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ORIGINAL PAPER

Thermal comfort in naturally ventilated and air-conditioned buildings in humid subtropical climate zone in China

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Abstract A thermal comfort field study has been carried out in five cities in the humid subtropical climate zone in China. The survey was performed in naturally ventilated and air-conditioned buildings during the summer season in 2006. There were 229 occupants from 111 buildings who participated in this study and 229 questionnaire responses were collected. Thermal acceptability assessment reveals that the indoor environment in naturally ventilated buildings could not meet the 80% acceptability criteria prescribed by ASHRAE Standard 55, and people tended to feel more comfortable in air-conditioned buildings with the air-conditioned occupants voting with higher acceptability (89%) than the naturally ventilated occupants (58%). The neutral temperatures in naturally ventilated and air-conditioned buildings were 28.3°C and 27.7°C, respectively. The range of accepted temperature in naturally ventilated buildings (25.0~31.6°C) was wider than that in air-conditioned buildings (25.1~30.3°C), which suggests that occupants in naturally ventilated buildings seemed to be more tolerant of higher temperatures. Preferred temperatures were 27.9°C and 27.3°C in naturally ventilated and air-conditioned buildings, respectively, both of which were 0.4°C cooler than neutral temperatures. This result suggests that people of hot climates may use words like "slightly cool" to describe their preferred thermal state. The relationship between draught sensation and indoor air velocity at different temperature ranges indicates that indoor air velocity had a significant influence over the occupants' comfort sensation, and air velocities required by occupants increased with the increasing of operative temperatures. Thus, an effective way of natural ventilation which can create the preferred higher air movement is called for. Finally, the indoor set-point temperature of 26°C or even higher in air-conditioned buildings was confirmed as making people comfortable, which supports the regulation in China that in public and office buildings the set-point temperature of air-conditioning system should not be lower than 26°C.

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Introduction

Many field studies on thermal comfort have been performed in humid subtropical climates. De Dear and Auliciems (1985) made a validation of the predicted mean vote of thermal comfort in six Australian field studies and found the neutral temperature in Brisbane was 23.8°C and 25.5°C for air-conditioned and free-running buildings, respectively. A comparative analysis of short-term and long-term thermal comfort surveys in Iran was carried out by Heidari and Sharples (2002), who found that people could achieve comfort at higher indoor air temperatures compared with the recommendations of international standards such as ISO7730. Kwok and Chun (2003) conducted surveys in naturally ventilated and air-conditioned schools in Japan and found that the naturally ventilated classrooms were 3°C warmer than the air-conditioned classrooms, but the naturally ventilated occupants voted with higher acceptability (74%) than the air-conditioned occupants (64%). A large-scale survey was performed by Mui and Chan (2003) to develop new notions about adaptive comfort temperature in buildings in humid subtropical Hong Kong. Hwang et al. (2006) conducted field experiments in 10 naturally ventilated and 26 air-conditioned campus classrooms in Taiwan, and found that occupants who have acclimated to the hot-humid climate can accept warmer thermal environments. Most of these studies were carried out in developed areas, where the subjects' race, living standards and habits, climatic experiences and expectations are different from those in developing countries like China. Additionally, all the studies aimed at investigating the effects of indoor climate on thermal perception, but few of them considered separately the effect of air velocity on thermal perception, whereas air movement is an important factor in determining comfort and compensates for warm temperatures in making people comfortable (Fountain 1991).

Thermal comfort in the humid subtropical climate zone in China (Fig. 1) should be studied carefully because of the different climatic conditions and social background from other areas of the world. The humid subtropical climate zone in China is located in the eastern Eurasia and faces the Pacific on the east, lying between latitudes 22°N and 34°N and longitudes 98°E and 123°E. The climate in this area is characterized by hot, humid summers and chilly winters. Under the control of subtropical high air pressure, high temperatures hold up through the whole summer and the maximum temperature can be higher than 40°C. The diurnal range is very small and the minimum temperature during the morning is often between 26°C and 30°C. Compared with other areas in the world at the same latitude, the temperature in humid subtropical China is obviously higher in summer. In winter, the minimum temperature of the coldest month is lower than −18°C and the percentage of sunshine time is very small. It is the coldest area at the same latitude in the world, and the relative humidity is high throughout the year (Feng 2004). Table 1 gives a comparison of the climatic conditions of different cities in subtropical zone.

Currently, environmental and energy problems have already become the bottleneck holding back the economic development of China, and building energy consumption (does not include building materials) amounted to 1/4 of the total energy consumption of the whole country as early as in 2001. In order to achieve the goal of building energy conservation, related governmental departments have issued standards and regulations about the planning, designing, construction and operation of buildings and their systems. For example, the General Office of the State Council issued a national regulation named "Set-point temperature standard in air-conditioned public buildings" in June 2007, which prescribes that indoor set-point temperature cannot be lower than 26°C in summer and cannot be higher than 20°C in winter. This makes the thermal comfort in China a particularly important fundamental research because there is no such experience in other places of the world where the set-point temperature is regulated so high. A question must be answered by thermal comfort research: can people in China feel comfortable at the temperature of 26°C or even higher in air-conditioned buildings? With the motivation to investigate this research area, a comprehensive field survey for both naturally ventilated and air-conditioned buildings was carried out. This study is expected to produce relevant and recent data to provide a better understanding of the adequacy

Fig. 1 Locations of the cities surveyed

Table 1 Climatic conditions of different cities in subtropical zone

Location	Latitude (N)	January average temperature(°C)	July average temperature(°C)
Nanjing	32°03′	2.3	28
Shanghai	31°14′	3.5	27.8
Wuhan	30°38′	3	28.8
Changsha	28°12′	4.7	29.3
Jiujiang	29°42′	5	29.6
Cairo	30°13′	13.8	27.9
Bagdad	33°14′	9.3	34
Charleston	32°47′	10	27.6
Port Said	31°17′	14.4	26.5
Agadir	30°23′	13.8	26.6
New Orleans	30°	12	27.3

Note: Cities of Nanjing, Shanghai, Wuhan, Changsha and Jiujiang are involved in this study
Data source: (1) National Meteorological Information Centre of China http://www.cma.gov.cn/)
(2) Deng (1998)

of existing indoor environment in providing thermal comfort in humid subtropical China.

