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RESEARCH ARTICLE

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Survey of thermal comfort in residential buildings under natural conditions in hot humid and cold wet seasons in Nanjing

Abstract Comfort standards (ISO 7730, ASHRAE 55) specify the exact physical criteria for producing acceptable thermal environments, such as temperature, air movement, and humidity limits. These, however, are often difficult to comply with, particularly in hot humid and cold wet seasons in Nanjing, China. Changing expectations of comfort is important in evaluating comfort, since naturally conditioned buildings in Nanjing are not typically air-conditioned. For this objective, a field study was conducted during the summer of 2000 and the winter of 2001. A total of 600 participants each answered a subjective questionnaire. Analyzing these field data shows that in natural conditions, the influence of gender and age on people's thermal sensations is insignificant compared with six main variables. In addition, people's thermal discomfort rapidly increases along with growth in relative humidity. Further, the variation of people's hot or cold sensations is in proportion to that of air movement, and the effect in winter is greater than that in summer. The range of acceptable temperatures in hot humid and cold wet Nanjing is between 14.14°C and 29.42°C.

Keywords thermal comfort, naturally conditioned, hot humid, cold wet, Nanjing

1 Introduction

Human thermal comfort is the state of mind that expresses satisfaction with the surrounding environment, according to ASHRAE Standard 55-2004 and ISO 7730-2005. Achieving thermal comfort for most occupants of buildings or other enclosures is a goal of architects and engineers of heating ventilating and air conditioning (HVAC).

Fundamental studies of thermal comfort, such as acceptable ranges of dry-bulb temperatures, relative humidities, and activity levels, were completed in the 1970s. Many of these studies, which contributed to the development and refinement of ASHRAE Standard 55 and ISO 7730, were performed at the Kansas State University by Ole Fanger and others. Some key findings were that not all occupants will be satisfied by a particular set of indoor environmental conditions, but in ranges of conditions, which is about 80% express satisfaction. If very good conditions are in place, a maximum of 95% of all occupants might be satisfied. Statistical methods were used to evaluate the thermal comfort opinions of many test subjects to yield what are known as comfort conditions; the predicted mean vote (PMV) and the predicted percentage dissatisfied (PPD) were two of the measures used.

Of utmost importance for achieving thermal comfort is the operative temperature. This is the average of the air dry-bulb temperature and the mean radiant temperature at the given place in a room. In addition, there should be low air velocities and no 'drafts', little variation in the radiant temperatures from different directions in the room, a comfortable humidity range, and air temperatures at a height of 0.1 m above the floor should not be more than 2°C lower than the temperature at the place of the occupant's head. In addition, the temperature should not change too rapidly, either across space or time.

In addition to environmental conditions, thermal comfort depends on the clothing and activity level of a person. The amount of clothing is measured against a standard amount that is roughly equivalent to a typical business suit, shirt, and undergarments. Activity level is compared to being seated quietly, such as in a classroom.

The comfort standards of ASHRAE 55 and ISO 7730

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specify the exact physical criteria for producing acceptable thermal environments, such as temperature, air movement, and humidity limits. These, however, are often difficult to comply with, particularly in hot-humid climates. Therefore, changing expectations of comfort [1] or using adaptive comfort standards derived from the results of local comfort surveys (in particular, the implications of air movement and humidity for adaptive comfort standards are considered [2]) are important in evaluating comfort since many buildings in hot-humid areas are not typically air-conditioned.

In previous field studies on naturally conditioned buildings in a hot-humid climate [3,4], less than 25% of classroom indoor climatic conditions fell within the ASHRAE 55 and ISO 7730 summer comfort zone boundaries. The occupants of naturally ventilated classrooms with conditions well outside of the ASHRAE and ISO comfort zone were comfortable. None of the naturally ventilated classrooms in Singapore evaluated by Wong and Khoo [5] had thermal conditions within the comfort zone of the ASHRAE 55 and ISO 7730 standards; yet, the occupants found these conditions thermally acceptable. These results agreed with field conditions in other hot-humid locations [1,6–14]. Results in all of these studies in hot-humid climates were consistent with the adaptive hypothesis introduced by Auliciems [15], where thermal perceptions of satisfaction with the indoor climate are shaped by expectations.

