Proceedings of Conference: ***Adapting to Change: New Thinking on Comfort***
Cumberland Lodge, Windsor, UK, 9-11 April 2010. London: Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Thermal Comfort Study in hot-humid area of China

Chen Huimei[★]**, Zhang Yufeng, Wang Jinyong and Meng Qinglin**
State Key Laboratory of Subtropical Building Science, Department of Architecture, South China University of Technology, Wushan, Guangzhou, 510640, PR China

Abstract

A climate chamber study was performed by using thirty subjects living in naturally ventilated buildings in hot-humid area of China with consistent experimental methods of the classic studies. The subjects dressed in standard clothing were exposed to conditions in a range from cool to warm and their subjective and physiological responses were collected. The results show that thermal sensation, comfort and acceptability have good linear relationships with modified temperature, and the temperature was 26.9°C for thermal neutrality and 26.4°C for most acceptable or comfortable state. Humid sensation was found to be a good linear function of water vapour pressure. Based on the experimental results, comprehensive comparisons with previous studies were performed in both psychological and physiological responses. It was found that the existing international standard based on the PMV model and the two-node model was not applicable for hot-humid area of China.

Keywords: Thermal comfort, climate chamber study, hot-humid area

1 INTRODUCTION

Since the 1920's, research into thermal comfort has been carried out in many countries, aiming to predict human perception of thermal environment and determine reasonable and feasible thermal environmental settings for buildings. Thermal comfort studies were performed mainly in climate chambers or in fields, and the climate chamber studies are very important to provide basic observations and establish thermal comfort theories and models. The first systematic climate chamber study was carried out by Nevins et al. (1966) by using 720 American students. Fanger (1970) reproduced that climate chamber study in Denmark in 1970, compared the results between American and Dane and established the PMV model based on these two studies. Similar studies were then conducted by other researchers in Japan, Singapore and Hong Kong et al. to validate the PMV model locally (Chung and Tong 1990; de Dear et al. 1991a, 1991b; Tanabe et al. 1987). The PMV model has been adopted by the existing ASHRAE Standard 55 (ASHRAE 2004) and ISO 7730 (ISO 2005).

Thermal comfort studies in China started lately in 1980s and the basic thermal comfort responses have not been observed and studied in climate chambers in hot-humid area of China and whether the PMV model and the existing international standards applicable or not remains unknown. By using the consistent experimental methods of the classic studies, a climate chamber study was conducted in hot-humid area of China and the results were comprehensively compared with previous studies in both psychological and physiological responses.

2 EXPERIMENTAL METHODS

The experiment was carried out in the State Key Laboratory of Subtropical Building Science at South China University of Technology during September of 2008.

2.1 Experimental design

A new climate chamber in South China University of Technology (see Figure 1) was used for this study. In the chamber air temperature can be controlled form 10ºC to 40ºC with a precision of ±0.2°C and relative humidity can be controlled from 40% to 90% with a precision of ±5%. Well-insulated windows were installed and regular office tables and chairs were supplied in the chambers to make the environment more like actual conditions.

