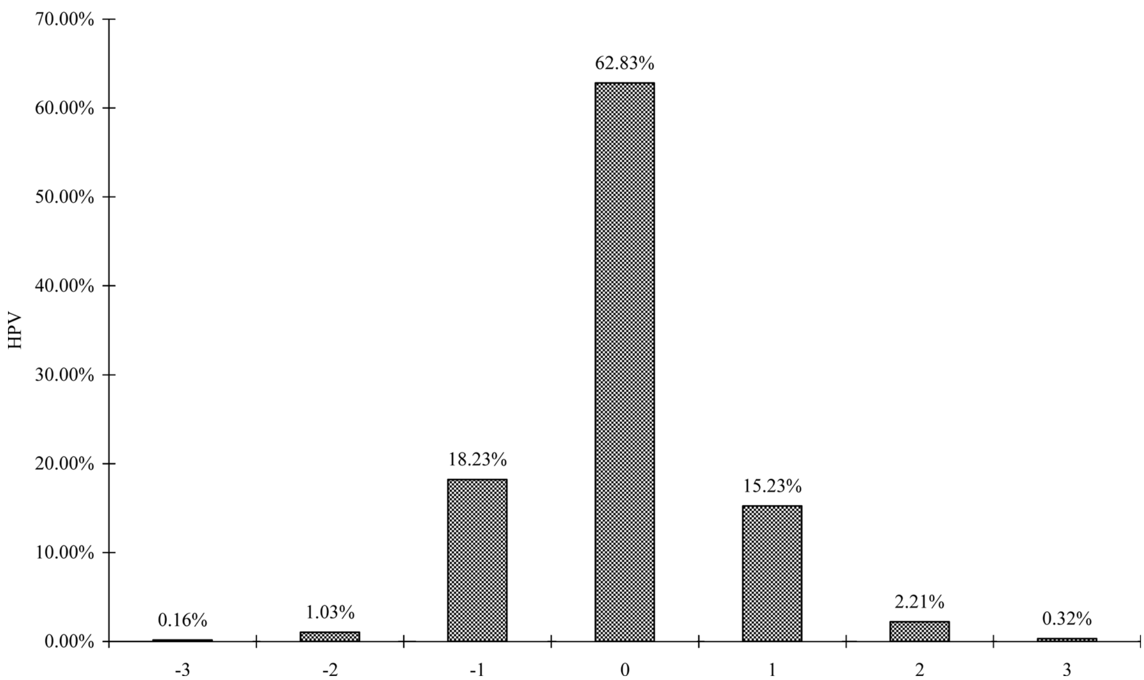

Fig. 4. Indoor Humidity Perception Vote (HPV) results.

motionless, a zero vote means that respondents feel the velocity just right. A large portion of subjects, 53.5%, perceived the air too steady, while 46.1% of the respondents felt the air velocity was just right and only 0.5% felt the velocity should be less. Interestingly, we found that students turned on the ceiling fans after the indoor air temperature reached 28°C. Both the field measurements and subjective investigation showed that the indoor air velocity may be a big problem in natural ventilation buildings.