To investigate the thermal responses of Nanjing residents in naturally conditioned buildings, we carried out a field survey during the summer of 2000 and the winter of 2001. A total of 600 participants each answered a subjective questionnaire. The main objectives of this study are listed as follows:

1) To study the effect of acclimatization to people's thermal responses in naturally conditioned buildings in hot humid and cold wet Nanjing;

2) To investigate the influence of age and gender on people's thermal comfort;

3) To determine the effect of relative humidity and air speed to the hot and cold sensations of local residents in hot humid and cold wet seasons in Nanjing.

2 Climate in Nanjing

Nanjing, with a total land area of 6598 km^2, is situated in one of the largest economic zones of China, the Yangtze River Delta, which is part of the downstream Yangtze River drainage basin. Nanjing has a temperate climate that is influenced by the East Asia Monsoon. Seasons are distinct in Nanjing, with hot summers and plenty of rainfall throughout the year. Located in the subtropical climatic zone and surrounded on all sides by mountains that keep heat in, Nanjing is known as one of the three "furnaces of China" (the other two are Wuhan and Chongqing). The average temperature during the year is 15.7°C, with the highest recorded temperature being 43°C (July 13, 1934) and the lowest –16.9°C (January 6, 1955). On the average, it rains 117 d out of the year, and the average annual rainfall is 1106.5 mm. The time from mid-June to the end of July is the plum blossom Meiyu season, during which the city experiences a period of mild rain as well as dampness. Average relative humidity (*RH*) ranges from 62% to 85% all the year round. However, *RH* usually exceeds 90% for one month in summer [16].

3 Questionnaires

In the questionnaires, we considered six main variables that determine people's hot or cold sensations. For the activity, we required the surveyed persons to be at rest or sedentary activity conditions (In these conditions, the body metabolic rate is $q_m = 70\ W/m^2$, and the required heat rate of the body is $q_g = 0\ W/m^2$ (ASHRAE, 2004)). For clothing, civilized clothing and convenient clothing were needed in summer and in winter, respectively. Generally, civilized clothing is typically composed of dressing shorts, thin trousers, thin short shirt, and sandals. Its thermal resistance is shown as follows:

$$R_{\text{civilized clothing}} = 0.008 + 0.040 + 0.031 = 0.0790\ m^2 \cdot K/W. \quad (1)$$

At the same time, convenient clothing typically consists of shorts, long underwear, long sleeve wool-sweater, jacket, thick trousers, stockings, and cotton shoes. Its thermal resistance is

$$R_{\text{convenient clothing}} = 0.835(0.008 + 0.023 \times 2 + 0.057 + 0.065 + 0.050 + 0.009 + 0.005) + 0.025 = 0.2254\ m^2 \cdot K/W. \quad (2)$$

Note: The standard amount of insulation required to keep a resting person warm in a windless room at 21.1°C is equal to one clo. The unit of clo can be converted to R-values by multiplying clo by 0.155, and the R-value can be converted to clo by multiplying the R-value by 6.45.

As to environmental factors, we required surveyed persons to write down the air temperature that corresponded to their hot or cold sensation according to related relative humidity (*RH*) and air speed (*AS*). The scales of *RH* and *AS* in the questionnaires were set from the sensitivity of local residents to these variables. For example, *RH* ranges from 40% to 90% or more because this is the case of rooms in Nanjing. Meanwhile, Nanjing people like to open their windows in order to breathe fresh air whether it is summer or winter. Therefore, usually, there is air movement in their rooms. Although without official statistical support, these data appear to be basically consistent with the ASHRAE 55-95a Addendum. To determine the effect of age and gender, these persons were comprised of 200 young people (younger than 18 years old), 200 mature persons (from 18 to 50), and 200 old persons (older than 50), including 300 males and 300 females. All of them had been living in Nanjing for over five years for the purpose of reflecting the effects of hot acclimatization. Because we wanted to discover people's hot and cold sensations in natural conditions (namely, natural ventilation in the summer and enclosed spaces, e.g., windows and doors closed, in winter), we asked them not to use any cooling or heating equipment; for example, air conditioners and heaters were not to be used. To allow surveyed subjects an understanding of their own thermal conditions, surveyors immediately measured the temperature, relative humidity (*RH*), and speed of the indoor air of their rooms with a high accuracy thermometer, hygrometer, and anemometer and explained to the subjects, in detail, the effects of these parameters on the thermal comfort of their bodies. The investigation was carried out in the summer and winter of 2001. The questionnaires are shown in Tables 1 and 2, respectively.