The main objectives of this study are as follows:

(1) To investigate the thermal comfort perception and preference of the occupants living in the humid subtropical climate zone of China.
(2) To determine the neutral temperature and acceptable temperature range for both naturally ventilated and air-conditioned buildings and compare the results with previous studies.
(3) To investigate the influences of air velocity on occupant thermal sensation and analyze the quantitative relationship between indoor air velocity and occupant draught sensation.
(4) To make sure whether the indoor set-point temperature of 26°C or even higher in air-conditioned buildings is appropriate for occupants.

Materials and methods

Site selection

Field surveys took place during the hot summer season, from 19 June to 2 September 2006. Five cities (Changsha, Wuhan, Shanghai, Jiujiang and Nanjing) in the humid subtropical climate zone were involved in this extensive field study. The locations of the cities are shown in Fig. 1. In each city, 40–50 occupants were selected and no more than 5 persons were interviewed in the same building. A total number of 229 respondents from 65 naturally ventilated and 46 air-conditioned buildings took part in the study. Approximately 56% of the respondents were from the naturally ventilated buildings and 44% from the air-conditioned buildings. Equilibrium between males and females has also been respected during the selection of respondents. Summaries of the subjects are given in Table 2. The survey was planned to select buildings that represent: (1) different locations in humid subtropical climate zone; and (2) typical types and sizes (i.e. private and public, residential and office, flats or two-storey buildings, air-conditioned and naturally ventilated buildings, etc.).

Data collection

Both objective and physical measurements and subjective assessment were adopted on each visit of the field survey.

Table 2 Summary of sample

	All	Building type	
		NV	AC
Sample size	229	129	100
Gender			
Male	136	71	65
Female	93	58	35
Age (years)			
Mean	30.2	30.9	29.3
SD	10.1	10.9	8.95
Minimum	12	12	21
Maximum	61	60	61
Years in China			
Mean	10.22	10.1	10.38
SD	15.08	15.7	14.29
Minimum	0.5	0.5	0.5
Maximum	60	60	55
CLO			
Mean	0.3	0.288	0.316
SD	0.089	0.093	0.082
Minimum	0.14	0.14	0.14
Maximum	0.57	0.53	0.57

NV Naturally ventilated; *AC* air-conditioned

The objective measurement aimed to collect indoor environment variables (air temperature, mean radiant temperature, relative humidity and air velocity), which were necessary for further thermal comfort analysis. The air temperature and relative humidity were measured using a portable monitor (TES-1360). The air velocity was measured using a hot-wire anemometer (Testo425). The mean radiant temperature was estimated from the globe temperature, using a 150-mm-diameter black globe thermometer. The operative temperature was calculated as the average of air temperature and mean radiant temperature. All measurements were taken at a height of 1.1 m above the floor, which represents the height of the occupant at seated level. The accuracy of the instrument conformed to ASHRAE Standard 55–1992 (ASHRAE 1992) and ISO 7726 (ISO 1985).

The subjective assessment was based on responses to a questionnaire survey, which was administered simultaneously with the physical measurements on each visit. The questionnaire consisted of three sections: demographic information, comfort sensation and the use of control actions. In the first section, respondents were asked about their age, gender, clothes, the city of residence and the usage of air-conditioners. The second section asked the respondents to assess thermal sensation, thermal preference and thermal acceptability. The thermal sensation scale was the traditional ASHRAE seven-point scale. Thermal preference was assessed by asking occupants this question: “At this point of time, would you prefer to feel warmer, cooler, or no change?” In this section, respondents were also asked to indicate their sensation and thermal preference of the air movement and air humidity. Finally, a question about the actions people performed in order to feel cooler or warmer was also asked. Table 3 summarizes the various scales used in the survey.

The methods of measurement and the scope and format of the questionnaire were based on previous thermal comfort field studies (de Dear et al. 1991a; de Dear and Brager 1998; Kwok and Chun 2003; Wong et al. 2002; Wong and Khoo 2003; Zhang et al. 2007).

Metabolic rate and clothing insulation were estimated in accordance with ASHRAE standard 55–1992 (ASHRAE 1992). The standard provided a checklist of typical activities and their corresponding metabolic rates. As the respondents were seated during the survey, the metabolic rate was taken to be 1.2 met (1 met=58.15 W/m^2), which represents the value for sedentary activities. Respondents indicated what they were wearing at the time of the field study by means of a clothing checklist that was included in the survey. The typical attire of people in this area is short T-shirt and short pants or short skirt in summer. The average clothing values was found to be 0.3 clo (1 clo=0.155°C m ^{2}/ W).

Results and discussion

Objective measurements

Indoor climate

The statistical summary of indoor climate variables measured during the survey is given in Table 4. The operative temperatures ranged from 27.9°C to 38.8°C with an average of 33.3°C in naturally ventilated buildings. In air-conditioned buildings, the operative temperatures ranged from 21.6°C to 33.2°C with an average value of 28.7°C. Mean air and radiant temperatures were 33.0°C and 33.6°C, respectively, in naturally ventilated buildings and 28.5°C and 28.9°C, respectively, in air-conditioned buildings. Relative humidity was 74.0% in the naturally ventilated and 72.4% in the air-conditioned buildings. Mean air velocity in naturally ventilated buildings was 0.17 m/s and in air-conditioned buildings, 0.13 m/s.

Relative humidity and air velocity were similar in both building types, but the difference between temperatures was obvious with air-conditioned buildings having much cooler conditions.

