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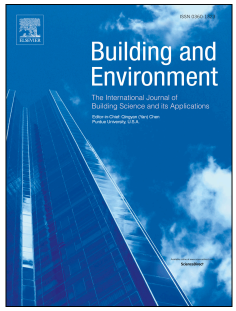

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Study of thermal comfort in underground construction based on field measurements and questionnaires in China

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A B S T R A C T

Underground buildings have the potential to reduce energy demand in comparison to conventional aboveground buildings. In China, previous studies on thermal comfort have been mainly focused on the building environment, such as offices, residential and non-residential buildings, but rarely on underground construction, especially the air-defence basement. To investigate the thermal comfort conditions in the unique and complex underground construction, comparative thermal comfort surveys including field measurements and questionnaires have been carried out in different underground air-defence basement in 95 nationwide typical cities. As a result, the mean thermal sensation (AMTS) from questionnaires is compared with PMV calculated based on the field data in different cities, and significant discrepancies are found. The occupant's actual cool feeling is larger in the cooler side, but occupants may sense the warmth as being less severe than the PMV predicts in warmer side. In addition, the neutral temperature model for underground construction is developed, and the thermal acceptability and preference are discussed. It shows that thermal acceptable temperature range is unsymmetrically distributed with respect to the thermal neutral temperature and changes with the ground temperature. Ultimately, the recommend temperature ranges for different cities through thermal comfort model are discussed based on psychrometric chart.

Keywords: thermal sensation; underground construction; thermal neutral temperature; acceptable temperature ranges

1. Introduction

1.1 Need for study

Underground construction is perceived to be environmental friendly and sustainable as it is the higher protection against the climatic influences by constant surrounding soil temperature [1,2] and a pleasant thermal comfort can be ensured with less energy [3,4]. In recent years, there has been a great interest in underground construction (UC) including air-defence basement construction, subway, parking lots, shopping malls, exhibition halls and service facilities in China. At present, China's underground space development has entered a high-speed development period, the total quantity of air-defence basement ranks first in the world.

Thermal environment of underground construction is different from the aboveground buildings. In underground construction, since there is no direct influence from the solar radiation, the thermal sensation induced by direct solar radiation can be neglected. The mean ground temperature (T_g) greatly affects the heat transfer of surrounding rock-soil [5], [6] and the average radiation temperature (T_R), that plays an important role on the personal thermal sensation. Too high or low average radiation temperature generally causes bad effects on the thermal sensation [7]. Different T_g in different regions may cause different T_R. **Table.1** shows the T_R of the offices buildings measured by LSI thermal comfort device both in the aboveground and underground buildings in four typical cities. It could be seen that the T_R in aboveground building was generally 1-2 ℃ higher than the air temperature T_{in} in room. But the T_R in the underground construction is about 1 ℃ lower than that of air temperature, and different T_R is observed in different cities. Thermal comfort is defined as "that condition of mind which expresses satisfaction with the thermal environment"[8].

The variations of personal psychological state in underground facility would inevitably make the person's thermal sensation different from the aboveground.

There are no specific studies on thermal comfort of occupants in underground air defence basement in China. The occupants' thermal sensation in the underground construction needs to explore to provide a theoretical basis for the thermal environment design.

Table.1 The measured T_R in underground construction and aboveground buildings in different cities

Typical city	Test time	T_o (℃)	T_{in} of the Aboveground building (℃)	T_R of the Aboveground building (℃)	T_g (℃)	T_{in} of the underground construction (℃)	T_R of the underground construction (℃)
BeiJing	15:00-16:00 in Aug. 23, 2008	32.6	29.7	30.8	13.7	24.3	22.2
NanJing	11:15-12:15 in Jul.25, 2007	36.4	28.7	30.5	17.4	25.3	24.1
Changsha	16:00-17:00 in Jul.26, 2008	33.7	28.4	29.8	17.9	26.5	24.8
Guangzhou	14:30-15:30 in Aug. 4, 2008	36.2	28.3	30.4	23.8	27.4	25.6

1.2 Learning's from earlier thermal comfort studies

The theoretical basis for field study of thermal comfort could be classified in two categories: the predicted mean vote (PMV) and percentage of people dissatisfied (PPD) methods [7] developed by Fanger and adaptive model proposed by Nicol and Humphreys [9,10].

PMV model is used in practice in the ISO 7730 [11] and ASHRAE-55 [12] standards. More and more studies put PMV-PPD model into question [13,14,15] recently. The argument is that PMV-PPD model ignores the important parameters such as cultural, climatic, social and contextual dimensions of comfort and thus denying all processes of thermal adaptation [16], especially in free-running buildings. An extension of the PMV model that includes an expectancy factor is also introduced by Fanger et.al [17] for using in non-air-conditioned buildings in warm climates. Subsequent thermal comfort models [18,19,20]]based on PMV model have been developed.

The adaptive thermal comfort model is a paradigm shift versus the predicted mean vote (PMV) approach. According to the field studies, linear regressions relating indoor operative temperatures to prevailing outdoor air temperatures are established. It is being widely accepted in the thermal comfort research community that state of mind is widely driven by perception and expectation of the occupants. The adaptive model was first included in the ASHRAE standard 55 [21] in 2004 as an optional method for evaluating naturally ventilated buildings. In 2007 the adaptive model was also included in EN 152515 [22]. Recently, Humphreys M et.al [23] updated the adaptive model through the new insights and an extended database.

Many field studies for thermal comfort have been carried out in different continents (Europe[24,25,26,27], Asia[28,29,30,31],Africa[32], etc.) and involves a variety of building types such as office buildings [33], residential building [34,35], educational building [36,37,38].However, most of them are for aboveground buildings and there has been limited study on underground construction.