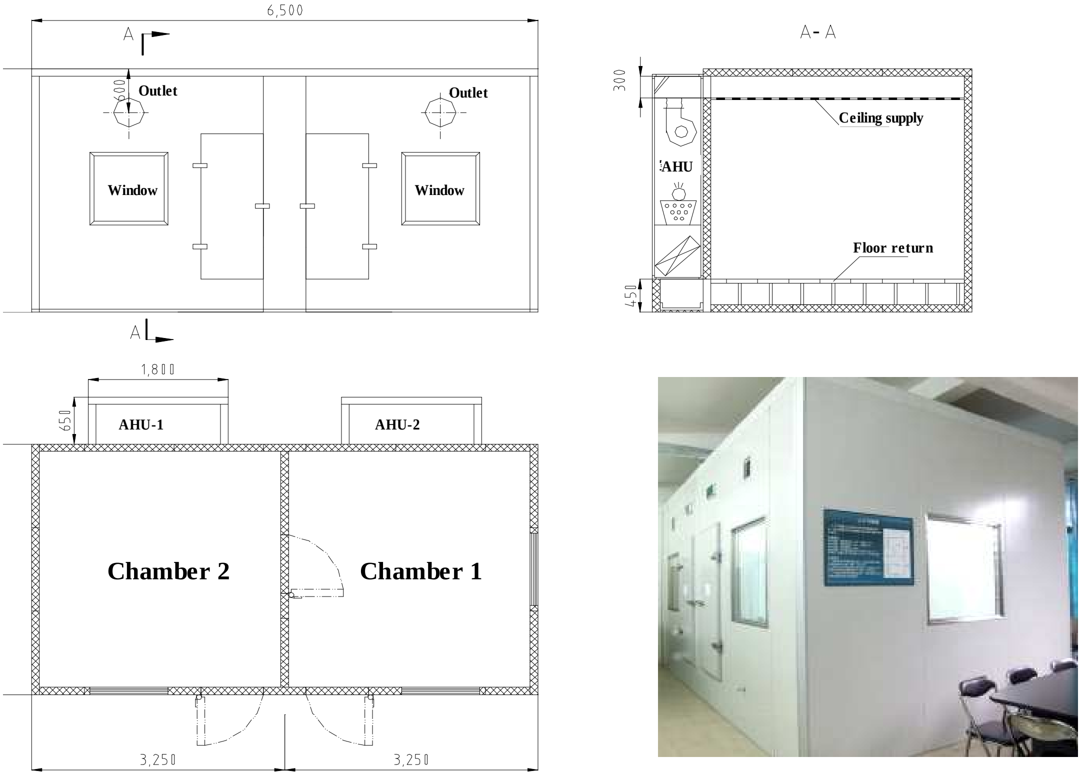


Figure 1 Climate chamber in South China University of Technology

The conditions to be tested were designed to cover a wide range of temperatures from 20ºC to 32ºC and two levels of humidity (see Table 1) to obtain the responses to cool, neutral, warm and humid environments. The air speed in the chamber was maintained less than 0.1m/s and the mean radiant temperature was close to the ambient air temperature. Thermal indices (ET*, MT, PMV and PPD) were accordingly calculated using the UC Berkeley Thermal Comfort Program for each condition with consideration of the clothing and activity levels of the subjects (Table 1), where modified temperature (*MT*) is defined as that air temperature of 5*0% rh* and *0.1m/s* mean air velocity, which would provide the same thermal sensation as in the actual thermal environment (Tanabe et al., 1987).

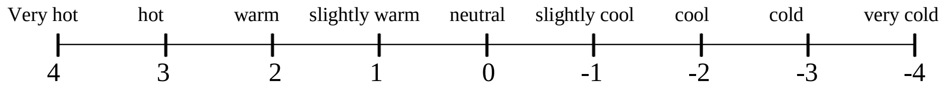
Table 1 Experimental conditions

Condition	Air temperature (ºC)	Relative humidity (%)	ET* (ºC)	MT (ºC)	PMV	PPD (%)
P	26	50	26	26	0.17	6
A	20	50	20	20	-1.91	72
B	23	50	23	23	-0.86	21
C	29	50	29	29	1.22	36
D	29	70	30.1	29.6	1.43	47
E	32	50	32	32	2.31	88
F	32	70	34	32.7	2.56	95

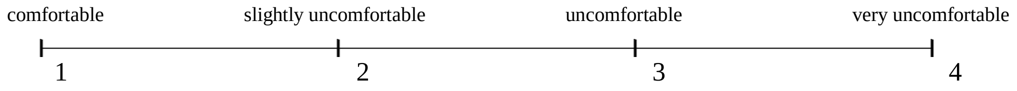
Note: Condition P represents pre-conditioning condition and conditions A-F represent 6 tested conditions.

2.2 Measurements

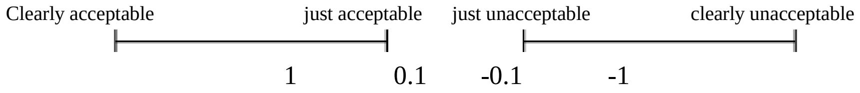
Subjective and physiological responses were collected and measured during the experiments. Subjects reported their thermal sensation, comfort, acceptability and humid sensation on a questionnaire (Figure 2). Questionnaire in local language using in the survey could be found in the end of the paper.



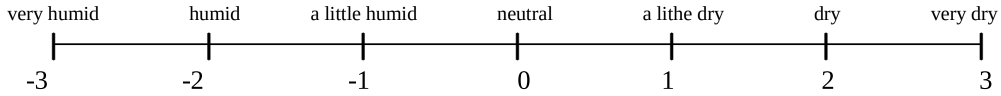
a. Thermal sensation scale



b. Thermal comfort scale



c. Thermal acceptability scale



d. Humid sensation scale

Figure 2 Voting scales

Skin temperature, weight, heart rate and blood pressure were recorded during the experiments. Skin temperatures was measured by attaching the thermal couples (±0.2°C precision) covered with a thin sheet of copper at four human body parts: chest, upper arm, thigh and calf (Figure 3), and the mean skin temperature was calculated by using the equation (Ramanathan 1964):

$$T_s = 0.3T_1 + 0.3T_2 + 0.2T_3 + 0.2T_4 \qquad (1)$$

where T_s is mean skin temperature, T_1 is skin temperature at chest, T_2 is skin temperature at upper arm, T_3 is skin temperature at thigh and T_4 is skin temperature at calf.

An accurate balance (±1g precision) was used to measure the weights of the subjects before and after each test (Figure 3). Three sphygmomanometers (±5% precision for heart rate and ±4mmHg precision for blood pressure) were used to measure the subjects' heart rates and the blood pressures (Figure 3).