Table 1 Summer thermal comfortable temperature/°C

air speed (*AS*)/(m·s^{-1})	relative humidity(*RH*)/%		
	$40 \leqslant RH < 65$	$65 \leqslant RH < 90$	$RH \geqslant 90$
$0 \leqslant AS < 0.25$			
$0.25 \leqslant AS < 0.40$			
$0.40 \leqslant AS < 0.50$			
$0.50 \leqslant AS < 0.80$			
$AS \geqslant 0.80$			

Notes: The questionnaires also include name, age, gender, address, time lived (above five years is required), and the requirements (un-air-conditioned; civilized clothing, i.e., dressing shorts, thin trousers, thin short shirt, and sandals; and at rest and sedentary activity conditions).

Table 2 Winter thermal comfortable temperature/°C

air speed (*AS*)/(m·s^{-1})	relative humidity(*RH*)/%		
	$40 \leqslant RH < 65$	$65 \leqslant RH < 90$	$RH \geqslant 90$
$0 \leqslant AS < 0.1$			
$0.1 \leqslant AS < 0.2$			
$0.2 \leqslant AS < 0.3$			
$0.3 \leqslant AS < 0.4$			
$0.4 \leqslant AS < 0.5$			
$AS \geqslant 0.50$			

Notes: The questionnaires also include name, age, gender, address, time lived (above five years is required), and the requirements (no heating; convenient clothing, usually including shorts, long underwear, long sleeve wool-sweater, jacket, thick trousers, stockings, and cotton shoes; and at rest and sedentary activity conditions).

4 Hot sensation analysis of Nanjing's residents in naturally ventilated conditions in summer

In naturally ventilated conditions, people's hot sensation is clearly different from that in air-conditioned situations because it is affected greatly by air speed and relative humidity, in addition to temperature. The temperature parameter includes air temperature and mean radiant temperature, body activity, and clothing. The statistical data of the hot responses of 600 of Nanjing's residents are shown in Table 3, according to age, and Table 4, based on gender. Under various conditions, about 90% of the subjects expressed the same sensations. Table 5 shows the general statistic mean of the thermal feeling of these residents.

Some comparisons of hot sensation under naturally ventilated conditions in the summer have been made among mature people, young persons, and old persons. Table 3 shows that in summer the D-value, at the relevant positions in the questionnaires, between mature people and young people is about 0.24°C, that between mature people and old people is approximately 0.52°C; and that between young people and old people is about 0.28°C. On one hand, these data reveal that the comfortable temperature for mature persons is the highest in the summer, followed by young people, and that of old persons is the lowest. The reason for these differences might be that the body conditions of mature persons are good, in contrast to old persons' health conditions, which usually are the poorest. On the other hand, these data also demonstrate that age affects people's thermal comfort in an insignificant way because the D-value among various age groups is very small. This result is consistent with ISO7730 and ASHRAE Standard 55.

Similarly, we compare the thermal responses between female and male in summer under naturally ventilated conditions (see Table 4). D-value in Table 4 shows that the summer's comfortable temperature for females is higher than that of males. However, the difference is insignificant because the D-value is approximately 0.39°C. In other words, gender's effect on people's thermal comfort in summer is insignificant under the steady-state situation. This result is in agreement with previous studies, including Rohles, Nevins [17], Fanger [18], and ISO7730 and ASHRAE Standard 55.