Clothing level

Clothing is an important factor in achieving comfort in hot and humid conditions. A small scatter of the clothing value has been observed, from 0.14 clo to 0.57 clo during the survey. The relatively low mean clothing value of 0.28 clo and 0.32 clo in both types of buildings reflect the casual

Table 3 Scales used for subjective assessment in the survey

ASHRAE scale	Humidity sensation	Draught sensation	Preference	Acceptability
−3 cold	−3 too dry	−3 too still	Warmer	Acceptable
−2 cool	−2 dry	−2 still	No change	Unacceptable
−1 slightly cool	−1 slightly dry	−1 slightly still	Cooler	
0 neutral	0 just right	0 just right		
+1 slightly warm	+1 slightly humid	+1 slightly breezy		
+2 warm	+2 humid	+2 breezy		
+3 hot	+3 too humid	+3 too breezy		

Table 4 Summary of indoor climate

	Naturally ventilated				Air-conditioned			
	65 buildings visited, 129 respondents				46 buildings visited, 100 respondents			
	Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum
Air temperature(°C)	33.0	2.4	27.8	38.1	28.5	2.5	21.3	33.3
Mean radiant temperature(°C)	33.6	2.6	28.0	39.4	28.9	2.6	21.9	33.4
Relative humidity(%)	74.0	11.6	51.0	93.2	72.4	11.8	51.4	95.8
Air velocity(m/s)	0.17	0.19	0.01	1.10	0.13	0.07	0.03	0.34
Operative temperature(°C)	33.3	2.4	27.9	38.8	28.7	2.5	21.6	33.2

dress codes of occupants during their daily life. People would prefer to wear lighter clothing when the indoor air temperature increases during the hot season. The typical attire is a combination of short T-shirt and short pants or short skirt in summer. Footwear is sandals for most respondents. Interestingly, some of the male respondents were observed to wear only pants with the upper body bared during the hot afternoon survey in their homes. Although people changed their clothing level to try and achieve comfort at different temperatures, no significant correlation was found between the clothing value and operative temperature. The reason for the poor correlation is probably that the amount of clothing was reduced to a level that was culturally acceptable and could not be reduced beyond that level regardless of air temperature.

Subjective measurements

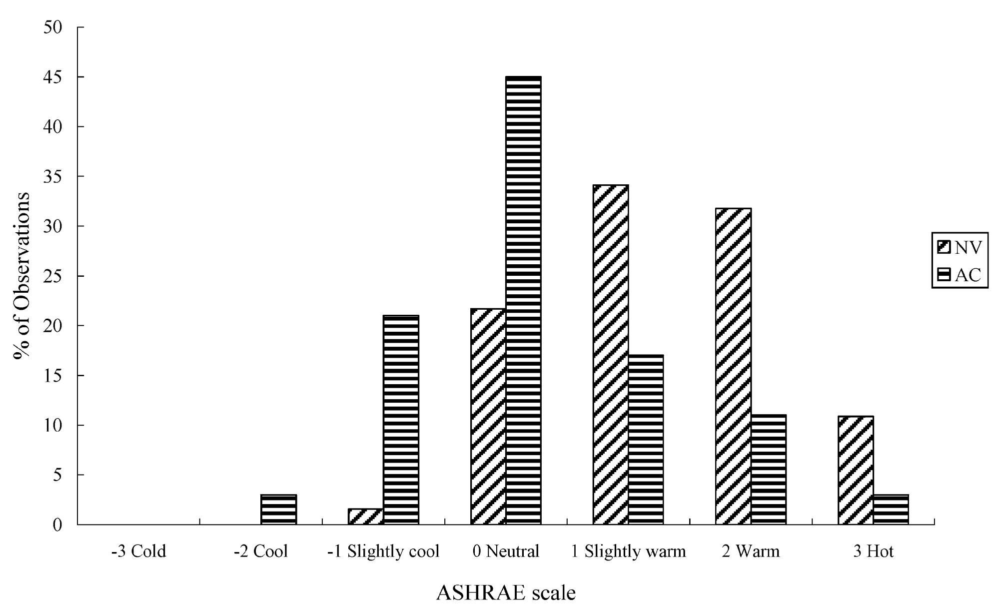
Thermal sensation

Figure 2 shows the distribution of thermal sensation votes for the two types of buildings. For air-conditioned buildings, 83% of occupants voted within the central three categories (−1, 0, +1) with a mean vote at 0.21. A much lower percentage of 57% was found in naturally ventilated buildings, as expected, since the thermal responses were shifted towards the warmer sensation categories (+2, +3) with a mean vote of 1.29. This is consistent with the objective data, which shows that the air-conditioned buildings had cooler conditions as compared to the naturally ventilated buildings.

Humidity sensation

Humidity has been investigated in a number of filed surveys in hot climates, and found to have a significant effect on the thermal comfort (Nicol 2004). Figure 3 shows the frequency profile of humidity sensation votes for both building types. As we can see in this figure, only 48.8% of the respondents who occupied naturally ventilated buildings voted within the three central categories, whereas 42.6% of the respondents voted in the +2 and +3 category (humid and too humid). In air-conditioned buildings, 82% of the responses centered within −1 and 1, which means that

Fig. 2 Distribution of thermal sensation votes



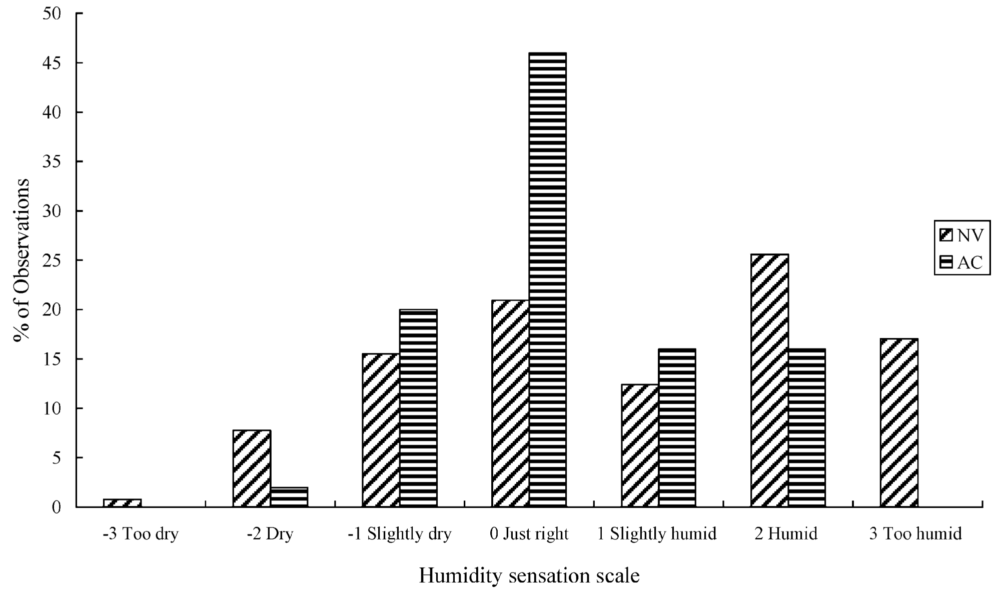


Fig. 3 Distribution of humidity sensation votes

occupants may not have sensitive sensations to humidity, and always show their satisfaction about the humidity. It is known that human thermal perception of comfort/discomfort was closely related to the skin wettedness in warm conditions (Gagge et al. 1972). Under conditions of high humidity, the evaporation of sweat from the skin decreases and the skin wettedness increases. Discomfort could then result from a clinging sensation of clothing on the wet skin caused by the increased skin wettedness. The operative temperature in naturally ventilated buildings was high, with an average value of 33.3°C. If the humidity increases in such hot conditions, the sultry environment will make occupants uncomfortable. In fact, many respondents complained about the extremely hot and humid weather which made them perspire continuously. In air-conditioned buildings, the air temperature was relatively lower and the humidity effect to thermal comfort was inconspicuous. This result confirms that the impact of humidity on thermal comfort may be very little in a certain range, and the obvious influence mainly appeared in high temperature occasions (Toftum et al. 1998).