Figure 3 Physiological measurements

2.3 Subjects and clothing

Repeated-measures design with thirty subjects was used in the present study, which has been successfully used in the study on the environmental effects on simulated office work in a closely controlled environment at the International Centre for Indoor Environment & Energy in DTU (Wyon 2001). Thirty college-age subjects were recruited, who were born in the Pearl River Delta (a typical hot-humid area of China) and have been living for long time in the naturally ventilated buildings in the same area (Table 2).

Table 2 Anthropometric data for the subjects

Sex	Number	Age	Height (cm)	Weight (kg)	BMI* (kg/m^2)
Male	15	22.2±0.7#	170.5±5.6	60.9±7.2	20.9±1.6
Female	15	21.7±0.8	160.9±3.9	48.7±2.9	18.8±0.8
Male + Female	30	22.0±0.8	165.7±6.8	54.8±8.2	19.9±1.6

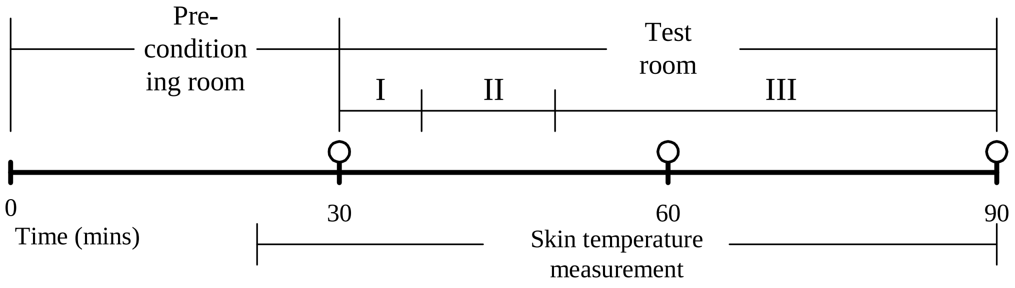
*Body mass index, BMI = weight/stature^2, normally between 18 and 25.
#Standard deviation.

To be compatible with the results of previous studies, all subjects were clothed in standard cotton shirts and trousers with an insulation of 0.6clo, which is same as the KSU （Kansas State University） standard uniform (Fanger 1970).

2.4 Experimental procedure

The subjects were asked to previously have a normal night's sleep and a normal meal at least one hour before arrival. After entering the pre-conditioning chamber the subjects changed their clothing with the uniforms and seated for half an hour, during which the skin temperature sensors were attached and one questionnaire was asked to report. Then the subjects entered the test chamber and seated, and asked to read, study or perform equally quiet activities. Quiet conversation not concerning the thermal environment and test was allowed. Each test lasted for one hour, during which subjective and physiological responses were both collected. Figure 4 shows the details of the experimental procedure.

Each subject participate the tests of all conditions and the total duration was 9 hours for each subject. The sequence of presentation was balanced for the subjects using Latin squares to avoid the effects of learning, increased familiarity and over-familiarity (boredom) (Wyon 2001).



Note: ○: Heart rate, blood pressure and weight measurement

I: Vote in 1 mins intervals

II: Vote in 3 mins intervals

III: Vote in 10 mins intervals

Figure 4 The experimental procedure

3 RESULTS

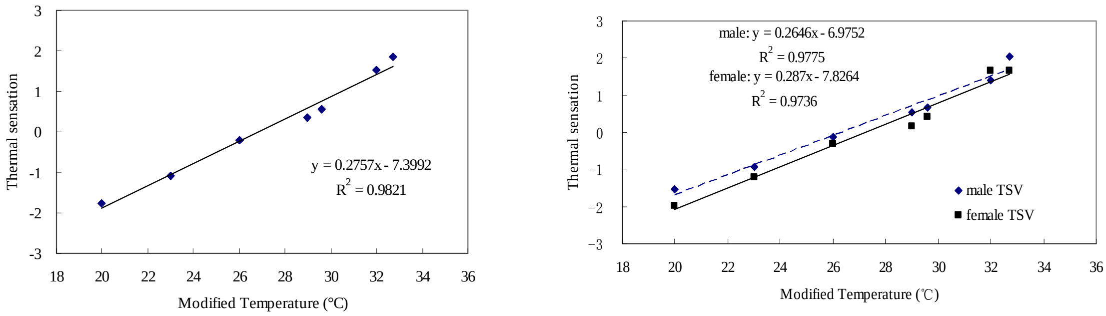
Shapiro-Wilk's W test was applied and the results show that human responses obtained in all conditions were normally distributed. They were therefore analysed using repeated measure ANOVA and paired-sample t-tests. It was found that human responses reached steady state within 30 minutes ($p>0.05$) in all conditions. If not mentioned specifically, all responses reported below are steady state responses, which are mean of 60-90 minutes.

3.1 Thermal sensation

A good linear relationship between thermal sensation (TS) and modified temperature (MT) was found (Figure 5a):

$$TS = 0.276MT - 7.399 \quad (2)$$

Thermal sensation responses were further compared in term of gender. It was found that the female subjects voted a little cooler than the male subjects, and their differences became greater with decreased air temperature (Figure 5b). However, t-test shows that the differences are not significant.

