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Field measurement of human thermal comfort in winter across China

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Abstract: Energy use in building for heating depends on the thermal comfort requirements of the occupants. Personal thermal comfort and clothing behaviours in buildings during winter were studied. The Chinese Thermal Comfort Database contains 41977 sets of data which are from five climatic zones: Severe cold, Cold, Hot Summer and Cold Winter, Hot Summer and Warm Winter and Temperate zones. The database includes indoor and outdoor thermal environmental parameters and thermal responses of the occupants. 14646 sets of data from winter conditions in buildings were screened for analysis. Clothing insulation in Hot Summers and Cold Winter region was classified into seven levels for further studies. Logistic regression was adopted to estimate the change of thermal sensation in the response to indoor operative temperatures. The results indicated that the neutral temperature ranges for occupants in 1.0-clo garments were [17.0 - 24.1 °C] in Severe cold zone, [15.4 - 24.0 °C] in Cold zone and [15.0 - 23.1 °C] in Hot Summer and Cold Winter zone. Adding clothing insulation improves occupants' thermal comfort in winter, but the limitation is maximum clothing insulation of 1.9 clo. The study provides a reference for the creation of comfortable thermal environments with a low energy use.

Keywords: Thermal comfort, clothing level, climatic zones, field study, neutral temperature range.

1. Introduction

With the development of modern technology, mechanical means are used to provide a desired comfortable temperature for occupants, which led to increased energy use in the building stock (IPCC, 2007). Reducing the energy use in buildings is an urgent goal worldwide. China, as a developing country, is also playing a significant role in the global promotion of a sustainable development. It is reported that the northern urban heating (NUH) in China the energy use for heating in 2016 (BERC, 2018) accounted for 21% of the total energy use in commercial buildings. Owing to the significant improvement in the efficiencies of heating systems and equipment, the energy use in NUH part for an entire heating system primarily depends on the thermal comfort requirements of the occupants. Therefore, an insight into personal thermal comfort during winter is important for predicting the needed heating and increasing building energy performance.

Thermal comfort is defined as a status of mind which expresses satisfaction with the thermal environment (ISO 7730, 2005). It is complicated to predict the range of temperatures for thermal comfort conditions, as the required conditions are affected by multiply factors (Taleghani et al., 2013), e.g., cultural influences, environmental and personal factors. Due to the variability of climatic characteristics, indoor environments and the thermal comfort of occupants have been studied in different climate regions (Yan et al., 2017; Toe and Kubota, 2013). The individuals' thermal adaptability varied according to the climate region they lived in (de Dear, 2020). The requirements of comfortable thermal environments were found to be separate in different regions, which mainly related to the environment they usually were exposed to (Humphreys et al., 2013). China is a vast geographical country with a large south-north span, where regional distinction exists in outdoor climates and indoor environments. The comfort temperature was nearly equal to the indoor mean air temperature in the severe cold zone of Harbin, where indoor heating systems were adopted (Wang, 2006). An obvious difference between the comfort temperature and the indoor temperature was found in other climate zones of China (Yan et al., 2017). Therefore, the thermal comfort of occupants in different climate zones was studied.

Clothing insulation (I_{clo}) is an important factor when predicting or evaluating the indoor thermal environment and the adjustment of clothing insulation is a powerful behavioural response to changeable climatic conditions (de Dear and Brager, 1998). Allowing a greater clothing adaption and a wider range of indoor climatic conditions could save a significant amount of energy without sacrificing thermal comfort (Schiavon and Melikov, 2008). The choice of clothing is easily affected by external and indoor climatic conditions. Clothing resistance was more likely to rely on the outdoor air temperature early in the morning while indoor air temperature seems to influence the change of clothes during the day (Carli et al., 2007). In existing standards, clothing is specified at a constant value for cooling mode (0.5 clo) and heating mode (1.0 clo). People might change their clothes according to indoor environments. In this study, the preference of indoor temperatures for occupants at different clothing levels was studied.