Considering the complex underground thermal environment, Agus P. Sasmito et.al [39] found that the virgin rock temperature (T_g) had a great relation with the thermal comfort. Maidment G et.al [40] studied the thermal comfort conditions in underground railway environments in the UK. It shows that the acceptable thermal comfort criteria for an office may not be achievable in an underground railway environment. Based on the building information model of the subways, Mohamed Marzouk et.al (2014)[41] gave the ways to track the thermal comfort problems. In China, Hu Songtao et.al [42] performed the field test of thermal environment parameters and the subjective questionnaire in underground railway trains in different cities. Gang Liu [43] studied on thermal comfort of passenger at high-speed railway station in transition season. The air-defence basement is the underground building with large space and high density of people in wartime, the thermal comfort of the occupants in air-defence basement should be a concern.

It is not possible to obtain a generalized thermal comfort model for all climatic zone because adaptation process, expectation and perception of people are region specific [44].Toe and Kubota [45] found that the typical adaptive actions, occupants' ability and avenues for adaptation, and comfort temperatures differed with climate. Manoj Kumar Singh et.al [46] developed the thermal comfort models for various climatic zones of North-East India. Recently, based on field studies and laboratory studies from different climate zones in China, the Chinese evaluation standard for the indoor thermal environment for aboveground buildings was proposed [47]. However, the widely used design standard for air defence basement in China is the *Design Code for Civil air defence basement (GB50038-2005)*[48], which recommends same thermal comfort zones for underground engineering in different regions. It ignores thermal environment difference and occupant adaptability in different regions and may lead to the usage of the standard be widely limited. China has a very broad geographical area and therefore having large differences of thermal environment parameters in different regions. The large variations can also be seen from the annual mean ground temperature T_g, which are 5.4 ℃, 13.4 ℃ and 23.8 ℃ in Harbin, Beijing and Guangzhou, respectively. The thermal environment particularity and different psychological and physiological reactions of occupants in the underground would make the acceptable thermal comfort criteria for different areas may be different. But the reasonable thermal comfort model for different climatic zones in underground environment has not been discussed.

1.3. Aims and objectives

Accordingly, the aims of this study are as follows: a) Comparing the actual mean thermal sensation (AMTS) from questionnaires with PMV calculated from the field measurements to find the 'acceptable' thermal comfort criteria for underground environment in different cities; b) Establishing thermal neutral temperature model and acceptable temperature ranges to provide a design basis for thermal environment of underground environment; c) Comparing and exploring the recommend temperature ranges through new thermal comfort model with the original temperature ranges for underground environment in different areas.

2. Methodology

The field studies were conducted in different air-defence basement in 95 nationwide typical cities over a period of 6 years in China. The methodology for this work consists of both subjective and objective study. The subjective study consists of administering questionnaire to subjects during the field study. During the process of filling up the questionnaire, other micro-climatic parameters are measured simultaneously and discussed in the objective study. Field investigations on thermal environment are mainly carried out in the air-defence basement or the underground store offices in different cities as shown in **Fig.1**. Until October 2014, 825 data samples and 1318 effective questionnaires were recorded from field studies in 95 nationwide typical cities.

(a)Underground air-defence basement in Nanjing (b) Underground air-defence basement in Beijing

Fig.1 The typical underground air-defence basement in Nanjing (a) and Beijng (b)

2.1. Subjective study

To assess the clothing, activity level, background information and thermal comfort of the occupants, a questionnaire was designed based on the Thermal Environment Survey of Standard 55 [49].The questionnaire consists of two main parts: I: Basic information, which includes the height, weight and age and the clothing and level of activity of subjects. II: Thermal comfort, which includes the thermal sensation, thermal preference, and thermal acceptance of subjects. The ASHRAE seven-point scale of thermal sensation (+3 (hot), +2 (warm), +1 (slightly warm), 0 (neutral), -1 (slightly cool), -2 (cool), -3 (cold)) are adopted in the subject questionnaires. Two persons were responsible for guiding people to fill-in thermal sensation questionnaires. The main contents of subjective questionnaire on thermal comfort Part II are included in **Appendix A**.

Table.2 represents the different comfort survey indicators. The number of questionnaires filled depended on the geographical area, 432 copies in the area with ground temperature T_g <12 ℃, 502 copies in the area with 12 ℃< T_g <20 ℃ and 384 copies in the area with 20 ℃< T_g. The gender, age, height and weight distributions of the investigated occupants are also shown in **Table 2**.

Table 2 Comfort survey indicators

T_g in filed areas	T_g <12 ℃	12 ℃< T_g <20 ℃	20 ℃< T_g

Cities	Harbin, Changchun, Xining, Urumq, Datong, ShenYang, Yinchuan, Taiyuan, Lanzhou	Nanjing, Beijing, Zhengzhou, Shanghai, Hangzhou, Hefei, Anqing, Wuhan, Changsha, Jinan	Fuzhou, Xiamen, Jinjiang, Nanning, Guanghzou, Qinzhou, Haikou
Subjects	Male:316/432 female:116/432	male:326/502 female:176/502	male:282/384 female:102/384
Respondent Age(%)	>60: 3% 40-60: 22.6% 20-40: 69.9% <20: 4.4%	>60: 3.6% 40-60: 20.5% 20-40: 70.3% <20: 5.6%	>60: 2.3% 40-60: 19.8% 20-40: 74.7% <20: 3.1%
Respondent Age mean （min. max.）	26 （16-61）	27 （18-63）	23 （19-63）
Respondent height (m) mean （min. max.）	174.6 （155-184）	171.4（150-186）	170.5（150-178）
Respondent weight (kg) mean （min. max.）	67.8（45-89）	62.8 （48-91）	62.3 （45-88）

Individual clothing articles indicated in the survey responses are converted into their respective thermal insulation values using the garment values according to ASHRAE Standard 55. **Fig.2** gives clothing thermal insulation values as function of the internal air temperature T_{in}. In **Fig.2**, the thermal insulation varies from 0.5 Clo to 1.2 Clo with the T_{in} ranging from 18.5 ℃ to 29.3 ℃.