Table 5 and Fig. 1 show that in summer, under naturally ventilated conditions, people's thermal responses are increasingly affected by relative humidity, air speed, temperature, activity, and clothing. People expected that temperature declines along with increase in relative humidity. Generally, 90%*RH* is a watershed. People's thermal uncomfortable sensations will rapidly increase, usually over 1°C, when exceeding this watershed, especially in windless weather conditions. This is the

Table 3 The statistical thermal comfortable temperature of all age groups in summer/°C

air speed (AS)/($m \cdot s^{-1}$)		relative humidity (RH)/%						
		$40 \leqslant RH < 65$		$65 \leqslant RH < 90$		$RH \geqslant 90$		average
		mean	S.D.	mean	S.D.	mean	S.D.	
$0 \leqslant AS < 0.25$	mature	28.13	0.33	27.59	0.33	27.08	0.33	27.60
	young	27.90	0.33	27.34	0.33	26.85	0.33	27.36
	old	27.61	0.32	27.10	0.32	26.47	0.33	27.06
	T_{mature}-T_{young}	0.23		0.25		0.23		0.24
	T_{mature}-T_{old}	0.52		0.49		0.61		0.54
	T_{young}-T_{old}	0.29		0.24		0.38		0.30
$0.25 \leqslant AS < 0.40$	mature	28.70	0.33	28.12	0.33	27.64	0.33	28.15
	young	28.41	0.32	27.92	0.33	27.37	0.32	27.90
	old	28.16	0.33	27.67	0.32	27.16	0.32	27.66
	T_{mature}-T_{young}	0.29		0.20		0.27		0.25
	T_{mature}-T_{old}	0.54		0.45		0.48		0.49
	T_{young}-T_{old}	0.25		0.25		0.21		0.24
$0.40 \leqslant AS < 0.5$	mature	29.14	0.31	28.63	0.30	28.10	0.30	28.62
	young	28.93	0.31	28.38	0.30	27.86	0.30	28.39
	old	28.66	0.30	28.18	0.31	27.60	0.31	28.15
	T_{mature}-T_{young}	0.21		0.25		0.24		0.23
	T_{mature}-T_{old}	0.48		0.45		0.50		0.48
	T_{young}-T_{old}	0.27		0.20		0.26		0.24
$0.5 \leqslant AS < 0.8$	mature	29.69	0.33	29.20	0.32	28.66	0.33	29.18
	young	29.47	0.33	28.98	0.33	28.40	0.32	28.95
	old	29.10	0.32	28.71	0.32	28.10	0.32	28.64
	T_{mature}-T_{young}	0.22		0.22		0.26		0.23
	T_{mature}-T_{old}	0.59		0.49		0.56		0.55
	T_{young}-T_{old}	0.37		0.27		0.30		0.31
$AS \geqslant 0.8$	mature	29.68	0.32	29.19	0.32	28.56	0.32	29.14
	young	29.46	0.32	28.87	0.32	28.37	0.33	28.90
	old	29.11	0.32	28.61	0.33	28.04	0.33	28.59
	T_{mature}-T_{young}	0.22		0.32		0.19		0.24
	T_{mature}-T_{old}	0.57		0.58		0.52		0.56
	T_{young}-T_{old}	0.35		0.26		0.33		0.31
average	mature	29.07		28.55		28.01		28.50
	young	28.83		28.30		27.77		28.30
	old	28.53		28.05		27.47		28.02
	T_{mature}-T_{young}	0.23		0.25		0.24		0.24
	T_{mature}-T_{old}	0.54		0.49		0.53		0.52
	T_{young}-T_{old}	0.31		0.24		0.30		0.28

Table 4 The statistical thermal comfortable temperature of the male group and female group in summer/°C

air speed (AS)/($m \cdot s^{-1}$)		relative humidity (RH)/%						
		$40 \leqslant RH < 65$		$65 \leqslant RH < 90$		$RH \geqslant 90$		average
		mean	S.D.	mean	S.D.	mean	S.D.	
$0 \leqslant AS < 0.25$	male	27.67	0.32	27.14	0.33	26.61	0.33	27.14
	female	28.08	0.32	27.54	0.33	26.99	0.33	27.54
	T_{female}-T_{male}	0.41		0.40		0.38		0.40