The measurement of thermal sensation is usually done by the ASHRAE seven-point scale, which builds a correlation between a linguistic expression and a numeric voting, such as the explanation of “Neutral” when TSV (Thermal sensation vote) equals “0”. However, the actual thermal sensation felt by human subjects might not always be the point on the ASHRAE scale (Humphreys and Hancock, 2007), especially for the interval scale. Thermal neutrality was usually regarded as the optimal thermal comfort condition. “TSV = 0” was widely used to describe thermal neutrality (Hwang, 2007). It is found that people had confusion on deciding the appropriate vote of their thermal status when they were close to the thermal neutrality (Xie et al., 2019). A comfort range of temperature is recommended to represent the neutral status (ASHRAE 55, 2017). In the present study, a neutral range of operative temperature was estimated for the different climatic zones.

Based on a national-wide field survey in China, the following objectives are used in the present study.

1) To study thermal environments and thermal comfort of occupants from different climatic zones.

2) To investigate the influence of clothing insulation on individual thermal comfort.

3) To give the neutral temperature ranges when occupants wear 1.0-clo garments.

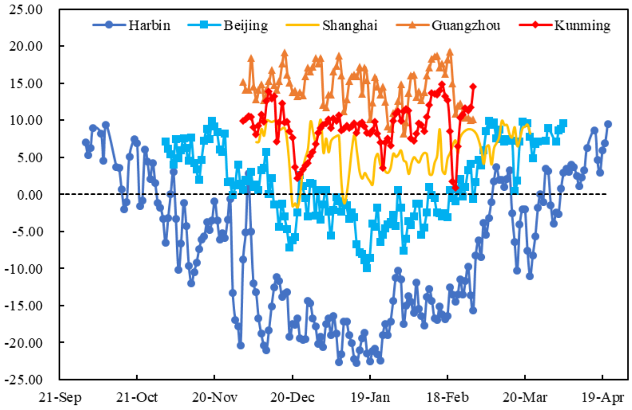
2. Research methods

2.1 Background

There are five different climatic zones across China: severe cold (SC), Cold, Hot Summer and Cold Winter (HSCW), Hot Summer and Warm Winter (HSWW) and Temperate zones (Temp) (GB 50176-2016). The classification is based on average outdoor air temperatures of the coldest month and of the hottest month. The geographical location of the five Climatic zones is shown in Figure 1. The regional variation impacts the difference in indoor climate and thermal preference of occupants (Su et al., 2022). The outdoor weather in winter is freezing in the north part of China, while the weather in the south part of China is warmer.

Figure 1. Climatic zones in China

Figure 2 displays the daily mean outdoor air temperature in typical cities of the five climatic zones, which were collected by meteorological information centre of China Meteorological Administration. The outdoor mean air temperature is below 0 °C in the coldest month and low temperatures last longer in Harbin and Beijing, which are located in the northern parts of China. However, the mean outdoor air temperature exceeds 0 °C during the whole winter in Guangzhou and Kunming. The heating system is operated differently in the north and south regions, separated based on the Qinling Mountain-Huai River line. There is a huge demand of heating in winter in the northern China.



Note: Harbin represents “Severe cold region”, Beijing represents “Cold region”, Shanghai represents “Hot summer and cold winter region”, Guangzhou represents “Hot summer and warm winter region”, and Kunming represents “Temperate region”.

Figure 2. Daily mean outdoor temperate of five Climatic zones in winter

2.2 Data source

The Chinese Thermal Comfort Database was established in 2018 based on “the 13th Five-Year” National Science and Technology Major Project of China - Fundamental Parameters on Building Energy Efficiency in China. It contains 41977 sets of data which are from widely distributed sites, covering 24 provinces and 50 cities in 5 climatic zones of China. The contents in the database include indoor and outdoor thermal environmental parameters and thermal responses of the occupants for local and whole-body comfort, which were obtained through strict requirements of the Chinese industry standard (MOHURD, 2014).

The objective measured parameters indoor air temperature, relative humidity, and air velocity, etc. The information from individuals includes their clothing insulation, activity level and subjective evaluations of the indoor climate. Questions of thermal sensation applied ASHRAE seven-point scale (−3 cold, −2 cool, −1 slightly cool, 0 neutral, +1 slightly warm, +2 warm, +3 hot); Thermal comfort applied a five-point scale (1 comfortable, 2 slightly uncomfortable, 3 uncomfortable, 4 very uncomfortable, 5 unbearable); In most cases, the sensation and comfort votes were discrete. Thermal acceptability vote (-1 unacceptable, -0.1 slightly unacceptable, 0.1 slightly acceptable, 1 very acceptable) used the continuous scale with the breakpoint at "0" (-1 unacceptable, -0.1 slightly unacceptable, 0.1 slightly acceptable, 1 very acceptable). The metabolic rate of the subject was determined according to the reference value of ASHRAE Standard 55 and ISO 7730. In this study, the data was collected from the five climatic zones in winter. The data were all from surveys in field buildings. The underlying assumption of the field survey is that people were able to control their environment in such a way that they tried to reach comfort. A total of 14646 valid questionnaires were gathered for further analysis.

