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Field study on occupants' thermal comfort and residential thermal environment in a hot-humid climate of China

Jie Han[a], Guoqiang Zhang[a,*], Quan Zhang[a], Jinwen Zhang[a], Jianlong Liu[a], Liwei Tian[a], Cong Zheng[a], Junhong Hao[b], Jianping Lin[b], Yanhui Liu[b], Demetrios. J. Moschandreas[a,c]

[a] *College of Civil Engineering, Hunan University, Changsha 410082, PR China*
[b] *China Architecture Design & Research Group, Beijing 100044, PR China*
[c] *Illinois Institute of Technology, Chicago, IL, USA*

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Abstract

This paper discusses thermal comfort inside residences of three cities in the hot-humid climate of central southern China. Only a few thermal comfort studies have been performed in hot-humid climates and none in Central Southern China. Field sampling took place in the summers of 2003 and 2004 by obtaining 110 responses to a survey questionnaire and measuring environmental comfort variables in three rooms in each of 26 residences. The objectives are to measure and characterize occupant thermal perceptions in residences, compare observed and predicted percent of dissatisfied and discern differences between this study and similar studies performed in different climate zones. Average clothing insulation for seated subjects was 0.54 clo with 0.15 clo of chairs. Only 48.2% of the measured variables are within the ASHRAE Standard 55-1992 summer comfort zone, but approximately 87.3% of the occupants perceived their thermal conditions acceptable, for subjects adapt to prevailing conditions. The operative temperature denoting the thermal environment accepted by 90% of occupants is 22.0–25.9°. In the ASHRAE seven-point sensation scale, thermal neutral temperature occurs at 28.6°. Preferred temperature, mean temperature requested by respondents, is 22.8°. Results of this study can be used to design low energy consumption systems for occupant thermal comfort in central southern China.

Keywords: Field study; Residential thermal environment; Occupant comfort; Hot-humid climates

1. Introduction

International thermal comfort standards, such as ASHRAE 55-1992 and ISO 7730, are almost exclusively based on theoretical analyses of human heat exchange and obtain data from climate chamber experiments performed in mid-latitude climatic regions in North America and northern Europe (ASHRAE [1]). Nevertheless, the climate chamber method fails to include many subjects and raises concerns from practicing engineers regarding real-world situations. Moreover, these standards are suitable for static, uniformly thermal conditions. However, "real" people live in changeable, inconsistent environments, which may cause concerns when the standards are applied to residents living in real-world situations (Mclntyre [2]; Schiller [3]; Benton et al. [4]). Finally, different climatic regions, such as the tropics, may require different levels of comfort parameters mandated in the standard. Field studies of thermal comfort do not suffer from above flaws because they are conducted in actual buildings under normal conditions of occupancy and involve much larger and diverse samples of "real" occupants as opposed to "paid college-age subjects" (Cena [5]). So a large number of field studies have been performed around the world (Humphreys [6]; Howell and Kennedy [7]; Howell and Stramler [8]; de Dear and Auliciems [9]; Xia et al. [10], Cena and de Dear [11]; Wang et al. [12]; Nicol [13]). The results of such field studies indicate that the agreement between the expression of thermal comfort proposed by ASHRAE 55-1992 and ISO 7730 and sensations people really feel is not good. Throughout northern China, such as Beijing, Harbin, there have been a

*Corresponding author. Tel.: +86 731 882 5398; fax: +86 731 882 1005.
E-mail addresses: gqzhang@vip.sina.com (G. Zhang), zhangquan@hnu.cn (Q. Zhang).

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few literature reports of field study on occupants' comfort and residential thermal environment (Xia et al. [10]; Wang et al. [12]). However, to the best of our knowledge, there is little information available concerning occupant comfort and residential thermal environment in central southern China. Thus, the purpose of this study was to conduct a field study on comfort and residential thermal environment in a typical hot-humid climate of central southern China. Specific study objectives are to measure and characterize thermal perceptions of occupants in their residence, compare observed and predicted percent of dissatisfied (PPD) occupants and discern differences between the study area and other climate zones where similar studies have been performed.