(*Continued*)

air speed (AS)/($\mathrm{m \cdot s^{-1}}$)		relative humidity (RH)/%						
		$40 \leqslant RH < 65$		$65 \leqslant RH < 90$		$RH \geqslant 90$		average
$0.25 \leqslant AS < 0.40$	male	28.24	0.32	27.70	0.32	27.21	0.33	27.72
	female	28.60	0.33	28.09	0.33	27.58	0.32	28.09
	T_{female}-T_{male}	0.36		0.39		0.37		0.37
$0.40 \leqslant AS < 0.5$	male	28.72	0.31	28.21	0.30	27.65	0.30	28.19
	female	29.10	0.30	28.60	0.30	28.05	0.31	28.58
	T_{female}-T_{male}	0.38		0.39		0.40		0.39
$0.5 \leqslant AS < 0.8$	male	29.22	0.32	28.76	0.32	28.20	0.33	28.73
	female	29.61	0.32	29.15	0.32	28.59	0.33	29.12
	T_{female}-T_{male}	0.39		0.39		0.39		0.39
$AS \geqslant 0.8$	male	29.21	0.33	28.68	0.33	28.12	0.32	28.67
	female	29.63	0.32	29.09	0.32	28.51	0.32	29.08
	T_{female}-T_{male}	0.42		0.41		0.39		0.41
average	male	28.61		28.10		27.56		28.09
	female	29.00		28.49		27.94		28.48
	T_{female}-T_{male}	0.39		0.40		0.39		0.39

Table 5 The statistical thermal comfortable temperature of Nanjing residents in summer/°C

air speed (AS)/($\mathrm{m \cdot s^{-1}}$)	relative humidity (RH)/%						
	$40 \leqslant RH < 65$		$65 \leqslant RH < 90$		$RH \geqslant 90$		50%RH-90%RH
	mean	S.D.	mean	S.D.	mean	S.D.	
$0 \leqslant AS < 0.25$	27.88	0.49	27.34	0.49	26.80	0.50	1.08
$0.25 \leqslant AS < 0.40$	28.42	0.48	27.90	0.50	27.39	0.49	1.03
$0.40 \leqslant AS < 0.5$	28.91	0.46	28.40	0.45	27.85	0.46	1.06
$0.5 \leqslant AS < 0.8$	29.42	0.48	28.96	0.49	28.39	0.49	1.03
$AS \geqslant 0.8$	29.42	0.50	28.89	0.48	28.32	0.48	1.09
average	28.81		28.30		27.75		1.06

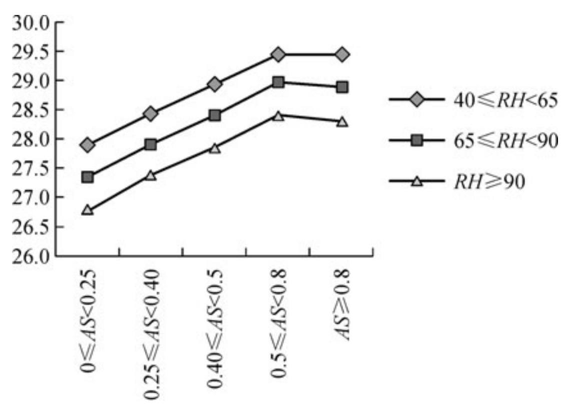

Fig. 1 The statistical thermal comfortable temperature of Nanjing residents in summer/°C

case of Nanjing residents in our study, although it cannot be well reflected in the table. Accidently, this result is in agreement with the findings of Nicol [2] in which he declared that people may require temperatures that are about 1°C lower to remain comfortable in a humid climate or in conditions when the relative humidity is high, but the main effect of higher humidity is to reduce the width of the comfort zone. Arens et al. also found the same fact that the 90%RH condition was typically the least favorably rated [19]. The reason for this phenomenon is that sweat cannot evaporate well when RH increases. At the same time, along with air speed increases, occupants' thermal expectations can increase. For example, these expectations can reach 29.42°C from 27.88°C when air speed increases to 0.8 m/s from 0.2 m/s (Table 5). The increased range gets to 1.54°C. In ventilated conditions, people's sweat can smoothly evaporate, and the heat on an individual's skin surface will be lost along with sweat evaporation. All these contribute to comfort levels. Another important fact is that local residents' thermal expectations are higher than 26°C, given the recommended value of thermal comfortable temperature in ISO7730 and ASHRAE Standard 55, from 27.88°C to 29.42°C when air speed and relative humidity are considered. These results are in agreement with other thermal comfort studies in hot and humid summer areas. For example, Ye et al. [11] found that the range of acceptable temperatures in Shanghai, near Nanjing, is between 14.7°C and 29.8°C in the adaptive thermal comfort study. Busch [6] carried out a field study and found that the thermal neutral temperature was 28.5°C in office buildings in Bangkok. Dear [9] and Kwok [4] found the neutral operative temperatures in Singapore and Hawaii to be 28.5°C and 27.4°C, respectively. Wong and Khoo [5] declared that the neutral operative temperature was 28.8°C in naturally ventilated classrooms in a secondary school in Singapore, when the average dry globe temperature was 30°C. Feriadi and Wong [12] studied the residential buildings in Indonesia; their study results show that the air temperatures ranged from 29.2°C to 29.8°C, and the neutral operative temperature was 29.2°C. Hwang et al. [14] found the margins of the acceptable zones in Taiwan using direct and indirect acceptability assessing methods to be 21.1°C–29.8°C ET* and 24.2°C–29.3°C ET*, respectively; both are distinctly different from the 23.0–26.0°C ET* criterion of ASHRAE Standard 55, especially at the upper boundary.