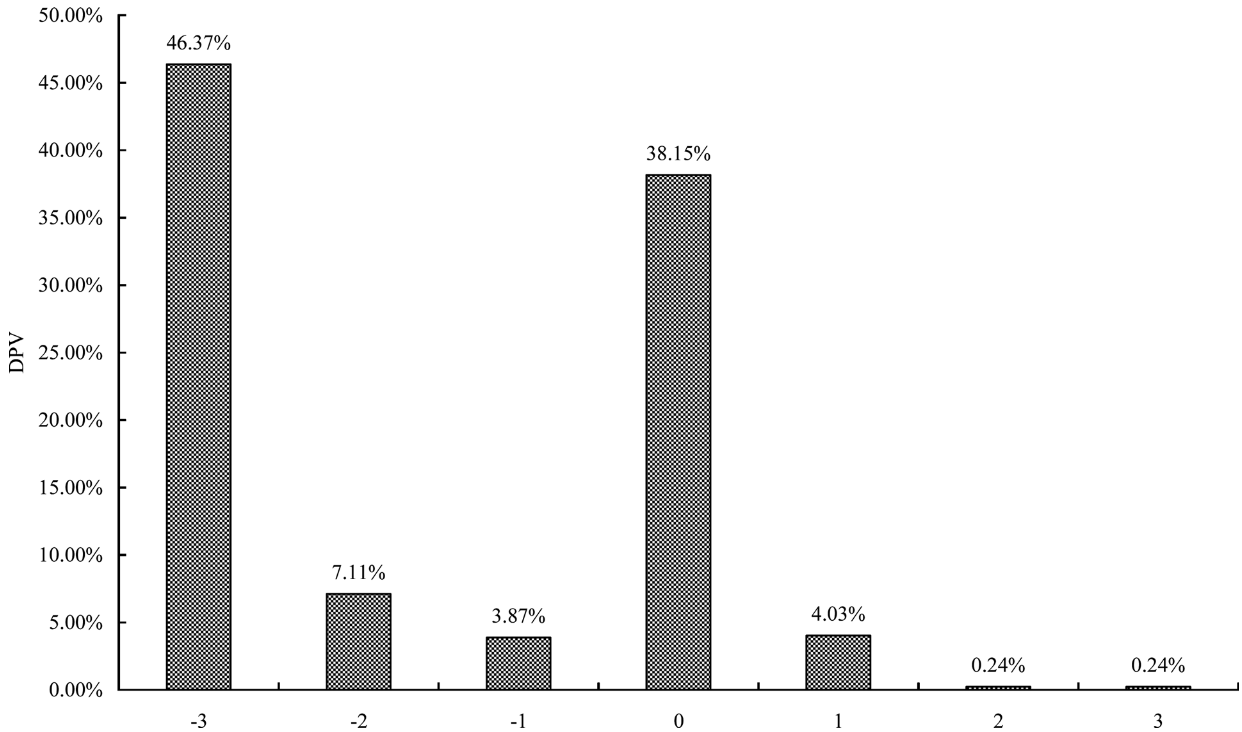

Fig. 5. Indoor draft perception vote (DPV) results.

Thermal preference

Responses to thermal preference questions revealed very different results in naturally ventilated classrooms, which are better understood by comparing simultaneous votes on both thermal sensation and preference scales as shown in Table 4. Among respondents 22.7% of those voting within the three central categories of the ASHRAE thermal sensation scale preferred to feel cooler, 26.5% respondents preferred warmer and the remaining 50.9% wanted no change. Overall, the results suggest that neutral thermal sensations are not always the preferred thermal state. These results align well with results from Taiwan in naturally ventilated classrooms, where 19% of the occupants in the 'neutral' category preferred cooler temperatures, 24% preferred warmer and 57% wanted no change [11]; but do not agree with classroom results from Japan and Singapore or with office results in Thailand [3,9,10,18].

The linear regression analysis was applied to estimate thermal preferred temperature from the thermal preference data. The preferred temperature is the temperature at the intersection of two regression lines from 'want to be warmer' and 'want to be cooler' subjects, respectively; (Figure 6). The preferred operative temperature[1] was 22.3°C.

Table 4. Cross-tabulation of thermal sensation and preference responses

Thermal sensation scales	Thermal preference scales		
	Want cooler	No change	Want warmer
−3, −2	0	0	13 (100%)
−1, 0, 1	280 (22.67%)	628 (50.85%)	327 (26.48%)
2, 3	18 (72%)	7 (28%)	0

Discussion and Analysis

Figure 7 relates operative temperature with average TSV in each investigated classroom; The number of classroom is larger than the 25 noted above because certain randomly selected classrooms were studied more than once. Within the operative temperature range of 17–30°C

[1]the operative temperature is a parameter devised to measure the cooling effect of the air on a human body. It is equal to the dry-bulb temperature.