2. Research methods

2.1. Outdoor climatic environment

Changsha, Guangzhou and Shenzhen are three cities in the typically hot-humid climate of central southern China, they are found in the sub-tropical wetness climatological region, see Fig. 1. Although the winter climates in these three cities are quite different, the summer climates are similar and extraordinary hot and humid. The surveys in this study were performed in the summer of 2003 and 2004. The mean daily maximum temperature was in the range of 30.5–35.5 °C from June to August. Meanwhile, the mean daily maximum relative humidity (RH) was in the range of 78.2–89.0%.

2.2. Subjects

A sample size of 110 subjects in 26 different residences in the three cities, Changsha $n = 19$. Guangzhou $n = 5$ and Shenzhen $n = 2$ were collected in two summer surveys and field measurements. The subjects participating in the study were composed of 59 females (53.6%) and 51 males (46.4%). The percentages of residences with and without air-conditioners were 44.5% and 55.5%, respectively. For the two sampling seasons, the average age of all respondents was 41.8 years, ranging from 20 to 67. The questionnaire, see Fig. 2, covered several areas including demographics (name, gender, age, etc.), years of living in their current cities and personal environmental control. The questionnaire also included the traditional scales of thermal sensation (TSENS) and thermal preference, current clothing garment and metabolic activity checklists. The TSENS scale was the ASHRAE seven-point scale of ranging from cold (-3) to hot ($+3$) with neutral (0) in the middle. The three-point thermal preference scale asked whether respondents would like to change their present thermal environment. Possible responses were "want warmer", "no change" or "want cooler". Clothing garment checklists were compiled from the extensive lists published in ISO [14]. Metabolic rates were assessed by a checklist of residential activities databases published in ASHRAE Standard 55-1992. Summary of the background characteristics of the subjects are presented in Table 1.

2.3. Measurement of indoor climate

The following instruments were used to measure physical comfort variables: a TES-1360 humidity/temperature meter and a Testo-425 anemometer with telescopic probe were used for collecting data of the indoor thermal environment, which tracked temperature, RH and air velocity with sensor accuracy of ± 0.8 °C, ± 3% and ± 0.01 m/s, respectively. These thermal comfort variables

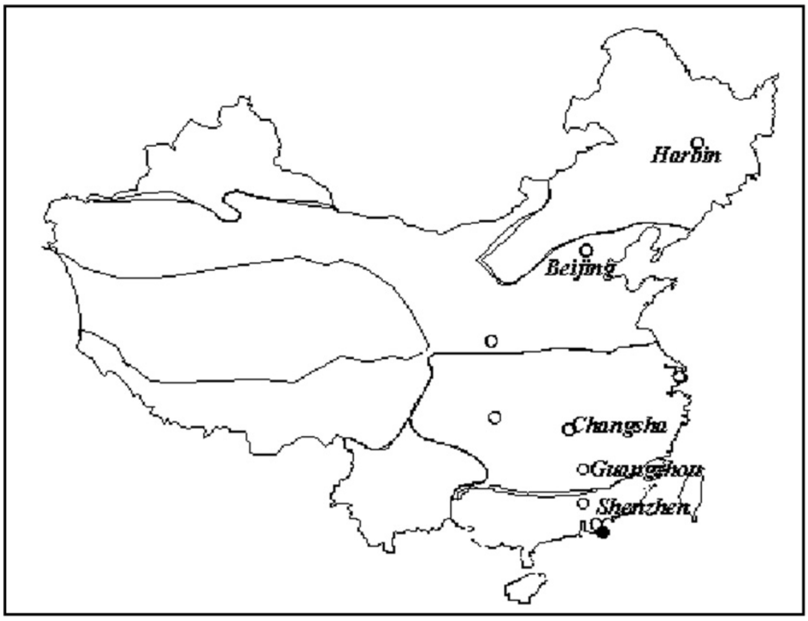

Fig. 1. Location of our survey.