These studies, including this paper, show that acclimatization greatly shapes people's thermal expectations.

5 Cold sensation analysis of Nanjing's residents in natural conditions in winter

In winter's natural conditions, such as closing windows and doors but without heating, people's thermal comfort levels, being similar as that of in summer, is also affected by temperature, air speed, relative humidity, clothing, and body's activity. The following tables, from Tables 6 to 8, show the statistical data of cold sensation for 600 Nanjing residents in winter according to age or gender. Under different ranges of conditions, about 90% of subjects expressed the same sensations.

Similarly, some comparisons of cold sensation in winter natural conditions among young people, mature persons, and old persons were made in Table 6. In Table 6, we can see that the thermal comfortable temperature of young people is about 0.26°C, which is higher than that of mature persons in winter; the acceptable temperature of old persons is about 0.49°C, which is higher than that of mature persons; and young people's comfortable temperature is approximately 0.23°C, which is lower than that of old persons. These data, on one hand, reflect the real health conditions among people: mature persons being the best, followed by young people, and old persons being the poorest. On the other hand, they also demonstrate that the thermal comfort of people is affected very little by age. This result is in agreement with ISO7730 and ASHRAE Standard 55.

As for the effect on thermal comfort of gender, Table 7 clearly shows that the D-value of cold sensation between female and male in winter is only about 0.47°C. These data indicate that thermal comfort is not significantly affected by gender, although females are afraid of the cold more than males. Again, this result is consistent with previous studies, including Rohles, Nevins [17], Fanger [18], and ISO7730 and ASHRAE Standard 55.

Table 8 and Fig. 2 show that the influence of relative humidity on people's cold responses in winter natural conditions is the same as that in summer natural situations. The acceptable temperature increases from 15.49°C to 16.53°C when relative humidity increases from 50% to 90%. The watershed is still at 90%*RH*. In addition, the sensitivity of people's cold responses in winter natural conditions to air speed is much greater than that in summer natural situations. Generally, the gradient of air speed is about 0.1 m/s in winter, but in summer, the air speed is approximately 0.25 m/s. For example, when air speed was added from 0.05 to 0.5 m/s, the comfortable temperature increased from 14.14°C to 17.13°C in winter. The temperature range may increase to about 2.99°C. In similar conditions, nevertheless, the range of increases is about 1.54°C (from 27.88°C to 29.42°C). The reason for such a difference under similar conditions probably is that bodies are more sensitive to air movement in winter than in summer. Further, the acceptable temperature of local residents can be reduced to 14.14°C, which is far lower than the recommendation value of ASHRAE Standard 55 and ISO 7730, 19.5°C and 20°C, respectively. The main reasons for this phenomenon are people's acclimatization and their thermal expectations. These results are in agreement with other thermal comfort studies in cold and humid winter areas. For example, Ye et al. [11] found the acceptable temperature for Shanghai residents to be about 14.7°C. Yoshino and Lou [13] also found that an acceptable temperature in Shanghai is about 15°C. Note that Shanghai is located at Nanjing's south side. According to China's policy, heating is not offered in these two places.