2.3 Data processing

The normality test shows that the operative temperature and clothing insulation follow the normal distribution. Since the probability of the majority of the data falling between average ± 3SD (standard deviation) is 99%, the value out of this range was regarded as outliers and was screened out.

One way ANOVA method was adopted for the variance analysis when there are at least 3 categories. The data when occupants vote "0" for the thermal sensation were particularly selected and marked as "thermally neutral state". Variation analysis of operative temperatures between a neutral state and all conditions was conducted by the independent sample t test.

Since a clothing insulation difference of 0.15 clo was the minimum value that should not be averaged to represent multiple occupants (ASHRAE 55, 2017), the continuous variable of clo-value was translated into categorical variables by Bin method at an interval of 0.3 clo, as shown in Table 1. It is inconvenient and uncomfortable for occupants to wear too thick clothes. Therefore, clothing insulation within the moderate range from 0.25 clo (underwear, T-shirt, shorts, socks, shoes) to 2.35 clo (underwear, long-sleeve shirt (thin), long-sleeve shirt (thick), long-sleeve sweater (thick), down jacket, thermos-trousers, jeans, stocking (thick), boots) was selected to study the influence on individuals' subjective perceptions. Moreover, a broad range of clothing insulation was seen in the Hot summer and cold winter (HSCW) region since there are no district heating systems and people adjust their clothing to obtain thermal comfort. Clothing data in this region was classified for understanding the influence of clothing on respondents' thermal comfort.

Table 1. Transferring clothing insulation into categorical variables

Level	Range	Mean value	Amount
1	0.25 - 0.55 clo	0.4 clo	271
2	0.55 - 0.85 clo	0.7 clo	277
3	0.85 - 1.15 clo	1.0 clo	578
4	1.15 - 1.45 clo	1.3 clo	743
5	1.45 - 1.75 clo	1.6 clo	820
6	1.75 - 2.05 clo	1.9 clo	384
7	2.05 - 2.35 clo	2.2 clo	383

Logistic regression was used to establish the relationship between the indoor operative temperature (t_o) and thermal sensation of occupants. Logistic regression was developed based on the logit transformation (Lancaster and Cox, 1971) as shown in equation (1) and the linear relationship between the independent variables and dependent variables is shown in equation (2). Moreover, the logit transformation deals with the odds ratio (OR) which quantifies the strength of the association.

$$\text{logit}\ (p) = ln\frac{p}{1-p} \tag{1}$$

$$\text{logit}\ (p) = \beta_0 + \beta_1 x_1 + \cdots + \beta_n x_n \tag{2}$$

The occurrence probability (p) represents the positive response in the logistic regression part. The points where the probability equalled 50% were considered as the threshold for transformation. For example, when x_i reached the threshold of stimulating 50% in the y-axis, it was termed entering the occurrence zone.

As the logistic regression aimed at dealing with a binary response, the thermal sensation from the survey was divided into two categories. The seven-point thermal sensation votes (TSV from "-3" to "+3") were arranged in "Cooler and neutral" (TSV ≤ 0) and "Cooler than neutral" (TSV < 0) respectively, as shown in Table 2. When t_o reached the threshold of stimulating 50% probability of the "neutral and cooler" transition curve, it was termed as entering the neutral zone; and when t_o decline to that of the "cooler than neutral" curve, leaving the neutral zone. The neutral range of operative temperature was between the two thresholds. Since it was hard to decide the difference when the voting was around thermally neutral status, or the status might last for a certain range of thermal stimulus in the environment, the concept of the thermally neutral range (Nikolopoulou and Lykoudis, 2006) could be alternative and used in the present study.