Questionnaire on thermal environment and occupants' thermal comfort

Number__________

1. Demographic information of occupants

name	sex	age	Living years in the current city

2. Occupants' Clothing

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)	outerwear trousers (thick、thin)	cotton-padded trousers	woolen trousers	short skirt (thick、thin)
one-piece dress	sport shoes	leather shoes	sandals	hat	scarf

3. Occupant' Activity Level (Check the one that is most appropriate)

Reclining	Seated	Standing	Walking	Others

4. Subjective thermal sensations from ASHRAE seven-point scale

Cold -3	Cool -2	slightly cool -1	Neutral 0	slightly warm 1	Warm 2	Hot 3

5. Thermal preference from Mclntyre's three-point scale

cooler -1	NO change 0	Warmer 1

6. Thermal acceptability

Yes	No

7. Methods of personal control thermal environment:

____

Fig. 2. Questionnaire on thermal environment and occupants' thermal comfort.

were measured at 1.1 m height, while each respondent responded to the questionnaire.

Mean radiant temperature (MRT) was estimated using Eq. (1) (Nagano [15]) assuming that conditions used to develop the MRT, T_a regression model are applicable to our study:

$$\mathrm{MRT} = 0.99T_a - 0.01, \quad R^2 = 0.99, \tag{1}$$

where T_a is the indoor air temperature.

Operative temperature was calculated as the average of air temperature and MRT.

2.4. Calculation of comfort indices

Environmental and comfort indices were calculated with the Fountain model of TSENS [16] and software (http://atmos.es.mq.edu.au/~rdedear/pmv/) using data from the survey questionnaire and thermal variable measurements. Clothing insulation including chair insulation was an input.

Table 1
Summary of the subjects of residential occupants and personal thermal variables

Season	2003 summer	2004 summer
Sample size (male/female)	68 (28/40)	42 (23/19)
Gender (% of sample)		
Male	41.2	54.8
Female	58.8	45.2
Mean age (year)		
(Mean, standard deviation)	(42.5, 15.7)	(41.1, 16.3)
(Minimum, maximum)	(22, 67)	(20, 67)
Mean years living in local address		
(Mean, standard deviation)	(11.2, 7.6)	(10.0, 6.3)
(Minimum, maximum)	(2, 41)	(2, 38)
Mean metabolism (met) ($58.2\,W/m^2 = 1met$)		
(Mean, standard deviation)	(1.27, 0.15)	(1.28, 0.15)
(Minimum, maximum)	(1,1.7)	(1,1.7)
Mean clothing insulation (added chair 0.15 clo)		
(Mean, standard deviation)	(0.56, 0.11)	(0.51, 0.10)
(Minimum, maximum)	(0.38, 0.59)	(0.38, 0.59)

The program was used to calculate effective temperature (ET*), standard effective temperature (SET*), TSENS, predicted mean vote (PMV) and predicted PPD.

3. Results and discussions

3.1. Indoor climate

Table 2 provides statistical summaries of the indoor measurements for 2003 and 2004 summer season samples. For the two sampling seasons, mean air temperature ranges between 24.6 and 36.4 °C; MRTs falls into the interval between 21.0 and 36.0 °C, and the mean RH values range from 44.3% to 90.1%. The mean air velocity is between 0.01 and 0.14 m/s.

3.2. Thermal comfort on the questionnaire

3.2.1. Thermal sensation

The distribution of frequency for TSENS responses is given, see Fig. 3a. The mean comfort votes by occupants were around neutral, over 80% of comfort votes recorded by occupants ranged from 0 (neutral) to +1 (slightly warm). A comparison of TSENS response frequency among the following three groups (i) all residences, (ii) air conditioned residences, and (iii) residences without air conditioner is illustrated in Fig. 3b. As expected few occupants of air-conditioned homes perceive the temperature too cold. No discernable portion of occupants in either all residences or residences without air conditioning perceives the environment to be too cold. Importantly over 60% of occupants in air conditioned residences find the environment acceptable while only 20% of occupants in residences without air conditioning find their indoor thermal environment acceptable. A large portion of occupants of residences with no air conditioning find their thermal environment hot (32%) and about 8% find it too hot. In addition, mean TSENS votes (MTSV) from the questionnaire and PMV calculated according to Fanger's model have been plotted versus operative temperature, see Fig. 4. This figure shows that the sensation unit or the rate of change of PMV with one unit change of operative temperature is 2.3 °C. The linear regression equation that best fits the survey data is

$$[\text{Mean\_thermal\_sensation\_vote}] = 0.409T_0 - 11.71, \quad R^2 = 0.8927, \tag{2}$$

$$\text{Predicted\_mean\_vote} = 0.242\,T_0 - 5.39, \quad R^2 = 0.9627, \tag{3}$$

where T_0 is the operative temperature.