6 Conclusions

From the analysis and discussions mentioned above, we can deduce the following conclusions. In natural conditions, the effects of gender and age on people's thermal sensations are insignificant compared with air temperature, mean radiant temperature, air speed, relative humidity, body activity, and clothing, whether in summer or in winter, in the Nanjing hot-humid climate. Furthermore, the influence of relative humidity on people's hot sensations in summer is similar to that on people's cold responses in winter. Generally, people's thermal uncomfortable sensation will rapidly increase, usually over 1°C, when exceeding 90%*RH*. Air speed variation increases the extent of people's hot or cold sensations in natural

Table 6 The statistical thermal comfortable temperature of all age groups in winter/°C

air speed (AS)/($m \cdot s^{-1}$)		relative humidity (RH)/%						
		$40 \leqslant RH < 65$		$65 \leqslant RH < 90$		$RH \geqslant 90$		average
		mean	S.D.	mean	S.D.	mean	S.D.	
$0 \leqslant AS < 0.1$	mature	13.91	0.32	14.45	0.31	14.93	0.32	14.43
	young	14.15	0.32	14.75	0.32	15.19	0.32	14.70
	old	14.35	0.32	14.94	0.32	15.41	0.31	14.90
	T_{young}-T_{mature}	0.24		0.30		0.26		0.27
	T_{old}-T_{mature}	0.44		0.49		0.48		0.47
	T_{old}-T_{young}	0.20		0.19		0.22		0.20
$0.1 \leqslant AS < 0.2$	mature	14.46	0.32	14.94	0.32	15.46	0.32	14.95
	young	14.71	0.32	15.21	0.31	15.71	0.31	15.21
	old	15.00	0.32	15.44	0.31	15.99	0.31	15.48
	T_{young}-T_{mature}	0.25		0.27		0.25		0.26
	T_{old}-T_{mature}	0.54		0.50		0.53		0.52
	T_{old}-T_{young}	0.29		0.23		0.28		0.27
$0.2 \leqslant AS < 0.3$	mature	14.96	0.30	15.44	0.29	15.99	0.29	15.46
	young	15.20	0.29	15.69	0.30	16.25	0.29	15.71
	old	15.41	0.29	15.90	0.30	16.45	0.30	15.92
	T_{young}-T_{mature}	0.24		0.25		0.26		0.25
	T_{old}-T_{mature}	0.45		0.46		0.46		0.46
	T_{old}-T_{young}	0.21		0.21		0.20		0.21
$0.3 \leqslant AS < 0.4$	mature	15.41	0.32	15.90	0.31	16.46	0.31	15.92
	young	15.65	0.32	16.20	0.32	16.68	0.31	16.18
	old	15.89	0.32	16.45	0.31	16.95	0.31	16.43
	T_{young}-T_{mature}	0.24		0.30		0.22		0.25
	T_{old}-T_{mature}	0.48		0.55		0.49		0.51
	T_{old}-T_{young}	0.24		0.25		0.27		0.25
$0.4 \leqslant AS < 0.5$	mature	15.84	0.31	16.33	0.31	16.91	0.31	16.36
	young	16.12	0.31	16.61	0.31	17.21	0.32	16.65
	old	16.35	0.31	16.83	0.32	17.46	0.32	16.88
	T_{young}-T_{mature}	0.28		0.28		0.30		0.29
	T_{old}-T_{mature}	0.51		0.50		0.55		0.52
	T_{old}-T_{young}	0.23		0.22		0.25		0.23
$AS \geqslant 0.5$	mature	16.88	0.30	17.34	0.29	17.97	0.29	17.40
	young	17.14	0.29	17.62	0.31	18.19	0.30	17.65
	old	17.36	0.29	17.82	0.31	18.39	0.31	17.86
	T_{young}-T_{mature}	0.26		0.28		0.22		0.25
	T_{old}-T_{mature}	0.48		0.48		0.42		0.46
	T_{old}-T_{young}	0.22		0.20		0.20		0.21
average	mature	15.24		15.73		16.29		15.75
	young	15.50		16.01		16.54		16.02
	old	15.73		16.23		16.78		16.25
	T_{young}-T_{mature}	0.25		0.28		0.25		0.26
	T_{old}-T_{mature}	0.48		0.50		0.49		0.49
	T_{old}-T_{young}	0.23		0.22		0.24		0.23