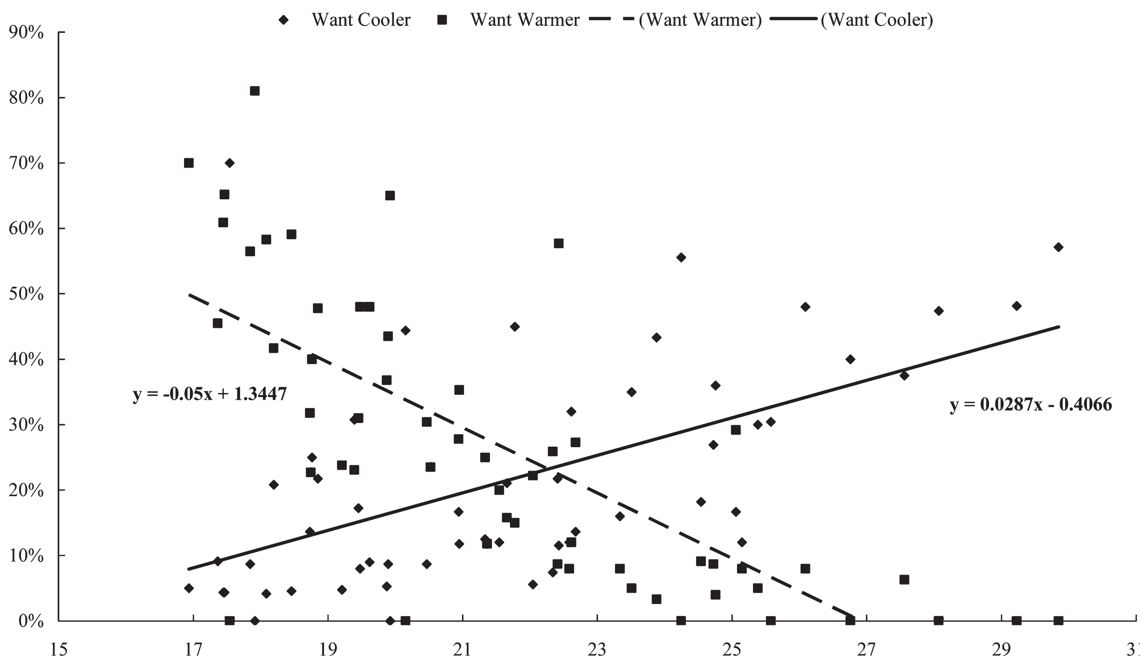

Fig. 6. Linear regression models for thermal preferred temperature.

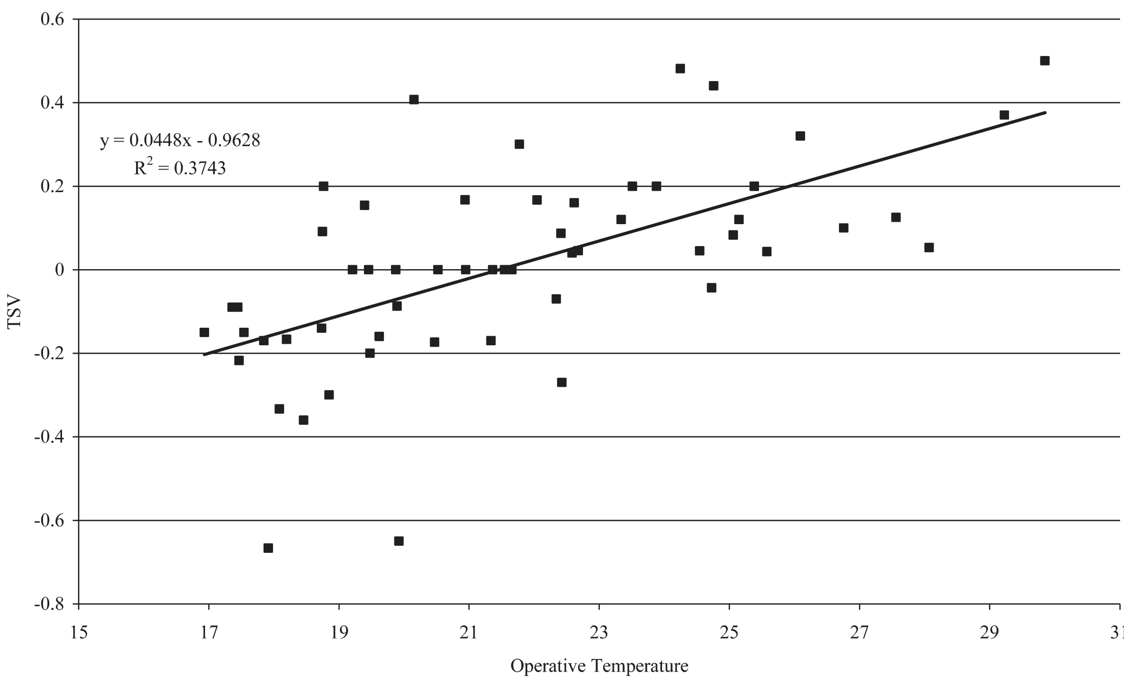

Fig. 7. Regression of observed thermal sensation votes (TSV) on operative temperature.