The annual mean ground temperature (T_g) is the important regional factor, which influences the thermal load in underground construction. **Fig.3** shows the clothing thermal insulation values vary with T_g. It could find that the clothing thermal insulation changes with the T_g. The average clothing insulation value is 1.0 Clo when the T_g below 12 ℃, while the T_g between 12 ℃ and 20 ℃, the average value is 0.7 Clo, and when the T_g above 20 ℃, the average value is only 0.5 Clo.

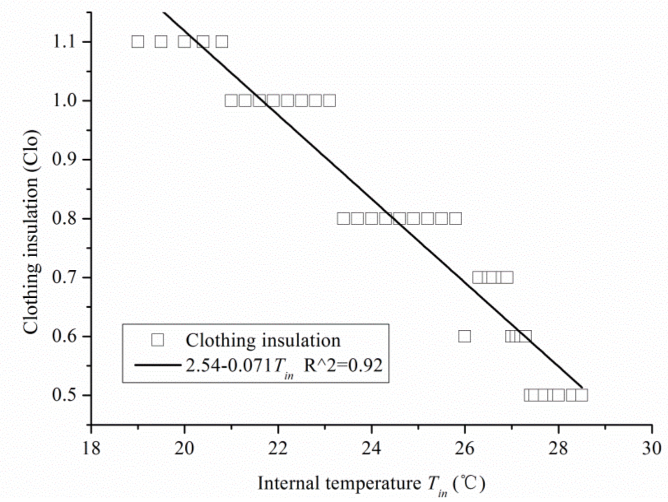


Fig.2 Thermal clothing insulation values as function of the internal temperature.

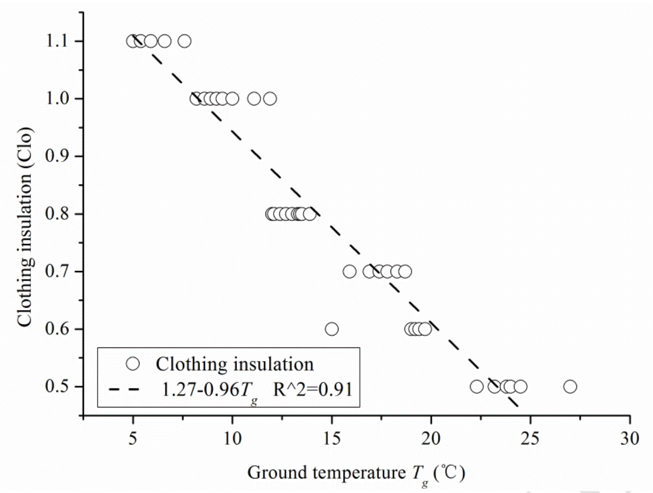


Fig.3 Thermal clothing insulation values as function of the ground temperature.

Metabolic rates are calculated from the descriptions of the activity of individuals in various questionnaires according to ISO 7730 [50]. In this study, activity levels vary from 1 met to 1.2 met and there is an average value equal to 1 met for the person in the underground construction. **Fig.4** confirms that metabolic rates slightly decrease with an increasing internal temperature.

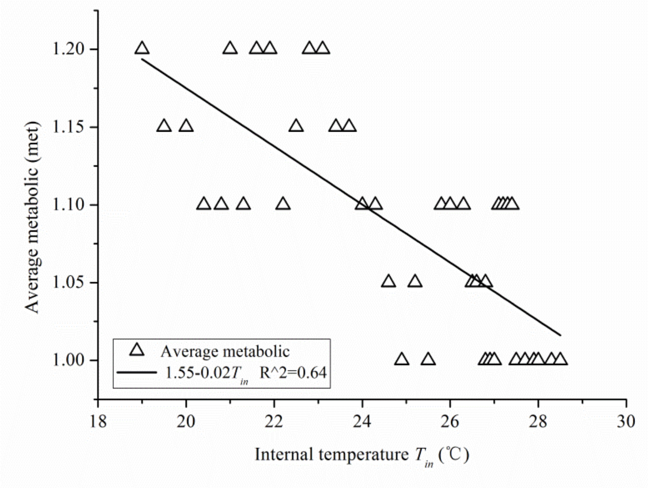


Fig.4 Average metabolic values as function of indoor operative temperature

2.2. Objective study

The variables measured contain internal air temperature (T_{in}), radiation temperature (T_R), ground temperature (T_g), relative humidity (*RH*), and the air velocity (V_A). The instruments, range and accuracy of each measured parameter are shown in **Fig.5** and **Table.3**. Until October 2014, 825 data samples were recorded from different underground construction in 95 nationwide typical cities.