Table 2
Statistical summary of indoor climatic date

Season	2003 summer	2004 summer
Mean air temperature (°C)		
(Mean, standard deviation)	(29.0, 2.3)	(30.5, 2.7)
(Minimum, maximum)	(17.2, 36.4)	(18.6, 35.3)
Mean radiant temperature (°C)		
(Mean, standard deviation)	(28.7, 2.3)	(30.1, 2.7)
(Minimum, maximum)	(17.0, 36.0)	(18.4, 34.9)
Mean operative temperature (°C)		
(Mean, Standard deviation)	(28.8, 2.3)	(30.3, 2.7)
(Minimum, maximum)	(17.1, 32.3)	(18.5,35.1)
Mean relative humidity (%)		
(Mean, standard deviation)	(71.3, 16.0)	(78.4, 8.9)
(Minimum, maximum)	(44.3, 88.8)	(61.1, 90.1)
Mean air velocity (m/s)		
(Mean, standard deviation)	(0.07, 0.04)	(0.05, 0.02)
(Minimum, maximum)	(0.01, 0.14)	(0.02, 0.13)
Effective temperature ET (°C)*		
(Mean, standard deviation)	(33.2, 3.45)	(34.0, 2.8)
(Minimum, maximum)	(22.7, 38.9)	(26.2, 37.3)
Standard effective temperature SET (°C)*		
(Mean, standard deviation)	(38.6, 2.6)	(39.1, 2.2)
(Minimum, maximum)	(31.3, 43.3)	(33.3, 41.9)
Thermal sensation (TSENS)		
(Mean, standard deviation)	(1.32, 0.34)	(1.24, 0.42)
(Minimum, maximum)	(−1.53, 2.06)	(−1.10, 2.05)
Predicted mean vote (PMV)		
(Mean, standard deviation)	(1.50, 0.52)	(1.47, 0.32)
(Minimum, maximum)	(−0.30, 2.26)	(−0.60, 2.02)
Predicted percent of dissatisfied (PPD) (%)		
(Mean, standard deviation)	(52.6, 21.2)	(49.8, 15.3)
(Minimum, maximum)	(10.8, 99.6)	(23.5, 77.9)