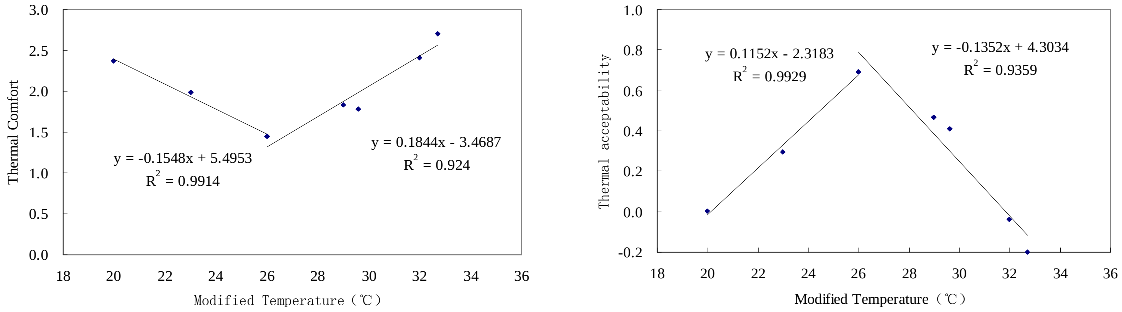


a Linear relationship b Gender difference

Figure 5 Thermal sensation as a function of modified temperature

3.2 Thermal comfort and acceptability

Figure 6 shows thermal comfort and acceptability as functions of modified temperature. The relationships can be expressed as two straight lines symmetrical to an optimal point for both thermal comfort and acceptability. The modified temperature corresponding to the optimal point is 26.4°C.



a Thermal comfort b Thermal acceptability

Figure 6 Thermal comfort and acceptability as functions of modified temperature

3.3 Humid sensation

Humid sensation was found to be a good linear function of water vapour pressure and the water vapour pressure corresponding to neutral humid sensation is around 3500Pa (Figure 7).

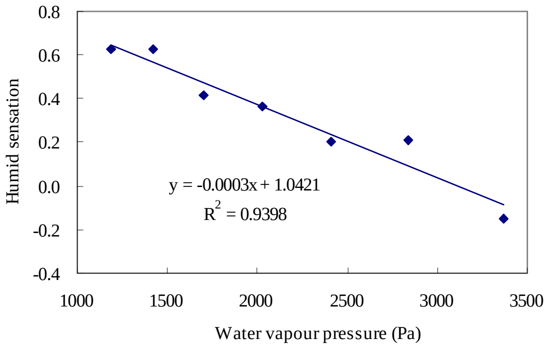
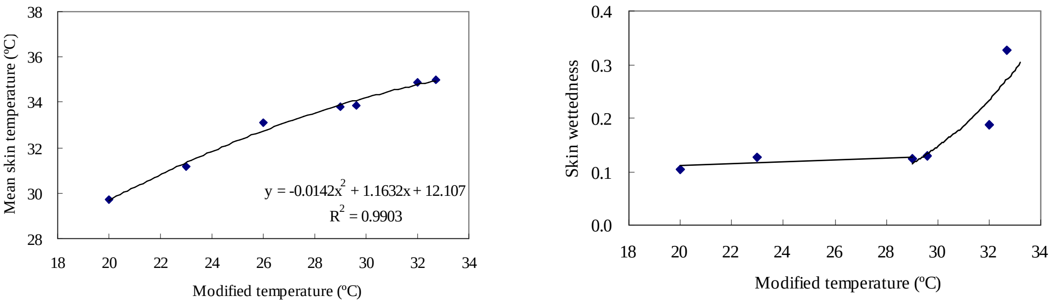


Figure 7 Humid sensation as a function of water vapour pressure

3.4 Skin temperature and wettedness

A good second-order polynomial relationship was found for skin temperature with modified temperature (Figure 8a). Mean skin temperature increases linearly with modified temperature in cold-warm range, and changed slowly in hot conditions due to evaporation of sweat at skin surface.

Skin wettedness was calculated based on the weight change for each subject and the mean skin wettedness changing with modified temperature is shown in Figure 8b. Skin wettedness is maintained at 0.1 while modified temperature is less than 30°C, which can be considered as natural diffusion. Regular sweating starts and skin wettedness increases rapidly when modified temperature is greater than 30°C.