all TSV were between −1 and 1; the neutral operative temperature estimated by the regression line for TSV equal to zero was 21.5°C. However, the relationship indicated in Figure 7 is not strong, $R^2 = 0.37$. The slope of the regression line is 0.0448/°C, which means a more than 20°C variation of operative temperature can cause the TSV result to vary by 1.

The linear regression model relating PMV with operative temperature is shown in Figure 8. The slope for the PMV gradient is about 0.12/°C, nearly three times that of

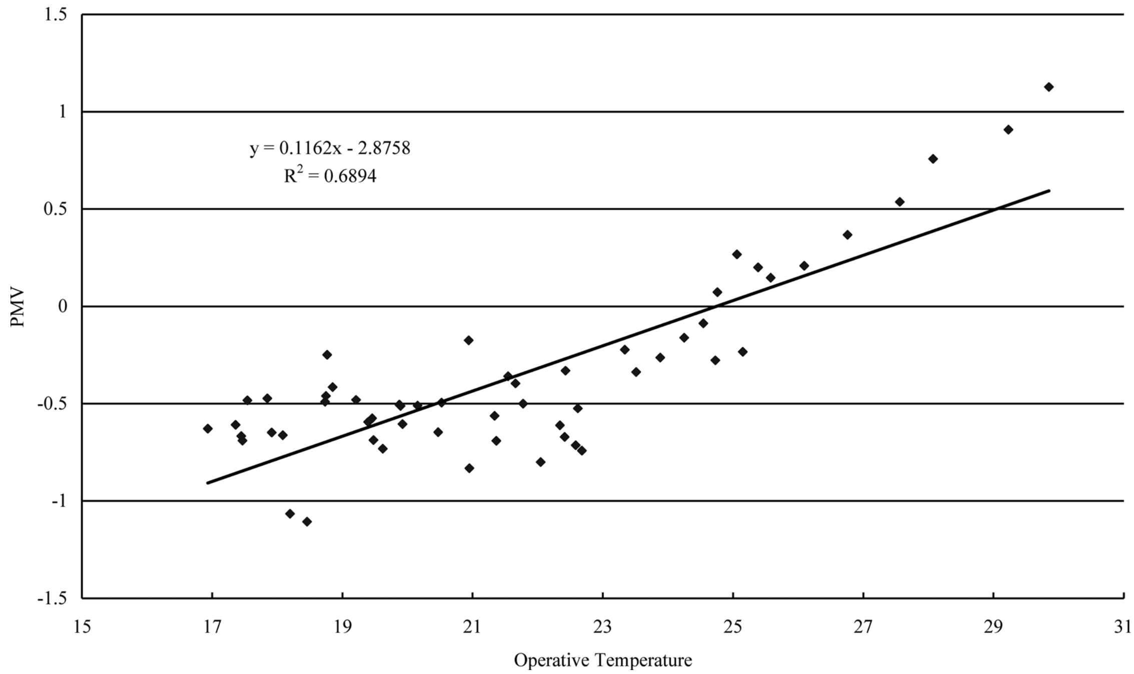

Fig. 8. Regression of predicted thermal votes (PMV) on operative temperature.

TSV in Figure 7. The regression analysis of mean PMV gives a thermal neutral temperature of 24.8°C (To), nearly 3°C higher than the regression result of mean TSV. This result is quite different from similar results in other thermal comfort studies (Table 5). The slope of the TSV gradient simulated in this study is much smaller than any other result, and all other studies show a better correlation between TSV and operative temperature (the smallest R^2 value is 0.6582), which indicates that the thermal sensation of occupants in the naturally ventilated classrooms in Hunan, may be greatly influenced by other factors.