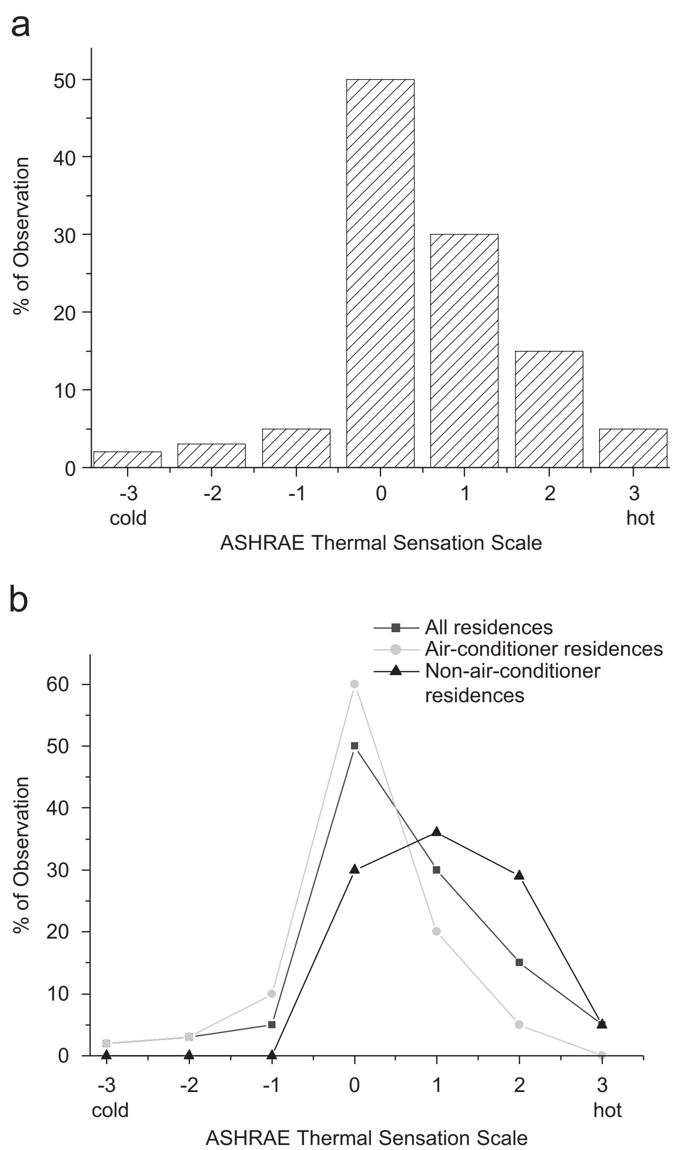

Fig. 3. (a) Frequency of thermal sensation responses. (b) Compare the frequency of thermal sensation responses with all residences, air conditioner residences and residences without air conditioner.

The neutrality value is estimated by solving Eq. (2) for a mean TSENS value equal to zero denoting a comfortable thermal environment; the neutral operative temperature is 28.6 °C.

3.3. Thermal preference

Preferred temperature is assessed directly according to the answers of the question: "At present time, would you prefer warmer, no change or cooler environment?" Simple linear regressions models are generated to associate temperature levels with prefer warmer or prefer cooler conditions. The preferred temperature is 22.8 °C as estimated from the intersection of the two fitted lines, see Fig. 5. These results show that the preferred operative temperature is lower than the neutral operative temperature in the hot and humid geographic area of this study.

3.4. Thermal acceptability

Thermal acceptability is the percentage of the respondents to the questionnaire who found "acceptable" their thermal conditions. About 87.3% of occupants considered their thermal environments acceptable. ASHRAE 55-1992 comfort zone 20–26 °C is for 1 clo and 23.8–28 °C for 0.5 clo. The average clothing in this study is 0.54 clo.This corresponds to a comfort range (PPD $<10\%$, PMV $<\pm 0.5$) from 23.4 to 27.8 °C, which were determined by the linear interpolation formula of ASHRAE 55-1992. About 48.2% of the thermal conditions fell in the comfort zone 23.4–27.8 °C. The acceptable temperature range is determined by people voting -1, 0, $+1$ that denotes comfort; all other votes denote discomfort. The operative range of temperatures at which over 75% of the occupants feel comfortable is between 22.0 and 27.0 °C, see Fig. 6a.

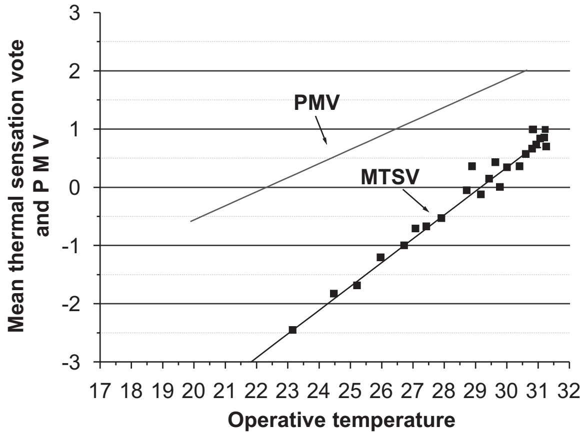

Fig. 4. Calculation of neutral temperature.

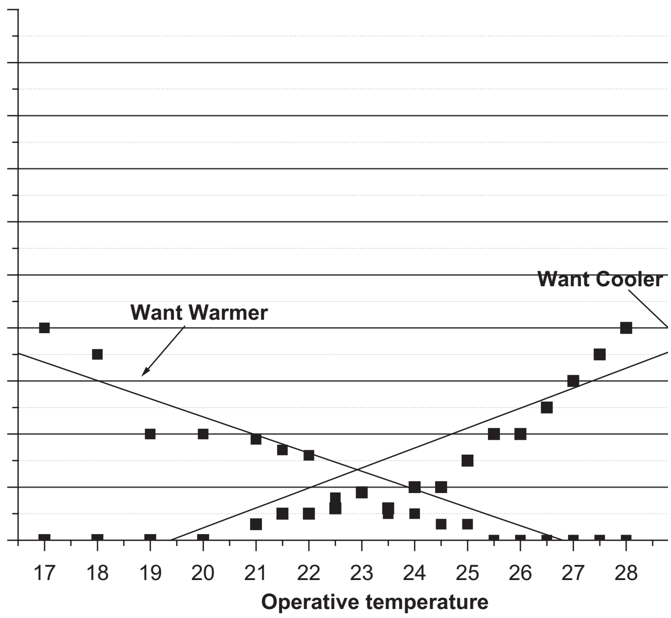

Fig. 5. Calculation of preferred temperature.