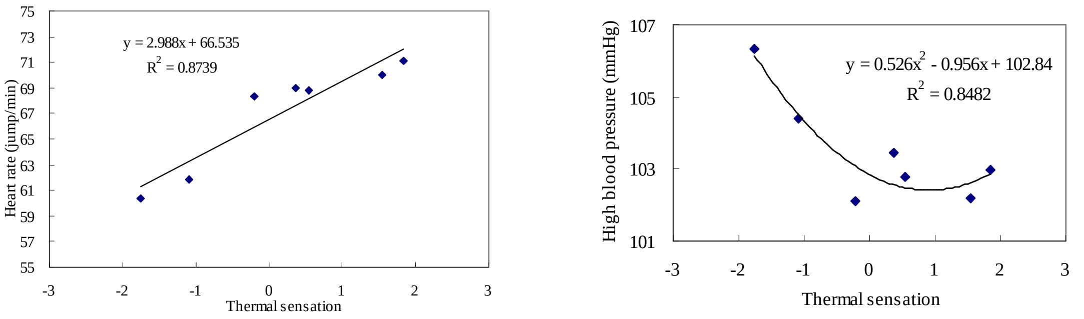


a Mean skin temperature b Skin wettedness

Figure 8 Skin temperature and wettedness change with modified temperature

3.5 Heart rate and blood pressure

It was found that heart rate changed linearly with thermal sensation (Figure 9a), which corresponds to vasoconstriction in cold environments and vasodilatation in warm environment. The heart rate is 66jump/min for thermal neutrality. High blood pressure was found to be a second-order polynomial function of thermal sensation (Figure 9b). Blood pressure is higher in cool-neutral range and changes slightly in neutral-warm range. Similar results were found for low blood pressure.



a Heart rate b High blood pressure

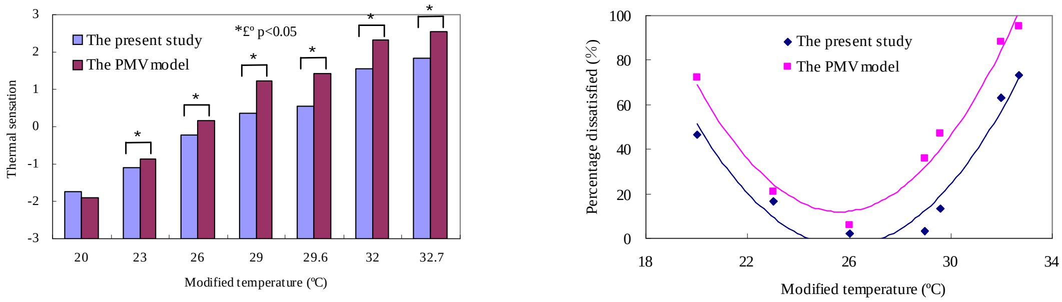
Figure 9 Heart rate and high blood pressure change with thermal sensation

4 DISCUSSIONS

4.1 Comparison with the PMV model

Comparison of the observed mean thermal sensation vote with PMV is shown in Figure 10a and significant differences ($p<0.05$) were found in all conditions except for the condition A. The PMV model overestimates the subjects' thermal sensation in both cool and warm conditions. The subjects feel more close to neutral in conditions with high temperature and humidity, which can be the results of their acclimatization in local hot-humid climate.

Percentage dissatisfied was calculated based on thermal acceptability votes and compared with PPD in Figure 10b. PPD overestimates percentage dissatisfied of the subjects in all conditions. The operative temperature range is 23.1-29.1°C for 90% acceptability and 22.2-29.9°C for 80% acceptability while assuming relative humidity maintains 50%. The acceptable operative range specified in the ASHRAE standard 55 is 24.1-26.9°C and 23.3-27.9°C respectively, which is based on the PMV model. The big difference on the acceptable range indicates that the standard and the PMV model are not suitable for the people living in hot-humid area of China, who have a wider acceptable range and a higher temperature upper limit. Lots of energy can be potentially conserved by well design of local thermal comfort standard for hot-humid area of China.



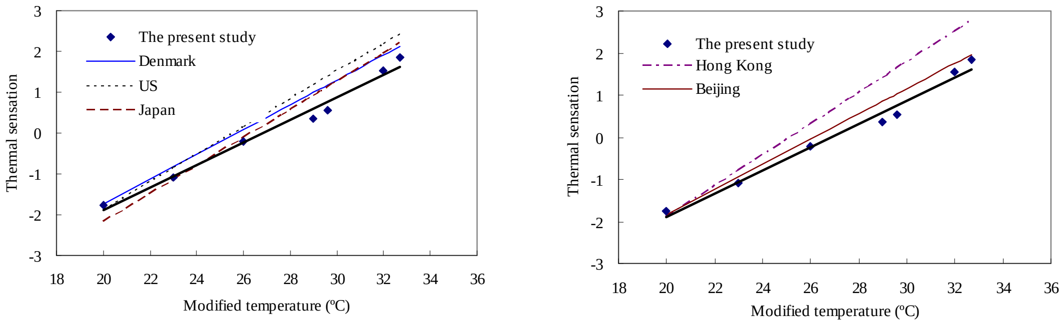
a Comparison of thermal sensation b Comparison of percentage dissatisfied

Figure 10 Comparison with the PMV model

4.2 Comparison with previous studies

Since the 1960s several thermal comfort studies have been systematically performed in climate chambers in US, Denmark and Japan. Figure 11a presents the comparison of the present study with those studies. It can be seen that the subjects from hot-humid area of China are least sensitive and feel more close to neutral in warm environments.