a．LSI thermal comfort device　　　b．CO_2、O_2、temperature and humidity instrument

Fig.5 Thermal environment test instruments

Table.3 Measuring range and accuracy of the instruments used in this study

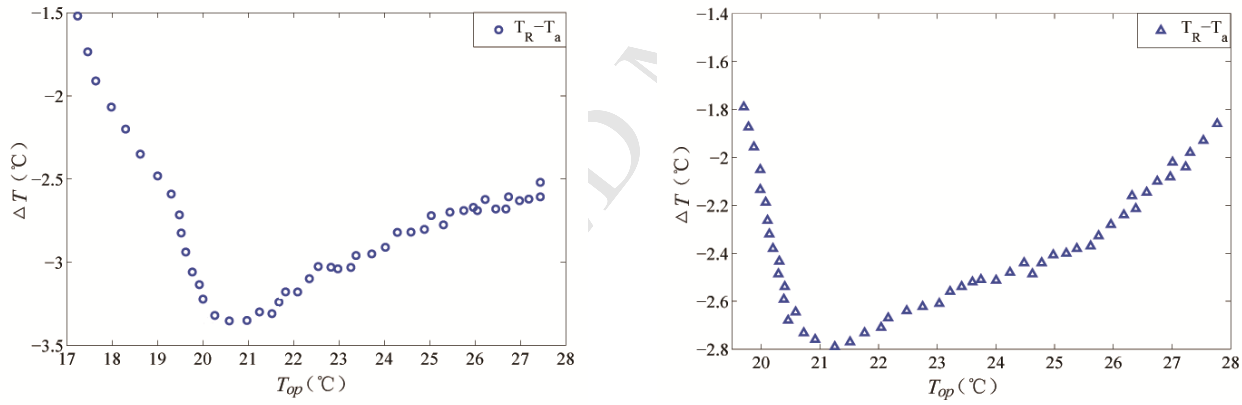
instrument	Parameters	Range	Accuracy
LSI thermal comfort device	T_{in}	10-35℃	±0.5 ℃
	T_R	10-35℃	±0.5 ℃
	RH	20-80%	±1.6%
	V_A	0-2m/s	±0.1 m/s
Testo 425	V_A	0-20m/s	±0.03 m/s
Testo 425	T_{in}	0-70 ℃	±0.5 ℃
HUMIPORT	*RH*	10-80%	±1.6%
KIMO TM200	T_R	50-250 ℃	±0.2℃

The actual mean thermal sensation vote (AMTS) could be obtained from the flied questionnaires and the predicted mean vote (PMV) values could be calculated through the measured thermal parameters. Then, the AMTS votes would compare with the PMV votes to find the thermal sensation variations in underground construction.

3 Results and analysis

3.1 Average radiation temperature

Based on the field tests, the operative temperature T_{op} could be simplified as an average value of the internal air temperature (T_{in}) and average radiation temperature (T_R) ($T_{op}= (T_R+T_{in})/2$) according to the conditions introduced in ASHRAE Standard55 [51]. The temperature difference ($\Delta T= T_R-T_{in}$) between T_R and T_{in} varying with the T_{op} in Nanjing and Harbin is shown in **Fig.6**.



a. ΔT changes with T_{op} in Harbin (T_g = 5.4 ℃)   **b.** ΔT changes with T_{op} in Nanjing (T_g = 17.4 ℃)

Fig.6 ΔT changes with T_{op} in cities of Harbin and Nanjing

In **Fig.6**, it could be found that the temperature difference (ΔT) between T_R and T_{in} in the typical cities: Harbin and Nanjing is negative, which means that T_R is lower than the internal air temperature. When the T_{op} is relative lower and varies in the range of 18 ℃ to 21 ℃, the ΔT decreases with increasing T_{op}. For example, in an underground construction in Harbin, the ΔT is -1.5 ℃ corresponding T_{op} of 17 ℃, however, the ΔT changes to -3.4 ℃ when T_{op} is 20.5 ℃. This may due to that when the T_{op} varies in the lower range from 18 ℃ to 21 ℃. Although the T_{in} rises, wall temperature and T_R have smaller changes due the larger thermal storage capacity of the rock-soil surrounding and relative lower T_g. This leads to the difference between the T_{in} and T_R becomes larger with the T_{op}. However, when the T_{op} varies in the higher range from 21 ℃ to 28 ℃ in **Fig.6**, the ΔT increases with the T_{op}. In **Fig.6b,** for an underground construction in Nanjing, the ΔT are found as -2.4 ℃ and -1.6 ℃ corresponding to the T_{op} 22.5 ℃ and 28 ℃, respectively. The temperature difference between the internal air and the wall become larger when the T_{op} above 22 ℃, thus, the wall temperature and T_R rise quickly and the difference between the T_R and T_{in} becomes smaller.

In aboveground buildings, the T_R is about 2-3 ℃ higher than the indoor air temperature in summer. The relative higher T_R has bad effects on the occupants' thermal comfort. However, in underground construction, the T_R is always lower than T_{in} due to the relative lower T_g. This would cause different thermal sensation for the occupants in underground construction and the acceptable thermal comfort criteria for aboveground may not be achievable in underground environment. Meanwhile, the thermal environment of underground construction is also different in different regions. This would lead to regional differences of personal thermal sensation.

3.2 Thermal sensation

The actual mean thermal sensation (AMTS) values of occupants for half-degree operative temperature bin are obtained directly from the questionnaires. PMV values varying with internal temperature are also calculated based on the field tests and compared with the AMTS values in typical cities of Harbin, Nanjing and Guangzhou shown in **Fig.7**. The regression analysis of PMV and AMTS votes with T_{in} are performed through the line and logarithmic function, respectively. The fitted AMTS and PMV equations in the typical cites are:

Harbin with T_g=5.4 ℃：

$$AMTS=1.86\ln(T_{in}-14.4)-3.89 \qquad R^2=0.82 \qquad (1)$$

$$PMV=0.237T_{in}-5.37 \qquad R^2=0.98 \qquad (2)$$

Nanjing with T_g =17.4 ℃：

$$\text{AMTS}=2.2\ln(T_{in}-17.7)-4.6 \qquad R^2=0.84 \qquad (3)$$

$$\text{PMV}=0.311T_{in}-7.97 \qquad R^2=0.98 \qquad (4)$$

Guangzhou with T_g =23.6 ℃ :