Draught sensation

In naturally ventilated buildings, it is believed that only higher wind speeds can create higher thermal comfort satisfaction as the indoor air temperature and humidity are almost impossible to modify. A high percentage (88%) of naturally ventilated buildings had their windows or doors open during the survey, but the indoor air velocity was quite small with an average value of 0.17 m/s. Furthermore, the proportion of cases of our survey in naturally ventilated buildings, in which the indoor air velocity is less than 0.2 m/s, is 78.5%. This is probably due to the frequent windless air movement outdoors. The distribution of draught sensation votes is plotted in Fig. 4. In naturally ventilated buildings, only 28.7% of the respondents felt that the air velocity was just right and 7.7% of them felt the air velocity slightly breezy. In air-conditioned buildings, 46% of the occupants considered the air velocity as just right. It is important to point out that no respondent chose to indicate their draught sensation in the breezy regions (i.e., +2, +3). This suggests that indoor air velocity may be a big problem in both the natural ventilation and air-conditioned buildings, and the lower air velocities in both buildings could not create sufficient cooling effect for occupants. The detailed correlation between air velocity and thermal comfort is discussed in the following section.

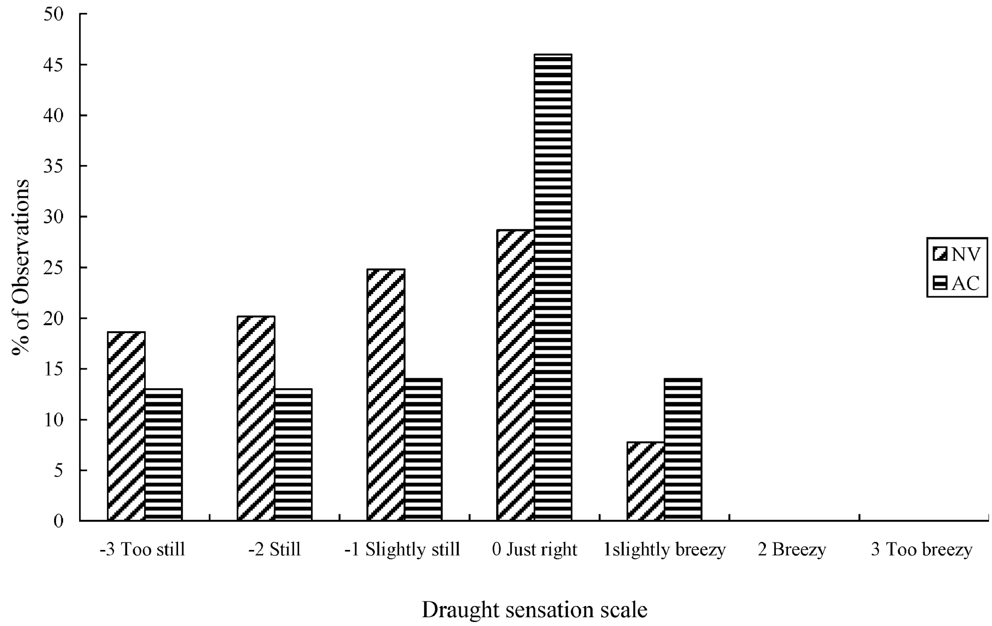
It is interesting to mention that the air-conditioned buildings had relatively lower air velocity but a lower percentage of subjects considering their draught sensation still (i.e., voting −2 and −3). This indicates that people tend to require higher air velocity at higher temperatures.

Thermal acceptability

ASHRAE Standard 55 specifies the conditions in which 80% or more of the occupants will find the environments thermally acceptable. In this study, thermal acceptability has been analyzed by three methods. Figure 5 gives the comparison of the three thermal acceptability assessing methods. For each assessing method, the levels of thermal acceptability obtained in naturally ventilated and air-conditioned buildings are different.

It is widely considered that subjects who vote within the central three categories (−1, 0, +1) of the ASHRAE scale are satisfied with their thermal environment (Schiller 1990). This approach was first proposed by Fanger (1970) in

Fig. 4 Distribution of draught sensation votes



explaining the concept of Predicted Percent Dissatisfied (PPD). By equating the central three categories with the notion of acceptability, the first method reveals that 57% and 83% of subjects in naturally ventilated and air-conditioned buildings, respectively, were assumed to be satisfied with the thermal conditions in their buildings.

The second method corresponds to the direct thermal acceptability question in the questionnaires. The percentages of thermal acceptability in naturally ventilated and air-conditioned buildings were 58% and 89%, respectively. This level was slightly higher than that obtained from the first method, but the differences are probably insignificant. Hence, there were few subjects who voted beyond the three categories and yet found their environment acceptable. This result may be due to the small sample size in this study.

The third method in which the subjects voted "no change" of thermal preference scale indicates that they were satisfied with their thermal environments. Percentages of acceptability from thermal preference votes in naturally ventilated and air-conditioned buildings were 14.7% and 49%, respectively. The thermal preference scale appears to be the most stringent measure of thermal acceptability. In general, the range of acceptability in subjects' subconscious is wider than the range of preferences (Hwang et al. 2006).