The thermal comfort of residents may be estimated by one of two methods: (1) use the residence air temperature, RH and velocity, which is the average of corresponding room measurements, and (2) use only the living room (LR) measured values where respondents answered the questionnaire. The output of the two methods is compared, see Fig. 6b. Firstly, since the window AC units are usually located to condition the LRs, this figure demonstrates the impact of AC operation because a change of 1 °C in the LR results in a smaller portion of unacceptable occupants than the corresponding change for the whole house. Thus, 1 °C change in temperature has a smaller impact in the LR than in the whole house. Secondly, the PPD values estimated using the Fanger model with the average operative temperature of the residence (the whole house) reproduce the observed percentage of dissatisfied occupants better than the PPD using the LR operative temperatures. This seems to support the notion of using average operative temperature to estimate the percentage of occupants who find their thermal environment unacceptable rather than the operative temperature of one specific room. Lastly, in the LR the operative temperature interval at which occupants feel comfortable is wider. Over 75% of occupants find comfortable thermal environments for the whole house between 22 and 27 °C. In the LR, the operative temperature range is between 17 and 25 °C.

3.5. Comparisons with previous thermal comfort field studies

In the Townsiville study (de Dear and Fountain [17]), the observed value of neutral region for both seasons (wet and dry) was 24.5 °C. The Motreal study (Donnini et al. [18]) showed the operative temperature defined neutralities to be 24.0 °C in summer. The thermal neutrality observed in Brishbane (de Dear and Auliciems [9]) was 23.8 °C. The summer values of thermal neutrality investigated by de Dear and Fountain [17] in the Townsiville, Donnini et al. [18] in the Motreal and de Dear and Auliciems [9] in Brishbane were very similar, 24.5, 24.0 and 23.8 °C, respectively. In the study, the thermal neutralities in south China residences 28.6 °C were higher than Townsiville, Motreal and Brishban's results. The preferred operative temperature in south China was 22.8 °C, which was lower than the "neutral" temperature. One possible explanation of the difference between our and the other studies focused on a climatic bias in the semantics of sensation scales. People in hot climates may prefer thermal state as "slightly cool", while people in cold climates may use the words "slightly warm" to denote their thermal preference. The calculated neutral temperature is 28.6 °C, over 40% of the subjects wanted it cooler. In addition to the semantic issues, the difference in neutral temperature and the similarity of the preferred temperature between this study and others in the literature is attributed to climatic conditions, which may affect a subject's preference. Finally, subjects might have different TSENS for the same environment as a function gender, age, clothing more so in the Chinese cultural background than in other cultures. The current data are consistent with this explanation. The sensation unit found in our study is more sensitive than temperature variations reported by the San Francisco and Harbin studies. A gradient of one sensation unit per 2 °C was found in both Townsville and Montreal studies, which were more sensitive than our study. A second possible explanation of the observed difference between our findings and those of other studies may be the difference in comfort perception among occupants of the same residence.

3.6. Comparisons between predicted indices and observed data

As seen in Fig. 4, the neutral operative temperature of the PMV regression model with chair insulation intersects