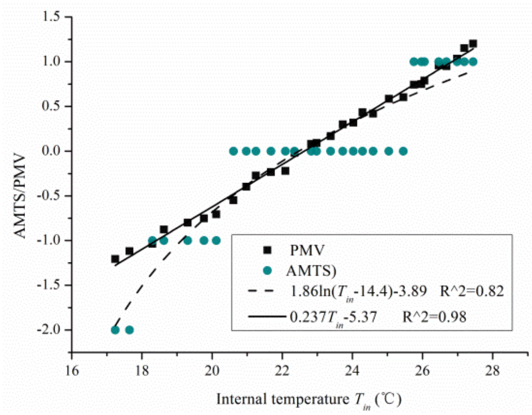
$$\text{AMTS}=3\ln(T_{in}-14.2)-7.48 \qquad R^2=0.83 \qquad (5)$$

$$\text{PMV}=0.3T_{in}-7.8 \qquad R^2=0.97 \qquad (6)$$

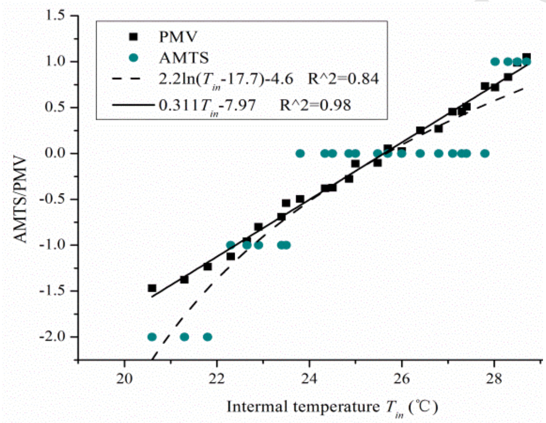
The regression relationships indicate that AMTS does not agree with PMV. In the **Fig.7**, the values of AMTS are lower than PMV when the internal temperature below 21 ℃, 23.5 ℃ and 24 ℃ in Harbin, Nanjing and Guangzhou, respectively. When the T_{in} is 20 ℃, the values of PMV is obtained as -1.45 while the corresponding AMTS is -2.0 in an underground construction in the Nanjing. In the city of Guangzhou with the T_g of 23.6 ℃ in **Fig.7c**, AMTS is 0.5 lower than PMV when the T_{in} is 22 ℃. It indicates that in the cooler side of the thermal sensation, the AMTS values are lower than PMV with the same T_{in}, the actual cool thermal sensation of the occupants is larger. This also indicates that the traditional PMV model may lead to some errors for evaluating the thermal environment of the underground construction.

When the T_{in} varies from 21 ℃ to 25.5 ℃ in Harbin in **Fig.7a**, from 23.5℃ to 26.4 ℃ in Nanjing in **Fig.7b**, from 24 ℃ to 27 ℃ in Guangzhou in **Fig.7c**, the average AMTS values are 0, the occupants' thermal sensation is comfortable and the PMV values are in the range of -0.5 to 0.5. When the T_{in} increases further, the value of AMTS is lower than PMV. In Harbin in **Fig.7a**, when the T_{in} is 27 ℃, the value of PMV is 0.3 larger than the AMTS, and the difference extends 0.5 when the T_{in} is 28 ℃. This shows that the people actual thermal sensation values of warmth are smaller than the calculated PMV. The occupants may sense the warmth as being less severe than the PMV predicts.

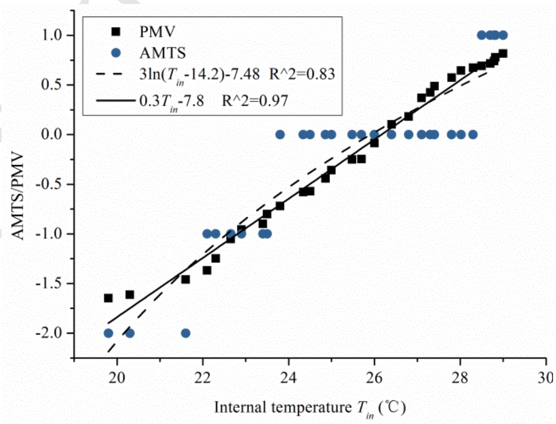
From **Fig.7**, compared with the AMTS in different areas, it could be found that the values of occupants' AMTS are smaller in the areas with higher T_g under the same T_{in}. For example, When the T_{in} is 19 ℃, the value of AMTS is found as -1.0 in the Harbin with T_g=5.4 ℃, whereas the AMTS value is -2.0 in Nanjing with T_g=17.4 ℃. When the T_{in} is 28℃, the occupants' AMTS are 1.0 and 0.5 in Nanjing (T_g =17.4 ℃) and Guangzhou (T_g =23.8 ℃), respectively. This is due to the thermal environment characteristic difference and adaption processes in different regions.



a. *PMV* and *AMTS* changes with T_{in} in Harbin



b. *PMV* and *AMTS* changes with T_{in} in Nanjing



c. *PMV* and *AMTS* changes with T_{in} in Guangzhou

Fig.7 *PMV* and *AMTS* changes with T_{in} in typical cities

3.3 Thermal neutral temperature and acceptable temperature range

Based on the thermal sensation questionnaires, the regression relationship between AMTS votes and T_{in} were given by logarithmic function in different cities. For example, in Harbin: AMTS=1.86ln (T_{in}-14.4)-3.89. The internal air temperature T_{in} corresponding to AMTS=0 in different cities with different T_g can be used to represent the neutral temperature T_{neu} in the underground construction. Therefore, the T_{neu} for different cities with different ground temperature T_g could be obtained. The annual mean ground temperature (T_g) are the main regional factors influence the thermal load in different cities in underground construction. Considering the T_g as a typical representative and stable in the underground construction, the temperature frequency method and weighted linear regression are used to obtain the fitting relationships between the T_{neu} and T_g shown as **Eq.7**. This could be taken as the new thermal comfort model for underground construction in China. **Fig.8** gives the T_{neu} varying with the T_g.