Although the results of thermal neutral temperatures in different studies are different, a common point is that they are all very close to the indoor air temperatures; Hwang [11] found that when the average indoor operative temperatures were around 26°C and 25°C, in naturally ventilated and air-conditioned classrooms, respectively, the neutral operative temperatures were 26.2 and 25.6°C, respectively. Wong and Khoo [10] declared that the neutral operative temperature was 28.8°C in naturally ventilated classrooms in a secondary school in Singapore, when the average dry globe temperature was 30°C. Feriadi and Wong [16] studied residential buildings in Indonesia, their study results show the air temperatures ranged from 29.2–29.8°C, and the neutral operative temperature was 29.2°C. Also, in this study, the neutral operative temperature was 21.5°C, while the average indoor air temperature was 20.9°C.

These findings are explained by the 'Adaptive Theory', which suggests that people are not passively receptive of their thermal environment [19,20] but they alter or adapt to the environment to suit themselves and if a change occurs that produces discomfort, people will tend to act to restore their comfort. Adaptive theory indicates that the range of acceptable conditions for comfort is greater than that predicted by ISO7730. Experts in the field believe that discrepancies between ISO7730 and field studies are due to errors in Fanger's equation rather than to adaptive behaviour. For example, Givoni [21] believes that problems with Fanger's equation arise because the effect of air velocity is taken into

Table 5. Regression formula of previous studies

	Regression formula	R^2
de Dear [2]	TSV = 0.522To − 12.67	0.9849
Donnini [5]	TSV = 0.493To − 11.69	0.9899
Cena [24]	TSV = 0.21To − 4.28 (Winter)	0.8426
	TSV = 0.27To − 6.29 (Summer)	0.8888
Hwang [11]	TSV = 0.1413ET*−3.762	0.8857
Wang [13]	TSV = 0.199To − 4.158 (Male)	0.6582
	TSV = 0.243To − 5.330 (Female)	0.8002

account only with respect to the convective heat exchange, although its effect on sweat evaporation is not included in the heat balance formula. The main reasons that contribute to our findings are: 1) the college students have already studied in naturally ventilated classrooms for several years and they are already used to this thermal environment and 2) respondents have been sitting for at least 20 mins while answering the questionnaire and this period is sufficient to acclimatize them to the thermal environment.

Fanger and Toftum also realized this problem, and thought the PMV model should take into account psychological adaptation and a reduction in metabolic rate. A new model was developed and named the 'extended PMV model'. This, it was proposed, would achieve a better prediction of the actual TSV [22–23]. The underlying assumption is that occupants of non-air-conditioned buildings have a lower expectation of their thermal environment and are likely to judge a given warm environment as less severe than people who are used to air-conditioning. They are also likely to slow down their pace of activity to reduce thermal strain. Hence, to improve the accuracy of the PMV model for predicting thermal sensations, Fanger and Toftum suggested a reduction of the estimated metabolic rate. They also proposed multiplying the PMV by an expectancy factor '*e*', for non-air-conditioned buildings. The expectancy factor *e* was assumed to depend on the duration of the warm weather over the year and whether there were many air-conditioned buildings in the region that could be compared with the non-air-conditioned building surveyed. Table 6 shows a rough estimation of the ranges for the expectancy factor. Applied to this study, the expectancy factor should be 0.8 and Figure 9 shows the linear regression lines of the

Table 6 Expectancy factor for non-air-conditioned buildings in a warm climate [23]

Expectation	Classification of nonair-conditioned buildings		Expectancy factor, *e*
	Location	Warm periods	
High	In regions where air-conditioned buildings are common	Occurring briefly during the summer season	0.9−1.0
Moderate	In regions with some	Summer season air-conditioned buildings	0.7−0.9
Low	In regions with few air-conditioned buildings	All seasons	0.5−0.7