The above findings clearly indicate that different measures of acceptability can produce widely differing

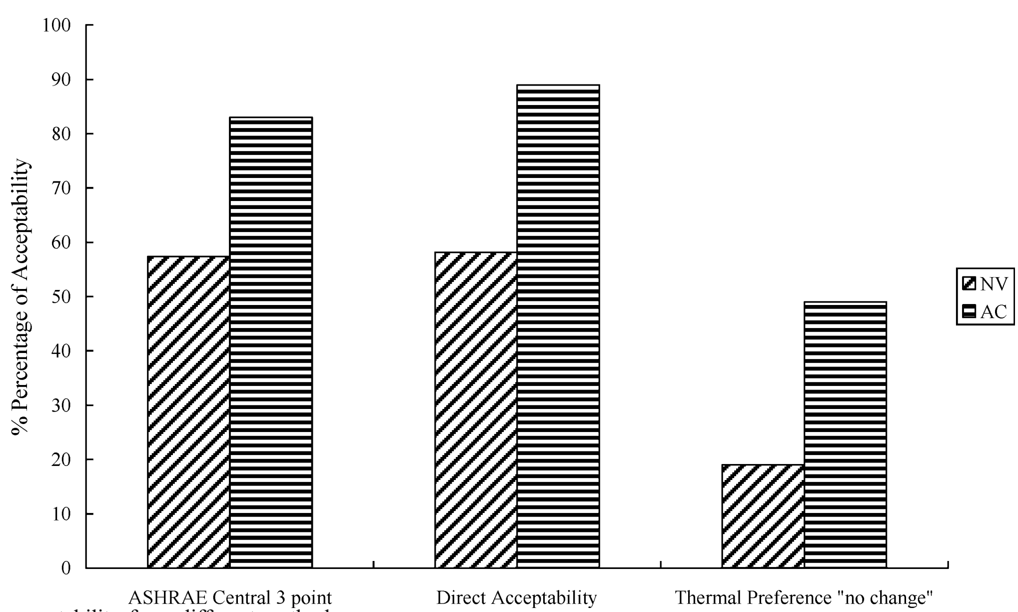


Fig. 5 Thermal acceptability from different methods

results. The direct thermal acceptability method gave the highest level of acceptability of 58% and 89% for naturally ventilated and air-conditioned buildings, respectively. The results seem to show that people tended to feel more comfortable in air-conditioned buildings in summer. Ironically, none of the methods in naturally ventilated buildings was able to achieve an acceptable thermal environment, with 80% of the occupants expressing satisfaction with the thermal conditions. The lower acceptability in naturally ventilated buildings can be explained by the following reasons:

(1) The rigorous climate in summer was extremely hot and humid with low air velocity. No matter what adaptive behaviors the occupants adopted, the indoor climate inside naturally ventilated buildings was often unacceptable.
(2) A large proportion of naturally ventilated buildings in the survey were residential buildings. Most of the respondents in these residences were working in the air-conditioned offices during workhours on the workdays. They may have become accustomed to a much cooler condition in air-conditioned offices and, consequently, some of them may have the same expectations of the indoor thermal conditions when they came back home where it was naturally ventilated. These respondents became less tolerant of the slightly warm conditions, which would make them uncomfortable.

Thermal neutrality

Neutral temperature and acceptable condition

Referring to previous thermal comfort study, thermal neutral temperature is obtained by analyzing the relationship between thermal sensation and operative temperature (de Dear and Brager 1998; Wong and Khoo 2003; Feriadi and Wong 2004; Ye et al. 2006). The present study used simple linear regression for the calculation of neutral temperature (Tn) and acceptable conditions. Neutral temperature is defined as the temperature at which people will on average be neither warm nor cool. Figure 6 displays the regression of thermal sensation (TSV) and operative temperature (To) in both naturally ventilated and air-conditioned buildings. Equations 1 and 2 shows the resulting regressions for both building types. The significance of the regression equation was tested using the coefficient of determination R^2 and the F-test. The correlation was statistically significant when the residual probability p associated with F was smaller than 0.05.

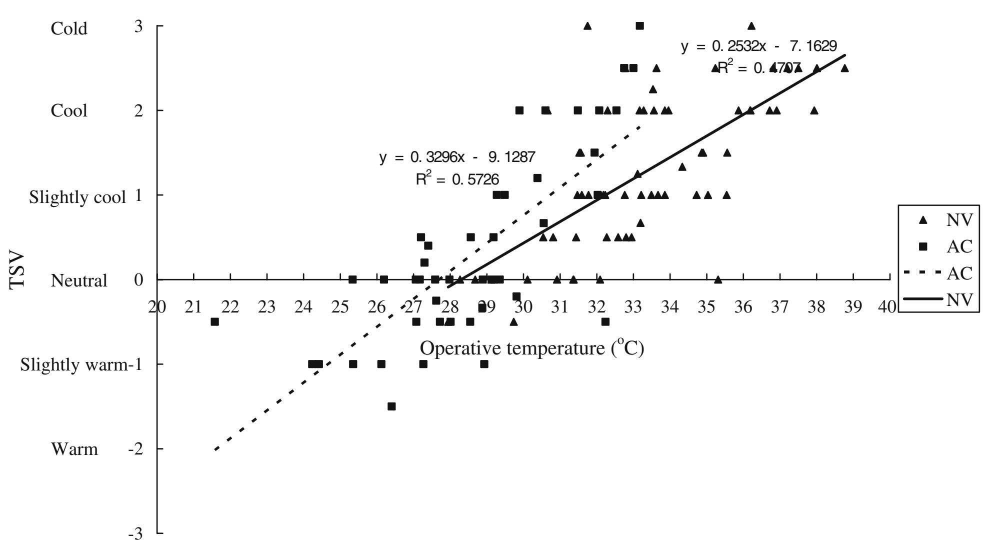
$$TSV = 0.25To - 7.16, \quad \left(R^2 = 0.47\right) \tag{1}$$

$$TSV = 0.32To - 9.12, \quad \left(R^2 = 0.57\right) \tag{2}$$

Both the regression models were statistically significant (F=56.03, p=0.000 in naturally ventilated buildings and F=58.94, p=0.000 in air-conditioned buildings). It is illustrated in Fig. 6 that the neutral point is found at 28.3°C and 27.7°C for naturally ventilated and air-conditioned buildings, respectively. According to ISO7730 (ISO 1994), predicted mean vote between the limits of ±0.85 corresponds with 80% of the group being satisfied. In line with this method, the acceptable conditions for 80% of subjects were calculated. The range of accepted operative temperature was 25.0~31.6°C and 25.1~30.3°C for naturally ventilated and air-conditioned buildings, respectively.