$$T_{neu}= 0.169T_g+22.38 \qquad R^2=0.975 \qquad (7)$$

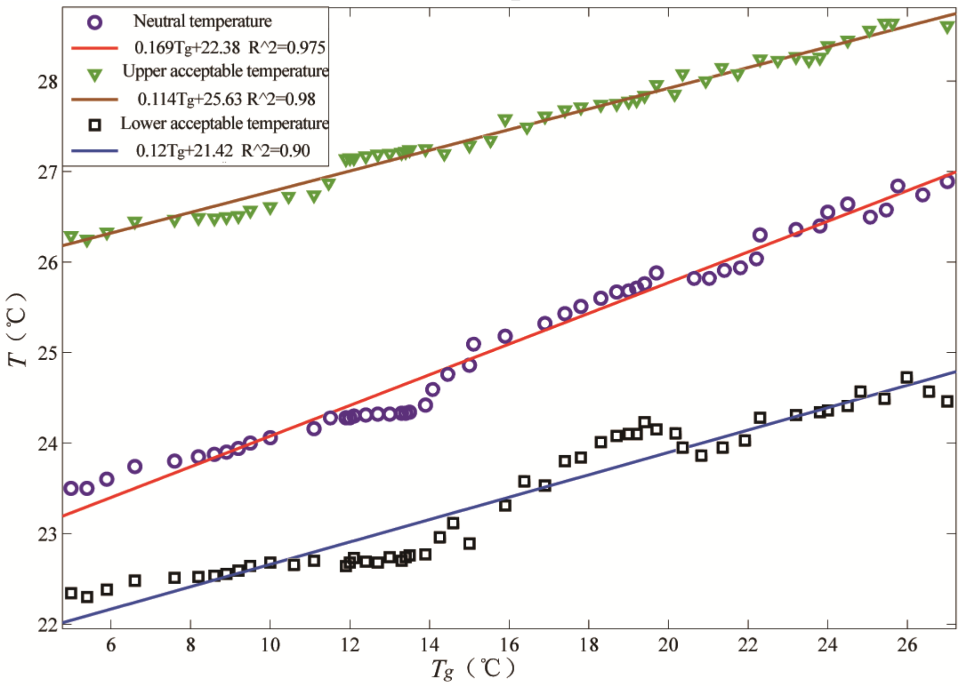


Fig.8 Neutral temperature model and acceptable temperature ranges for underground construction

It could be found that thermal neutral temperature models reflect linear relationship between the T_{neu} and T_g with respect to different regions. The neutral temperature is higher in the area with higher T_g and lower in the regions with lower T_g.

For example, in the city of Changchun with T_g =6.6 ℃, the neutral temperature for underground construction is 23.7℃. In the city of Beijing with T_g =13.9 ℃, the neutral temperature is 24.3℃.The thermal neutral temperature models take into account the thermal environment characteristic difference and occupants' adaptability of different regions. It would be more suitable for underground construction and can be referred by designers for energy conservation designing. De dear and Brager [52] indicated a range of ±3.5 ℃ about the neutral temperature as the acceptable thermal comfort ranges. The temperatures corresponding to the votes between ±0.5 on the 7-point scales are taken as the acceptable limits of temperature. Thermal comfort theory based on the PMV model [7] find that a comfort zone of 2-3 ℃ on either side of the neutral temperature is taken as acceptable. According to the ISO 7730 [53], the predicted mean vote between the limits of +0.85 and -0.85 corresponds to the point where 80% of the occupants feel satisfied. But in this paper the results from the questionnaires in underground construction did not conform to these conclusions. Thermal acceptability for this paper in underground construction is obtained directly from the occupants who answered 'acceptable' to the questionnaire, when asked whether their thermal conditions were acceptable or not. The percentage of actual acceptable votes for each half-degree operative temperature bin is recorded and analyzed. If the people acceptance ratio is 90% for the warmer side of thermal sensation, then the corresponding temperature is obtained as the upper limit of the acceptable temperature T_{com_upper}. If the people acceptance ratio is 90% for cooler side of thermal sensation, the corresponding temperature is obtained as the lower limit of the acceptable temperature T_{com_lower}. Based on the investigations, the T_{com_upper} and T_{com_lower} are estimated for different cities with different T_g. Then, the temperature frequency method and weighted linear regression are also used to obtain the fitting relationships between thermal acceptable upper, lower limits of temperatures and T_g:

$$T_{com\_upper}= 0.114T_g+25.63 \qquad R^2=0.98 \qquad (8)$$

$$T_{com\_lower}= 0.12T_g+21.42 \qquad R^2=0.90 \qquad (9)$$

Fig.8 also gives the upper and lower limit of thermal acceptable temperature model varying with T_g. **Fig.9** give the AMTS values varying with T_g corresponding to acceptable upper and lower limits of temperatures.