Since the 1980s two climate chamber studies were carried out in China by Chung and Tong (1990) and Zhou X (2008), and their results were compared with those of the present study (Figure 11b). Again, the subjects in the present study are least sensitive and feel more comfortable than the subjects in Beijing and Hong Kong. Hong Kong locates in hot-humid area of China as well, however, more difference was found with the Hong Kong study than the Beijing study, which may because that the subjects' long-time living conditions are air-conditioned in the Hong Kong study and naturally ventilated for the Beijing study.



a Studies outside of China b Studies in China

Figure 11 Comparison with other studies

Table 3 shows the neutral temperatures for the climate chamber studies. The neutral temperature in hot-humid area of China is the highest, which is closed to what had been found in Japan.

Table 3 Neutral temperatures of the climate chamber studies

Country (Area)	US	Denmark	Japan	China (Hong Kong)	China (Beijing)	The present study
Neutral temperature (in modified temperature, °C)	25.6	25.7	26.3	24.9	26.2	26.9

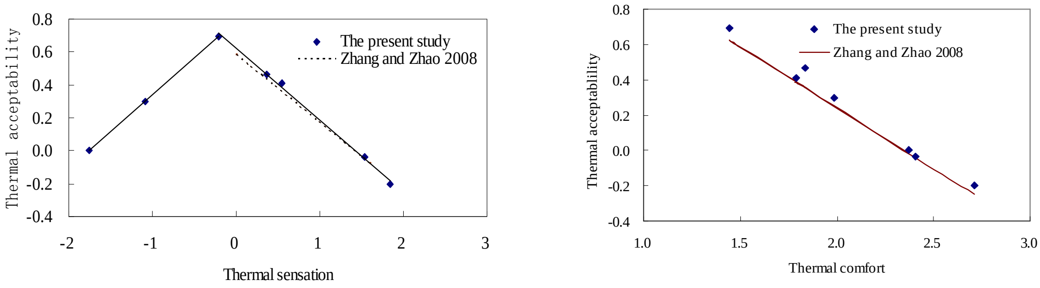
Compared with other climate chamber studies, people living in naturally ventilated buildings in hot-humid area of China have less sensitive sensations, higher neutral temperatures and more comfortable feelings in environments with high temperature and humidity. Long-time adaptations to both local climate and living conditions are the possible reasons for the differences.

4.3 Thermal sensation, comfort and acceptability

Zhang and Zhao (2008) found good linear relationships between thermal sensation, comfort and acceptability under uniform and steady environments in a climate chamber and mentioned that acceptable range runs from neutral to 1.5 on thermal sensation scale and contains all comfortable and slightly uncomfortable votes on thermal comfort scale. Similar linear relationships were found in the present study (Figure 12).

Thermal acceptability changes with thermal sensation symmetrically and one unit change of thermal sensation will produce 0.4 unit change of thermal acceptability in both warm and cool sides (Figure 12a), which indicates that the ASHRAE 7-point scale has equal psychological widths of the categories (McIntyre 1978) not only in sensation but also in acceptability. The optimal state corresponds thermal acceptability of 0.7 and thermal sensation of -0.2, which is in agreement with the results by McIntyre and Gonzalez (1976), who found that in hot climate ‘cool’ became the desirable state. Thermal sensation votes of -1.8 and 1.4 correspond to thermal acceptability vote of 0, which means acceptable thermal sensation range is from -1.8 to 1.4. Compared with the previous study (Zhang and Zhao 2008), the acceptable range in the present study is displaced towards cool.

Thermal acceptability has a good linear relationship with thermal comfort and thermal acceptability vote of 0 corresponds to thermal comfort vote of 2.35, and acceptable range covers all comfortable and slightly uncomfortable votes (Figure 12b). The psychological relationship between feelings of acceptability and comfort are very similar for people from various climates.