The gradient of the regression model is related to the sensitivity of mean thermal sensation to the operative temperature (de Dear and Brager 1998). The regression slope of the naturally ventilated buildings was 0.25/°C and

Fig. 6 Regression of thermal sensation and operative temperature



was lower than that of the air-conditioned buildings of 0.33/°C, which suggests that respondents in air-conditioned buildings were more sensitive to the thermal environment.

Comparison between air-conditioned and naturally ventilated buildings

The percentage of thermal acceptability in naturally ventilated buildings was much lower than that in air-conditioned buildings, which means that occupants in air-conditioned buildings felt more comfortable in summer. Nevertheless, the result of linear regression analysis of neutral temperature (27.7°C) in air-conditioned buildings was 0.6°C lower than that in naturally ventilated buildings (28.3°C). This indicates that occupants in naturally ventilated buildings seemed to be more tolerant of the high temperatures. Additionally, the regression slope in naturally ventilated buildings was lower compared to the air-conditioned buildings, which means that occupants in naturally ventilated buildings were less sensitive to the thermal environment variations.

The range of accepted operative temperature in naturally ventilated buildings (25.0~31.6°C) was slightly wider than that in air-conditioned buildings (25.1~30.3°C). The result shows that occupants were thermally comfortable in a wider range of temperatures than those in air-conditioned buildings. This may due to occupants in naturally ventilated buildings having a close interrelation with the outdoor environment and, consequently, they have a broader acceptability toward the changing and non-uniform thermal conditions in air-conditioned buildings.

Comparisons with other studies

We also compared our results with the studies conducted in the hot and humid climates. The summary of findings from some previous thermal comfort studies (Hwang et al. 2006; Busch 1990; de Dear et al. 1991a; Karyono 1998; Wong and Khoo 2003; Mui and Chan 2003; Ye et al. 2006) are shown in Table 5.

The neutral operative temperature of naturally ventilated buildings in this study is found to be 28.3°C, which is close to those found in Thailand (28.7°C), Singapore (28.5°C) and Shanghai (28.1°C). However, the neutral temperature (27.7°C) in air-conditioned buildings is higher when compared to previous thermal comfort studies. For example, the neutral temperatures found in air-conditioned buildings in Thailand, Singapore, Indonesia, Hong Kong and Taiwan are 24.8°C, 24.2°C, 26.7°C, 23.7°C and 25.6°C, respectively. There are two key reasons that contribute to a higher neutral temperature in air-conditioned buildings in this study.

The first reason is that the indoor temperature is higher than other studies, and occupants in this study have adapted physiologically and psychologically to the thermal conditions. Due to the concern about expensive energy cost incurred and the consideration of the Set-point of Standards in Air-conditioned Public Buildings, the most common air-conditioning set-point temperature in summer in China is 26~28°C. According to “Adaptive Theory”, people are not passive receivers of their thermal environment but alter or adapt to their environment to suit themselves, and if a change occurs that produces discomfort, people will tend to act to restore their comfort (Humphreys and Nicol 1998; de Dear and Brager 2002). Occupants can get adapted to elevated air-conditioning set-points if they are exposed to them long enough. Also, occupants will tend to be more tolerant ofany uncomfortable thermal conditions in their living environment.

The second reason related to the occupants’ attire having less clothing insulating value than other studies. The mean clothing value in air-conditioned buildings in this study is 0.32 clo, which is smaller than the mean insulation value of

Table 5 Thermal comfort studies in the hot and humid climates

Year	Source	Location	Buildings	Neutral temperature
1990	Busch 1990	Bangkok, Thailand	Office	28.7°C (ET) for NV building 24.8°C (ET) for AC building
1991	de Dear et al. 1991a	Singapore	Residential and office	28.5°C (To) for NV building 24.2°C (To) for AC building
1998	Karyono 1998	Jakarta, Indonesia	Office	26.7°C (To) for AC building
2003	Wong and Khoo 2003	Singapore	Classrooms	28.8°C (To) for NV classrooms
2003	Mui and Chan 2003	Hong Kong	Office	23.7°C (To) for AC building
2005	Hwang et al. 2006	Taiwan	Classrooms	26.2°C (To) for NV classrooms 25.6°C (To) for AC classrooms
2006	Ye et al. 2006	Shanghai, China	Residential	27.0°C (To) July for NV building 28.1°C (To) August

NV Naturally ventilated; *AC* air-conditioned; *ET* effective temperature; *To* operative temperature

0.44 clo and 0.55 clo obtained by de Dear et al. (1991a) and Busch (1990), respectively.

Thermal preference

Preferred temperature was assessed directly according to the answers to the question: "At this point of time, would you prefer to feel warmer, cooler, or no change?" Separate probit models were fitted to the want warmer and want cooler percentages within each half-degree operative temperature bin (de Dear and Brager 1998). Preferred temperature was obtained from the intersection of the two fitted probit lines. The goodness of fit of the probit model to the observed data was assessed using a nonparametric χ^2 test (Finney 1971).

Table 6 shows the probit results for both buildings types. In naturally ventilated buildings, the probit model for requests for warmer was good (χ^2=7.31, *df*=20, *p*=0.996), while the fit of the requests for cooler to the model was not good (χ^2=57.02, *df*=20, p=0.000), and the resulting preferred temperature was 27.9°C, only 0.4°C cooler than the corresponding neutral temperature. In air-conditioned buildings, the χ^2 test for warmer was less good (χ^2=26.29, *df*=15, *p* =0.035), while the fit of the requests for cooler to the model was good (χ^2=12.63, *df*=15, *p*=0.631). The intersection between the two models provided a preferred temperature of 27.3°C, also 0.4 degrees cooler than the corresponding neutral temperature.

It can be observed that, whatever the building type, preferred temperatures were cooler than neutral during the summer. The discrepancy between preferred temperature and neutral temperature confirms the idea that the ambient temperature corresponding to "neutral" on the ASHRAE seven-point scale was not necessarily the preferred temperature (de Dear et al. 1991b). The most famous analyses of thermal comfort and preference is the "semantic artefact hypothesis," which suggests the preferred temperature in cold climates may, in fact, be described as slightly warm, whereas residents of hot climates may use words like "slightly cool" to describe their preferred thermal state (de Dear and Brager 1998).