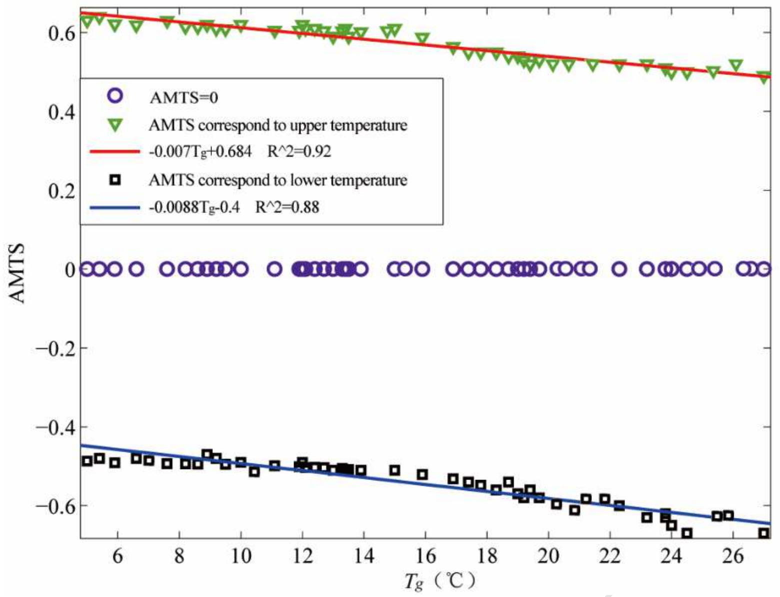


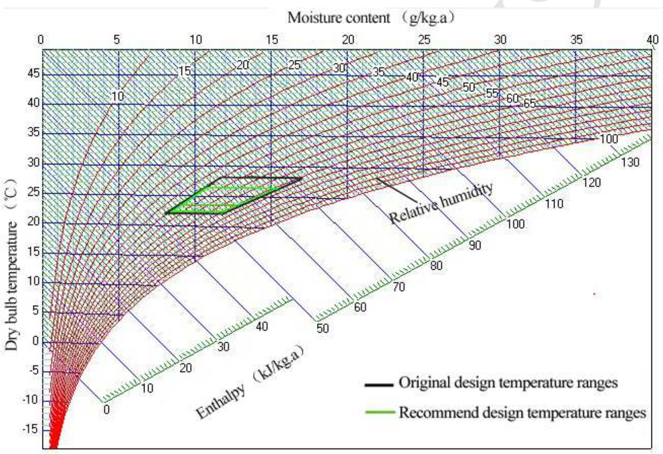
Fig.9. Neutral temperature model and acceptable temperature ranges for underground construction

It can be seen from Fig.8 and Fig.9 that the thermal acceptable temperature range is unsymmetrically distributed with respect to the thermal neutral temperature, and the AMTS corresponding to acceptable upper and lower limits of temperatures are not the same absolute value on either side of neutral temperature. When the T_g =5.4 ℃, the upper limit of the acceptable temperature is 26.8 ℃ and the corresponding the AMTS is +0.62. The neutral temperature is 23.5 ℃ corresponding with AMTS=0. The lower limit of the acceptable temperature is 22.3℃ corresponding the AMTS of -0.49. The acceptable temperature range in warmer side is about 3.5 ℃, but the acceptable temperature range in the cooler side is only 1.2 ℃. It also could be found that the acceptable temperature ranges vary with the T_g. **Table.4** gives the upper and lower limit of acceptable temperature in typical cites with different T_g. It shows that the acceptable temperature ranges in the warmer side is larger in the areas with lower T_g. For example, the acceptable temperature range in the warmer side of Harbin (T_g=5.4 ℃) is 3.5 ℃, but the acceptable temperature range in the warmer side of Hangzhou (T_g=13.9 ℃) is only 2.1 ℃. which is 1.4 ℃ lower than that of Harbin with the T_g of 5.4 ℃. However, with the T_g increasing, the acceptable temperature range in the cooler side becomes larger. The acceptable temperature range in the cooler side of Guangzhou (T_g=23.8 ℃) is only 2.0 ℃, but the acceptable temperature range in the cooler side of Haikou (T_g=24.6 ℃) extends to 2.5 ℃.

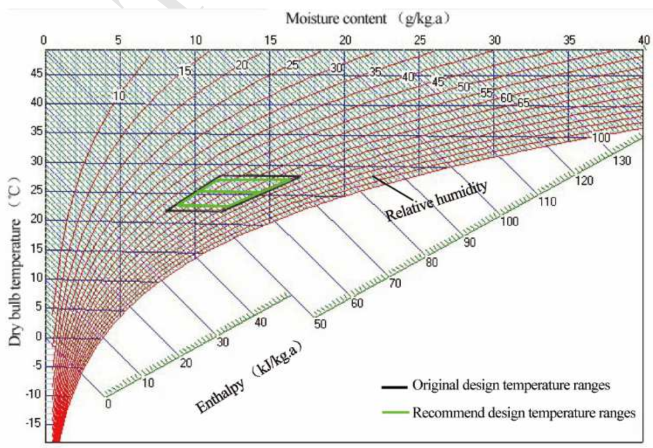
Table.4 The upper and lower limit of acceptable temperature in typical cites

Cities	T_g	T_{com_upper}	T_{neu}	T_{com_lower}	ΔT_{upper}	ΔT_{lower}	$AMTS_{upper}$	$AMTS_{lower}$
Harbin	5.4	26.25	23.5	22.3	2.75	1.2	0.64	-0.48
Hohhot	7.6	26.47	23.8	22.51	2.67	1.29	0.63	-0.49
Datong	9.2	26.51	23.94	22.59	2.57	1.35	0.61	-0.48
Shenyang	10	26.61	24.06	22.68	2.55	1.38	0.62	-0.49
Karamay	12.4	26.84	24.31	22.69	2.53	1.62	0.61	-0.50
Beijing	13.9	26.9	24.34	22.77	2.56	1.57	0.60	-0.51
Nanjing	17.4	27.65	25.43	23.8	2.22	1.63	0.55	-0.54
Hangzhou	18.3	27.7	25.6	24.01	2.1	1.59	0.55	-0.56
Wuhan	19.2	27.8	25.71	24.1	2.09	1.61	0.53	-0.58
Guangzhou	23.8	28.26	26.4	24.34	1.86	2.06	0.51	-0.63
Haikou	27	28.85	27	24.5	1.85	2.54	0.5	-0.63