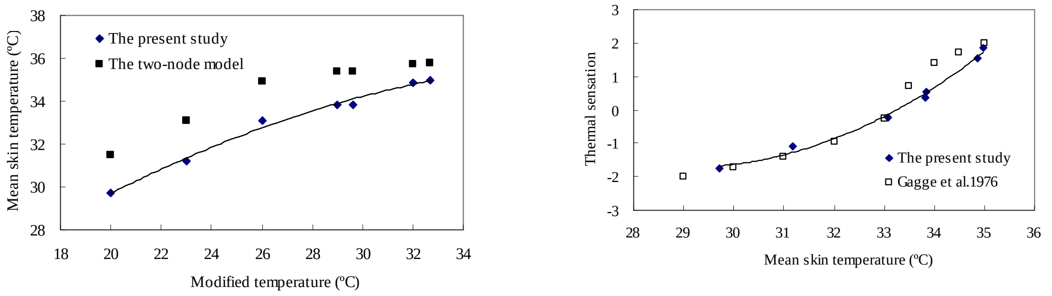


a Thermal acceptability and sensation b Thermal acceptability and comfort

Figure 12 Relationships between thermal sensation, comfort and acceptability

4.4 Skin temperature and thermal sensation

Mean skin temperature is a key physiological factor related to thermal sensation. The two-node model was established by Gagge et al. (1971) based on the results of experiment using subjects from US and Europe and it is widely accepted and applied to predict physiological responses and calculate SET. The mean skin temperature in the present study was compared with the calculation by the two-node model (Figure 13a). It was found that the two-node model overestimated the mean skin temperatures of the subjects in hot-humid area of China under both warm and cool conditions and their biggest difference was nearly 2°C. As an important indicator for acclimatization (Mao Z. and Wu T. 2000), the notable decrease of skin temperature to some extent proves that the subjects have acclimated to their living conditions and local warm climate.



a Mean skin temperature against modified temperature b Thermal sensation against mean skin temperature

Figure 13 Comparison of skin temperature and its relationship with thermal sensation

Gagge et al. (1967) are the first to systemically study the relationship between skin temperature and thermal sensation. They found that thermal sensation was very responsive to change of average skin temperature when skin temperature was below

35°C, and increased only slightly when skin temperature was above 35°C. Fiala (2002) collected many previous climate chamber studies and established a relationship between mean skin temperature and thermal sensation by using statistical methods. The relationship is linear when the mean skin temperature is between 3°C below and 1°C above its set point, but beyond those points, the relationship approaches the scale limits exponentially, where the set point of the mean skin temperature is the value when sensation is neutral. Zhang (2003) reanalyzed the results of Gagge et al. (1967) and proposed that thermal sensation was roughly a linear function of mean skin temperature between 29°C and 34°C, and as skin temperature moved above or below that the linear relationship disappeared and thermal sensation started to level off.

Figure 13b presents the thermal sensation against mean skin temperature in the present study and the study by Gagge et al (1967). They are very close when skin temperature is below 33°C, and separate in the temperature range of 33-35°C, and finally go closed to each other when skin temperature is 35°C. The set point of the mean skin temperature in the present study is 33.2 °C. Thermal sensation is a linear function of mean skin temperature between 30.2°C and 34.2°C and the linear relationship disappeared as skin temperature moves above, which is in agreement with the results of Fiala (2002) and Zhang (2003).

4.5 Skin wettedness and thermal comfort

The skin wettedness in the present study was compared with the calculations by the two-node model (Figure 14). The threshold for sensible sweating is 30°C for the present study, which is higher than that predicted by the two-node model (28°C). The two-node model overestimates the sweat of the subjects in hot-humid area of China under the conditions with high temperature and humidity, which agrees well with the findings in the climate chamber study by Tanabe et al. (1987), who found Japanese sweated less than Americans at a high temperature. Increase of sweating threshold and decrease of sweat are considered as key indicators for long-term acclimatization in many studies (Hori et al. 1978) and the results of the present study show that people living in naturally ventilated buildings in hot-humid area of China acclimate to local climate very well. Skin wettedness was found to be a good indicator for thermal comfort in high temperature conditions (Figure 15).

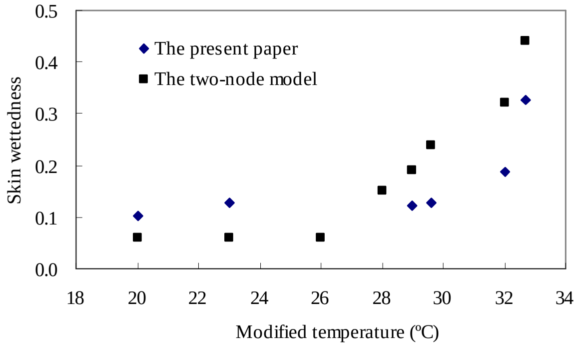


Figure 14 Comparison of skin wettedness

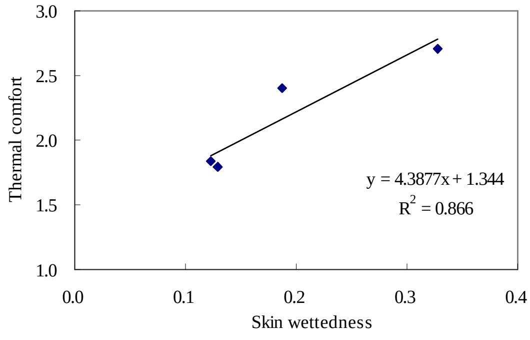


Figure 15 Thermal comfort change with skin wettedness

5 CONCLUSIONS

A climate chamber study was conducted in hot-humid area of China with consistent experimental methods of the classic studies and the results were comprehensively compared with previous studies in both psychological and physiological responses. The following are the major points.