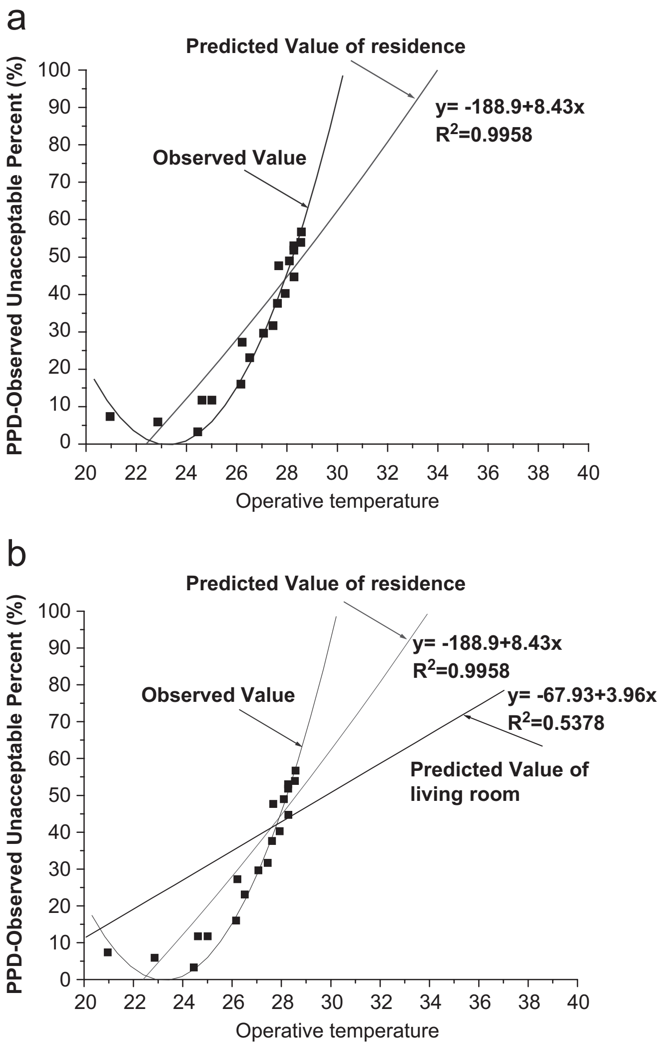

Fig. 6. (a) Observed thermal acceptability related to operative temperature. (b) Compare thermal acceptability between residences and living rooms.

is 6.3 °C lower than the neutral operative temperature of the observed TSENS votes' regression model. The gradient of predicted indices is less than observed data, which suggests that occupants are adjusting other parameters in their heat balance, such as clothing, windows and fan that greatly compensated for the departure of indoor air temperature from neutrality. In fact, the effects of behavioral, physiological and psychological adjustments appeared to have been overlooked when subjects were casting TSENS votes. This may explain differences between observed and predicted values, which are attributed to a subject's long-term behavior(open windows or fan), physiology (metabolism, clothing) and psychology that may not be accounted for by the short-term based on observation, so TSENS vote's sensitivity to temperature was much more remarkable than PMV.

4. Conclusions

This study investigates thermal environment and comfort of residences in the central southern China. A total of 110 occupants and 26 residences provided thermal perception data in the summers in 2003 and 2004 in the hot-humid cities of Changsha, Guangzhou and Shenzhen in the central south of China.

Occupant TSENS responses differ in homes with air conditioning and with out air conditioning. Consequently, combining the two types of residences may cause incorrect interpretation; in this study the change rate of TSENS in the LR is smaller than that of the whole house. We attribute this to the fact the air conditioners are usually located in the LR and 1 °C difference has a smaller effect.

The thermal neutral operative temperature in central south China residences is higher than Townsiville, Motreal and Brishban's results as indicated in the literature. A gradient of one sensation unit per 2.3 °C was gained, which is more sensitive than temperature variation reported by the San Francisco and Harbin studies, but less sensitive than Townsville and Montreal studies. The observed difference between this and similar studies may relate to subjects' inclination for a ''slightly cool'' thermal state in hot climates as opposed to ''slightly warm'' preference of those in cold climates. Not surprisingly this work supports the notion that climatic differences affect comfort perception.

The neutral operative temperature obtained from the PMV calculated by Fanger's model is lower than the MTSV obtained from the questionnaire data. The difference is attributed to the thermal adaptation of humans. In fact, people usually adapt to the thermal environment through adjusting other parameters in their heat balance, such as clothing, windows and fan, etc. This study also indicates that the use of the house average operative temperature with the Fanger model estimates the observed percentage of occupants who find their thermal environment unacceptable better than the using the operative temperature of one room.

The results of this field survey and measurement study can be used to design a low energy consumption system with consideration of occupant thermal comfort in central southern China.

Acknowledgments

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