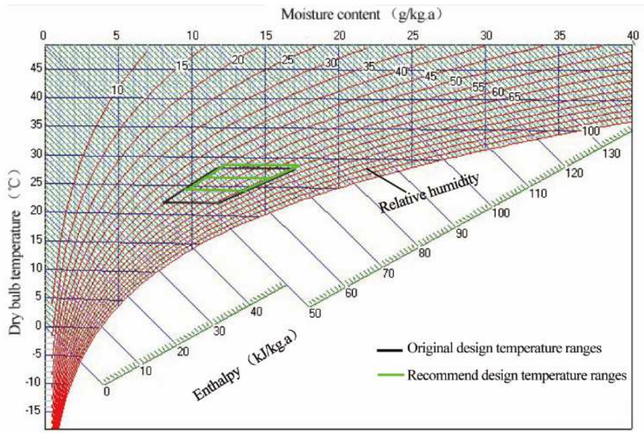
3.4 Applied analysis of thermal comfort model



a. the recommend thermal temperature range for Harbin



b. the recommend thermal temperature range for Nanjing



c. the recommend thermal temperature range for Guangzhou

Fig.10 the recommend thermal temperature range in psychrometric chart for different cities

Based on the psychrometric chart, **Fig.10** shows the recommend design temperature ranges for different cities through the thermal questionnaires and the original temperature ranges from the standard GB 50038-2005 [48]. The new thermal comfort model would be instrumental for researchers to formulate thermal standards and give the energy conservation design for underground construction in different areas.

In **Fig.10a,** the recommend design temperature is compared with the original temperature for the city of Harbin in psychrometric chart. It could be found that the recommend temperature is lower than the original temperature. The ground temperature in the Harbin is 5.4 ℃ and the lower recommend temperature could reduce lots of heating load for the underground construction in Harbin and save a larger number of energy consumption form equipment. This also could be found in the city of Guangzhou in Fig.**10c**, the higher recommend temperature ranges would reduce lots of cooling load and lots of passive energy conservation measures could be used.

4 Conclusions

The purpose of this research is to establish the reasonable thermal comfort model for underground construction, especially air-defence basement in China. Thermal comfort surveys including field measurements and questionnaires have been carried out in different underground constructions in 95 nationwide typical cities. The conclusions drawn from this study are as follows:

(1) In the underground construction, the occupant's actual cool feeling obtained from questionnaires is larger and the values of AMTS in cooler side of the thermal sensation are smaller in the areas with higher T_g. The values of PMV is obtained as -1.45 while the AMTS is -2 in an underground construction in the Nanjing, when the T_{in} is 20 ℃, but the value of AMTS is found as -1.0 in the Harbin with T_g=5.4 ℃ with the T_{in} of 20 ℃.

The occupants may sense the warmth as being less severe than the PMV predicts. For example, in Harbin, when the T_{in} is 27 ℃, the value of PMV is 0.3 larger than the value of AMTS. People have lower thermal sensation of warmth in the regions with higher T_g. For example, for an underground construction in Nanjing (T_g =17.4 ℃), when the T_{in} is 28℃, the occupant's AMTS is about 1.0 while the occupant's AMTS is only about 0.5 in the Guangzhou (T_g =23.8 ℃) with the same T_{in} of 28℃.

(2) The fitting relationships between the neutral temperature and T_g are obtained as: T_{neu}= 0.169T_g+22.38. The thermal acceptable upper and lower limits of temperatures vary with the T_g for underground construction also developed as: T_{com_upper}= 0.114T_g+25.63 and T_{com_lower}= 0.12T_g+21.42, respectively. It shows that the thermal acceptable temperature ranges are unsymmetrically distributed with respect to the thermal neutral temperature and change with the $T_{g,}$ The acceptable temperature range in the warmer side of Hohhot (T_g=7.6 ℃), Hangzhou (T_g=13.9 ℃) and Guangzhou (T_g=23.8 ℃) are 2.5 ℃, 2.1 ℃ and 1.86 ℃, respectively.

(3) Based on psychrometric chart, the recommended temperature ranges for different cities through thermal questionnaires are compared with the original temperature ranges. It shows that the recommend temperature ranges varying with the ground temperature could save lots of energy consumption.

Nomenclature

T_g annual mean ground temperature (℃)

T_{in} air temperature in underground construction (℃)

T_{op} operative temperature (℃)

T_R average radiation temperature (℃)

ΔT Temperature difference between T_R and T_a (℃)

T_{com_lower} the lower limit of acceptable temperature (℃)

T_{com_upper} the upper limit of acceptable temperature (℃)

T_{neu} thermal neutral temperature (℃)

$AMTS_{upper}$ actual mean thermal sensation corresponding the upper limit of acceptable temperature

$AMTS_{upper}$ actual mean thermal sensation corresponding the lower limit of acceptable temperature

Acronyms

AMTS actual mean thermal sensation

Appendix. A: Sample questionnaire

Thank you for your support for thermal environment survey in underground construction

subject detail				
Name	city name	Climatic zone	Time	occupation

Age	Sex		Height	Weight
	M ☐	F ☐		

Cloths worn by occupants		
Casually	At the time of voting	At social functions
☐	☐	☐

Thermal environment			
Temperature	Relative humidity	Air velocity	Underground details

Thermal sensation						
Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot
☐	☐	☐	☐	☐	☐	☐

How would you consider the room temperature?	
Acceptable	Not acceptable
☐	☐

How would you like to feel?						
Much too cool	Too cool	Comfortable Cool	Comfortable	Comfortable Warm	Too Warm	Much too Warm
☐	☐	☐	☐	☐	☐	☐

Level of Air movement should be:		
Lesser	As it is	More
☐	☐	☐

Level of Humidity should be:		
Lesser	As it is	More
☐	☐	

other visions on thermal environment survey in underground construction

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Highlights

► Comparative thermal comfort surveys have been carried out in underground constructions.

►The mean thermal sensation (AMTS) is compared with PMV in different cities

► Neutral temperature models and the acceptable limit temperature model are established.

►The recommend temperature ranges could save energy consumption in different areas.