Table 7 The statistical thermal comfortable temperature of the male group and female group in winter/°C

air speed (AS)/(m·s^{-1})		relative humidity (RH)/%						
		$40 \leqslant RH < 65$		$65 \leqslant RH < 90$		$RH \geqslant 90$		average
		mean	S.D.	mean	S.D.	mean	S.D.	
$0 \leqslant AS < 0.1$	male	13.90	0.32	14.48	0.32	14.95	0.31	14.44
	female	14.38	0.32	14.94	0.31	15.41	0.31	14.91
	T_{female}-T_{male}	0.48		0.46		0.46		0.47
$0.1 \leqslant AS < 0.2$	male	14.48	0.32	14.96	0.31	15.47	0.31	14.97
	female	14.96	0.32	15.44	0.32	15.97	0.31	15.46
	T_{female}-T_{male}	0.48		0.48		0.50		0.49
$0.2 \leqslant AS < 0.3$	male	14.96	0.29	15.44	0.30	15.99	0.30	15.46
	female	15.43	0.29	15.92	0.29	16.47	0.30	15.94
	T_{female}-T_{male}	0.47		0.48		0.48		0.47
$0.3 \leqslant AS < 0.4$	male	15.41	0.32	15.95	0.32	16.46	0.31	15.94
	female	15.89	0.31	16.41	0.31	16.94	0.31	16.41
	T_{female}-T_{male}	0.48		0.46		0.48		0.47
$0.4 \leqslant AS < 0.5$	male	15.86	0.31	16.36	0.31	16.96	0.32	16.39
	female	16.34	0.31	16.82	0.31	17.42	0.32	16.86
	T_{female}-T_{male}	0.48		0.47		0.46		0.47
$AS \geqslant 0.5$	male	16.90	0.29	17.35	0.31	17.93	0.31	17.39
	female	17.36	0.29	17.83	0.29	18.43	0.31	17.87
	T_{female}-T_{male}	0.46		0.48		0.50		0.48
$AS \geqslant 0.5$	male	15.25		15.76		15.76		15.76
	female	15.73		16.23		16.77		16.24
	T_{female}-T_{male}	0.46		0.47		0.48		0.47

Table 8 The statistical thermal comfortable temperature of Nanjing residents in winter/°C

air speed (AS)/(m·s^{-1})	relative humidity (RH)/%						
	$40 \leqslant RH < 65$		$65 \leqslant RH < 90$		$RH \geqslant 90$		90%RH–50%RH
	mean	S.D.	mean	S.D.	mean	S.D.	
$0 \leqslant AS < 0.1$	14.14	0.47	14.71	0.47	15.18	0.48	1.04
$0.1 \leqslant AS < 0.2$	14.72	0.47	15.20	0.48	15.72	0.47	1.00
$0.2 \leqslant AS < 0.3$	15.19	0.44	15.68	0.44	16.23	0.44	1.04
$0.3 \leqslant AS < 0.4$	15.65	0.47	16.18	0.47	16.70	0.47	1.05
$0.4 \leqslant AS < 0.5$	16.10	0.48	16.59	0.47	17.19	0.47	1.09
$AS \geqslant 0.5$	17.13	0.46	17.59	0.44	18.18	0.45	1.06
average	15.49		15.99		16.53		1.05

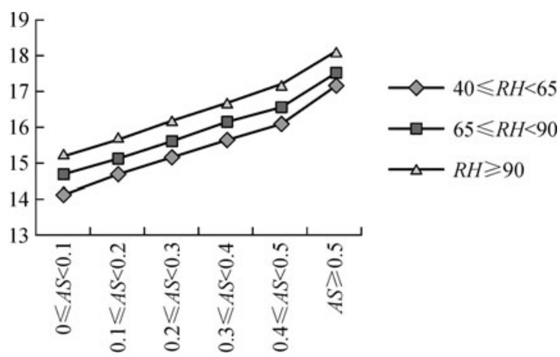

Fig. 2 The statistical thermal comfortable temperature of Nanjing residents in winter/°C

situations. Moreover, the effect in winter is bigger than that in summer. Therefore, it is very important to hinder the movement of airflow in winter by sealing any cracks around windows and doors and to increase air movement in summer by opening windows to allow air circulation in order to achieve more comfortable situations. The range of accepted temperature in hot-humid Nanjing is about between 14.14°C and 29.42°C in natural conditions, which did not fall within ISO7730 and ASHRAE Standard 55 comfort boundaries.

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