Responses to thermal preference questions revealed similar results which are better understood by comparing simultaneous votes on both the thermal sensation and preference scales, shown in Table 7. This table shows that there are a higher percentage of votes in the three central categories of the thermal sensation scale than thermal preference scale (no change). The trend of thermal preference can also be found out. As shown in Table 5, there were 60.3% of the occupants in both buildings preferred cooler, which indicates that the "neutral" scale on the ASHRAE seven-point scale does not necessarily mean the preferred thermal state.

In naturally ventilated buildings, 75.7% of those voting within the three central categories of the thermal sensation scale preferred to feel cooler and only 20.3% wanted no change. It was also found that in air-conditioned buildings a lower percentage (21.7%) of the occupants voting within the three central categories wanted to be cooler, and a higher percentage (57.8%) of the occupants preferred no change in their environments. Occupants in the naturally ventilated buildings expressed an urgent preference to be cooler than in air-conditioned buildings. This is reasonable as the air-conditioned buildings had relatively cooler thermal conditions.

Air velocity and thermal comfort

Relationship between draught sensation and indoor air velocity

In warm or hot weather, air movement is one of the best means of improving thermal comfort (Raja et al. 2001). Simple linear regression analysis was performed to find out the relationship between the draught sensation votes (DSV) and indoor air velocity (v) at different temperature limits. The regression lines are illustrated in Fig. 7 and the regression equations are listed in Table 8. The corresponding indoor air velocity preferred by occupants is the air velocity at which the regression line crosses the x-axis. The significance of the regression equation was tested in the same way as the regression of thermal sensation (TSV) and operative temperature (To).

From the *p*-values presented in Table 8, it can be seen that the correlation between DSV and indoor air velocity was significant for all the equations (*p*<0.05). At the operative

Table 6 Probit analysis for preferred temperatures

Building type	Probit model	χ^2test	*df*	*p*-value	Preferred temperature(°C)
NV	Requests for warmer	Probit=−0.45 To+12.11	7.31	20	0.996	27.9
	Requests for cooler	Probit=0.35 To−10.32	57.02	20	0.000	
AC	Requests for warmer	Probit=−0.32 To+7.99	26.29	15	0.035	27.3
	Requests for cooler	Probit=0.37 To−10.77	12.63	15	0.631	

NV Naturally ventilated; *AC* air-conditioned; *To* operative temperature

Table 7 Cross tabulation of thermal sensation and thermal preference scales, showing percentages with numbers of respondents in parentheses

Thermal sensation scale	Thermal preference scale			
	Cooler	No change	Warmer	Total respondents
Naturally ventilated				
+3, +2	92.7% (51)	7.3% (4)	(0)	55
+1, 0, −1	75.7% (56)	20.3% (15)	4.1% (3)	74
−3, −2	(0)	(0)	(0)	0
Totals	83.0% (107)	14.7% (19)	2.3% (3)	129
Air-conditioned				
+3, +2	92.9% (13)	7.1% (1)	(0)	14
+1, 0, −1	21.7% (18)	57.8% (48)	20.5% (17)	83
−3, −2	(0)	(0)	100% (3)	3
Totals	31.0% (31)	49.0%(49)	20.0% (20)	100
All				
+3, +2	92.8% (64)	7.2% (5)	(0)	69
+1, 0, −1	47.1% (74)	40.1% (63)	12.8% (20)	157
−3, −2	(0)	(0)	100% (3)	3
Totals	60.3%(138)	29.7% (68)	10.0% (23)	229

temperature range of 26~28°C, 28~30°C, 30~32°C, 32~34°C and 34~36°C, the preferred air velocities required by occupants were 0.18 m/s, 0.28 m/s, 0.49 m/s, 0.53 m/s and 0.67 m/s, respectively. This suggests that the higher the operative temperature, the higher the air velocity required by occupants in order to feel comfortable. The gradient of the regression model can be used to evaluate the draught sensitivity of the occupants to indoor air velocity. As shown in Table 8, there was a decreasing tendency of the regression slope from the temperature range of 26~28°C to 34~36°C, which varied from 7.77 to 2.62, suggesting that the occupants became less sensitive to the air velocity with increasing operative temperature.

We can come to the conclusion that the air velocity might have a great influence over the respondents' comfort sensation and people required a high level of air movement in order to be comfortable. Compared with the preferred indoor air velocities required by occupants (0.18~0.67 m/s), the actual indoor air velocity was much smaller (mean air velocity in naturally ventilated buildings was 0.17 m/s and in air-conditioned buildings, 0.13 m/s). Hence, the lower percentage of thermal acceptability votes in naturally ventilated buildings is probably due to the poor ventilation within the buildings, which aggravates the effects of high temperature and causes discomfort to the occupants. We can also presume that people could live comfortably in naturally ventilated buildings as long as they were provided with appropriate air velocities. Also, the set-point temperatures in air conditioned buildings can be lifted even higher (perhaps to 30°C) if the air velocities within the occupied zones are increased (e.g., with the assistance of ceiling fans).

A need for effective natural ventilation

China is a country with very limited energy resources and its electrical load is huge, especially in summer. Although a large number of the traditional naturally ventilated build-

Fig. 7 Regression analysis for draught sensation and indoor air velocity

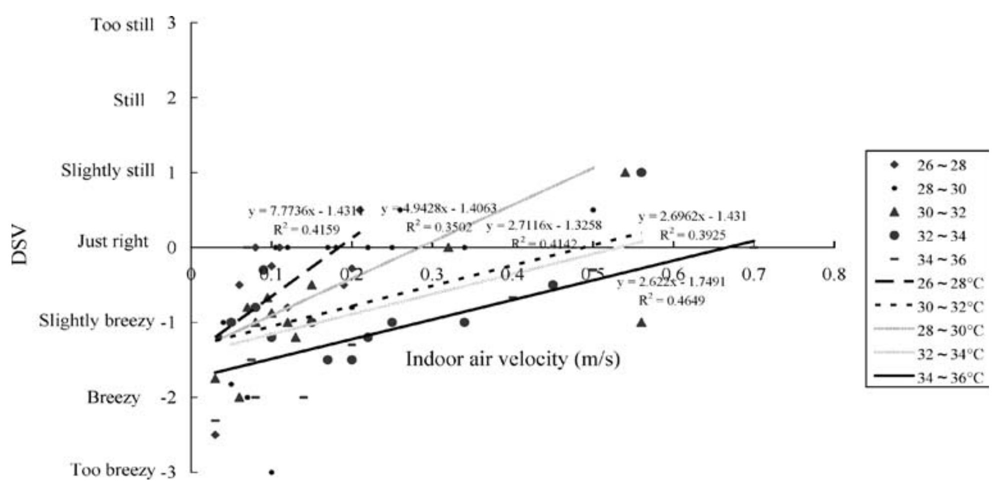


Table 8 Regression relationship between draught sensation and indoor air velocity