1. Good linear relationships were found between thermal sensation, comfort, acceptability and modified temperature, and the temperature was 26.9°C for thermal neutrality and 26.4°C for most acceptable or comfortable state.
2. Humid sensation was found to be a good linear function of water vapour pressure.
3. The PMV model overestimates the thermal sensation and percentage dissatisfied and the existing international thermal comfort standard is not applicable for people in hot-humid area of China, who have a wider acceptable range (22.2-29.9°C for 80% acceptability) and a higher temperature upper limit.
4. Compared with other climate chamber studies, people living in naturally ventilated buildings in hot-humid area of China have less sensitive sensations, higher neutral temperatures and more comfortable feelings in environments with high temperature and humidity.
5. The two-node model overestimates the mean skin temperature and skin wettedness for people in hot-humid area of China, who acclimate to their local climate and living conditions with lower skin temperature, higher sweating threshold and less sweat at a high temperature and humidity.

ACKNOWLEDGEMENT

This study was supported by National Natural Science Foundation of China (Project No. 50708038 and 50838003), and the State Key Laboratory of Subtropical Building Science at South China University of Technology (Project No. 2008ZC18).

REFERENCES

ASHRAE (2004), Thermal Environmental Conditions for Human Occupancy, *ASHRAE Standard 55-2004*. Atlanta.

Chung, T M and Tong, W C (1990), Thermal comfort study of young Chinese people in Hong Kong. Building and Environment, Vol.25, No.4, pp 317-328.

de Dear, R J, Leow, K G and Ameen, A (1991a), Thermal comfort in the humid tropics. Part I. Climate chamber experiments on temperature preferences in Singapore. ASHRAE Transactions, Vol.97, No.1, pp 874-879.

de Dear, R J, Leow, K G and Ameen, A (1991b), Thermal comfort in the humid tropics. Part II. Climate chamber experiments on thermal acceptability in Singapore. ASHRAE Transactions, Vol.97, No.1, pp 880-886.

Fanger, P O (1970), Thermal comfort. Danish Technical Press, Copenhagen.

Fiala, D (2002), First principles modeling of thermal sensation responses in steady state and transient conditions. ASHRAE Trans., Vol.109, No.1, pp 179-186.

Gagge, A P, Stolwijk, J A J and Hardy, J D (1967), Comfort and thermal sensations and associated physiological responses at various ambient temperatures. Environmental Research, Vol.1, pp 1-20.

Gagge, A P, Stolwijk, J A J and Nishi, Y (1971), An effective temperature scale based on a simple model of human physiological regulatory response. ASHRAE Trans., Vol.77, No.1, pp 247-262.

Hori, S, Tsujita, J and Tanaka, N (1978), Studies on heat tolerance of subtropical natives after migration to a trmperature zone. International Journal of Biometeorology, Vol.22, No.2, pp 82-93.

ISO (2005), Ergonomics of the thermal environment — Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria, *ISO International Standard 7730* (). Geneva.

Mao Z. and Wu T. (2000), Modern Heatstroke Diagnosis and Cure. People's surgeon press, Beijing, China. (in Chinese)

McIntyre, D A (1978), Seven point scales of warmth. Building Services Engineer, Vol.45, pp 215-226.

McIntyre, D A and Gonzalez, R R (1976), Man's thermal sensitivity during temperature changes at two levels of clothing, insulation and activity. ASHRAE Trans., Vol.82, No.2, pp 219-233.

Nevins, R G, Rohles, F H, Springer, W and Feyerherm, A M (1966), A temperature-humidity chart for thermal comfort of seated persons. ASHRAE Transactions, Vol.72, No.1, pp 283-291.

Ramanathan, N L (1964), A new weighting system for mean surface temperature of the human body. Journal of Applied Physiology, Vol.19, pp 531-533.

Tanabe, S, Kimura, K and Hara, T (1987), Thermal comfort requirements during the summer season in Japan. ASHRAE Transactions, Vol.93, No.1, pp 564-577.

Wyon, D P (2001), Methodology for indoor environmental research. The ICIE Symposium, 2001.

Zhang, H. (2003). *Human thermal sensation and comfort in transient and non-uniform thermal environment.* , University of California, Berkeley.

Zhang, Y and Zhao, R (2008), Overall thermal sensation, acceptability and comfort. Building and Environment, Vol.43, No.1, pp 44-50.

Zhou, X. (2008). *Effect factor and evaluation index of human thermal sensation in neutral-hot environment.* , Tsinghua University, PhD thesis, Beijing, China.

Questionnaire used in the survey in local language (Chinese):

1、您认为此时你所处的环境闷热吗?A、非常闷热　B闷热　C、有点闷热　D、不闷热

2、请给出您此刻全身的热感觉

热	暖	微暖	中性	微凉	凉	冷
hot	warm	slightly warm	neutral	slightly cool	cool	cold

3、您认为此时您所处环境空气的潮湿程度为:

很潮湿　潮湿　有点潮湿　中性　有点干燥　干燥　很干燥

4、您如何评价此刻室内热环境的舒适程度

舒适　有点不舒适　不舒适　非常不舒适

5、请给出您此刻对室内热环境的可接受程度的评价

完全可接受　刚刚可接受　刚刚不可接受　完全不可接受