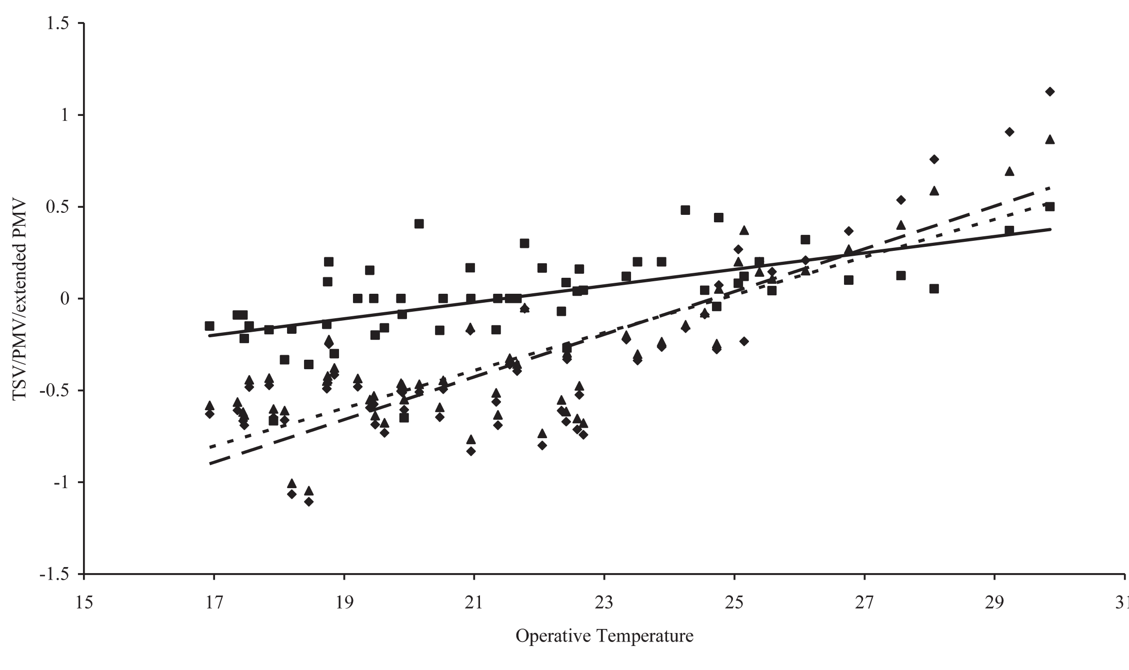

Fig. 9. Correlation between TSV, PMV, extended PMV and operative emperature.

PMV and TSV. The figure also shows that the extended PMV and TSV converge only at higher temperatures. At lower temperatures, there remains a gap between the actual TSV and the extended PMV, but this is smaller than that between TSV and the original PMV.

Conclusions

A field study was conducted in naturally ventilated classrooms with ceiling fans in the Chinese subtropics in order to investigate student thermal comfort. A total of 1273 students responded to a questionnaire administered in 25 different classrooms.

Overall, a large majority of the students found their thermal environment acceptable. Among the respondents, 97% voted within the three central categories of the ASHRAE thermal sensation scale, which indicated they were satisfied with the level of thermal comfort in their classroom. The effects of humidity on thermal comfort may be very small over a certain range and only becomes apparent in high temperature levels. Only 46.1% of the respondents felt the air velocity was just right. Indoor air velocity is a big problem in naturally ventilated classrooms.

Only 50% of the students who voted within the three central categories of the ASHRAE thermal sensation scale preferred their thermal conditions. This implies that neutral thermal sensations are not always the preferred thermal state. The relationship between the operative temperature and TSV was not strong and the slope of the regression line relating operative temperature and TSV was much smaller than in other similar studies. This result indicates that thermal sensation of students in the present study may be greatly influenced by other factors.

It was found that the PMV model prediction overestimated the students' sensitivity to the operative temperature. Chinese students appear to be more tolerant than others. This study also shows that the extended PMV and TSV converge only at higher temperatures, and at lower temperatures the gap between the TSV and extended PMV remains, but it is smaller than that between TSV and original PMV.

Acknowledgements

The work described in this paper was financially supported by the National Natural Science Foundation of China (No.50078020, 50478055), Specialized Research Fund for the Doctoral Program of Higher Education (No.20040532020), Asia-Link Project of European Community (CN/Asia-Link/012 (93520)) and the Teaching and Research Award Program for Outstanding Young Teachers in Higher Education Institutions of MOE, People's Republic of China.

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