Operative temperature (°C)	Regression equation	R^2	*F*-test	*p*-value	Preferred indoor air velocity (m/s)
26~28	DSV=7.77v−1.43	0.42	6.409	0.032	0.18
28~30	DSV=4.94v−1.41	0.35	7.005	0.020	0.28
30~32	DSV=2.71v−1.32	0.41	7.071	0.024	0.49
32~34	DSV=2.69v−1.43	0.39	6.460	0.029	0.53
34~36	DSV=2.62v−1.75	0.47	6.950	0.030	0.67

ings could not provide a comfortable indoor thermal environment for occupants in humid subtropical zone during the summer, the need for air conditioning should not be magnified under the current economic situation of China. The sustainable way is to reduce the need for air-conditioning and increase the possibilities for achieving comfort by using simple passive cooling and heating techniques.

Future research into how the overheating of naturally ventilated buildings in the humid subtropical zone can be reduced without disrupting the comfort and productivity of their occupants is needed. The design of energy-efficient buildings in this area must consider the heat loss and cooling heat storage under conditions of natural ventilation during night time and the period between two high-temperature sunny days in summer (Feng 2004). Natural ventilation can play an important role in controlling the indoor air quality and temperature in summer, preventing overheating by adopting adequate ventilation (Raja et al. 2001). This study shows that the poor ventilation was probably the most important reason for the discomfort of occupants in naturally ventilated buildings. In fact, people can live comfortably in naturally ventilated buildings given that they are allowed to have higher air velocities. Thus, it is recommended the layout of the buildings should be such that the long facades are facing the north and south. This orientation will increase the potential of using natural ventilation for cooling since the prevailing wind directions in humid subtropical China are north and south in summer. Furthermore, the night-time ventilation should be enhanced due to its favorable cooling effect.

Indoor set-point temperature for air-conditioned buildings

As living standards rise and people become increasingly rich in China, a higher expectation of thermal comfort in buildings is anticipated by occupants. Air-conditioning systems are becoming popular to help in achieving a comfortable internal thermal environment. The number of household air-conditioner units in China has increased greatly from only 31,350,000 in 2002 to 68,494,000 in 2006. This increasing number of air-conditioners will be a big threat to the national aim of cutting down energy consumption by 20% in the 11th Five Year Plan, from the year of 2006 to 2010. The indoor set-point temperature in air-conditioned buildings is very important to energy conservation as lifting the set-point temperature 1~2°C in summer can save 6%~10% of the electric energy.

From the above results, the neutral temperature in naturally ventilated buildings was 28.3°C and in air-conditioned buildings, 27.7°C, both of which exceeded the temperature of 26°C prescribed by the General Office of the State Council of China. From this point of view, the indoor set-point temperature in air-conditioned buildings can be regulated at 26°C or even higher; thus the set-point temperature standard is supported scientifically by this study. Provided with appropriate air velocities, occupants could be comfortable at higher temperatures in air-conditioned buildings and in naturally ventilated buildings. The set-point temperature in air-conditioned residential buildings, or the outdoor climate conditions in which an air-conditioner is needed to be installed or to be run in rural areas where 80% of the population live, will be another fundamental question to be answered in China, for the sake of improving residents' comfort and saving energy at the same time.

Conclusions

The field study was performed in 65 naturally ventilated and 46 air-conditioned buildings located in five cities in the humid subtropical climate zone of China. Two hundred and twenty-nine individuals participated in the field survey. The important conclusions of this study are as follows:

(1) A comparison of the various methods of assessing thermal comfort reveals that they produce diverse results, with the direct thermal acceptability method giving the highest level of acceptability of 58% and 89% for naturally ventilated and air-conditioned buildings, respectively. This indicates that occupants were more comfortable in air-conditioned buildings.

(2) The neutral temperature in air-conditioned buildings was 27.7°C, which was 0.6°C lower than that in naturally ventilated buildings (28.3°C). The range of accepted temperature in naturally ventilated buildings (25.0~31.6°C) was slightly wider than that in air-

conditioned buildings (25.1~30.3°C). The results indicate that occupants in naturally ventilated buildings seemed to be more tolerant of the high temperatures and were thermally comfortable in a wider range of temperatures. This discrepancy could be attributed to the different contexts in the two types of buildings.

(3) Preferred temperature was 27.9°C and 27.3°C in naturally ventilated and air-conditioned buildings, respectively, both of which were 0.4°C cooler than neutral temperatures. The result indicates that people in hot climates may use words like “slightly cool” to describe their preferred thermal state. A cross comparison of votes on the thermal sensation and thermal preference scale shows that the “neutral” scale on the ASHRAE seven-point scale does not necessarily mean the preferred thermal state.

(4) The significant correlation between the draught sensation and indoor air velocity reveals that indoor air velocity has a significant influence over the respondents’ comfort sensation, and people required a high level of air movement in order to feel comfortable. Also, the higher the operative temperature, the higher the air velocity required by occupants in order to feel comfortable.

(5) Although natural ventilation has proven to be an energy-efficient alternative to reducing the running costs in buildings, the traditional way of construction cannot provide a comfortable indoor thermal environment for occupants in humid subtropical China. Increasing air velocity will become an effective means to improve thermal comfort in naturally ventilated buildings. Therefore, an effective way of natural ventilation which can create the preferred higher air movement is called for.

(6) The indoor set-point temperature in air-conditioned buildings can be regulated at 26°C or even higher, which supports the set-point temperature regulation in air-conditioned public buildings in China.

Finally, our study is a first step towards a thermal comfort research for the humid subtropical climate zone in China. In pursuing this research further, we plan to expand the study to bigger samples and to rural areas, conduct the study during the cooler months of the year, and make seasonal evaluations on perceptions of comfort.

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