Table 2. Arrangements of thermal sensation vote

Description	Abbreviation
Cooler than neutral	TSV < 0 (TSV = -1, -2, -3)
Cool and neutral	TSV ≤ 0 (TSV = 0, -1, -2, -3)

3. Results

3.1 Distribution of indoor environments

The database contains the environmental parameters including indoor air temperature (t_a), relative humidity (RH) and air velocity (v_a), which are directly measured in the field studies. It also includes mean radiant temperature (t_{mrt}), which is measured either by globe thermometer and then calculated through the equation combining t_a, v_a and globe temperature or by the definition equation combining angle factor weighted average of surface temperatures. The results showed a significant difference between t_a and t_{mrt} in the non-uniform environments: t_{mrt} in SC and cold areas was about 1 °C lower than t_a, due to the influence of the cold weather and corresponding cold indoor surfaces (windows, walls). On the contrary, t_{mrt} in HSCW zone was higher than that of t_a, which resulted from the solar radiation during the day. Therefore, operative temperature (t_o) (Winslow et al, 1937) as a comprehensive thermal index of the environment is used in the subsequent analysis. t_o is defined as a uniform temperature of a radiantly black enclosure in which an occupant would exchange the same amount of heat by radiation and convection as in the actual non-uniform environment. It is the weighted mean of the air temperature and the mean radiation temperature by the heat transfer coefficient of convection and radiation, respectively. When the air velocity is less than 0.2m/s, the value is the arithmetic mean of the two types of temperature. The operative temperature distribution is shown in Figure 3. The neutral operative temperature when occupants vote “0” was also illustrated for comparison. Although the outdoor air temperature (Figure 2) in severe cold (SC) and cold regions is low in winter, t_o is significantly higher than that in hot summer and cold winter (HSCW) regions and temperate regions when considering all votes of subjects (right part in Figure 3). The difference of neutral operative temperature between climatic zones became smaller (left part), indicating the neutral temperature tends to be consistent. The mean value of t_o for neutral state in HSCW (17.8 °C) and Temp (15.8 °C) areas were significantly higher than that for all votes merged (HSCW: 16.7 °C, Temp: 13.6 °C). This indicates an essence of increasing the indoor air temperature for pursuing the neutral thermal state. Since the data collected in hot summer and warm winter zone (HSWW) were only from rooms with centralized heating, the t_o in this region was concentrated at a higher value of 23.8 °C in all conditions. The mean value of t_o was almost the same in the neutral state and all conditions in SC and Cold zones, which attributes to the central heating system adopted in both zones.

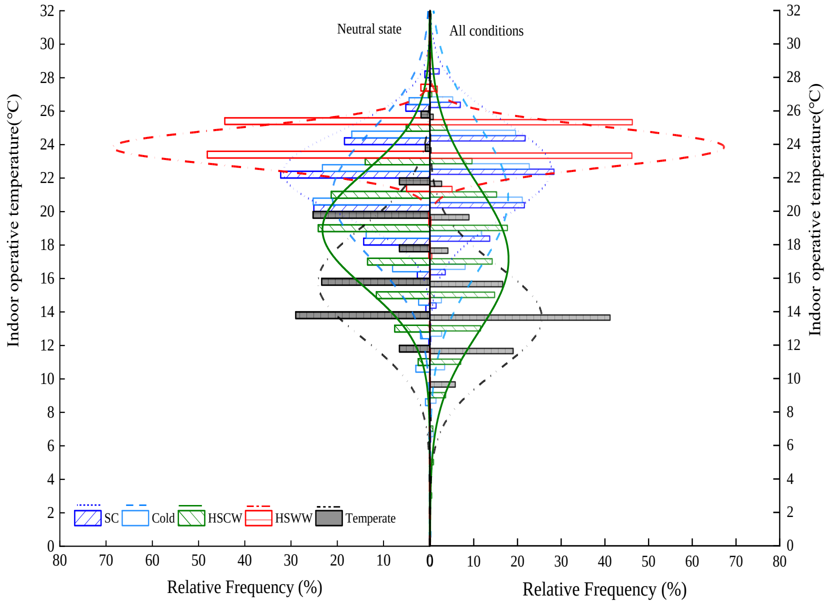


Figure 3. Indoor operative temperature among five climatic zones

Table 3 summarizes the measurements of relative humidity (RH) and air velocity (v_a) in the investigated buildings in five climatic zones.

Table 3. Measurements of relative humidity (RH) and air velocity (v_a)

Zones	SC	Cold	HSCW	HSWW	Temperate
RH (%)	33± 11[a]	34± 19	52 ± 13	53 ± 10	17 ± 14
v_a (m/s)	0.06 ± 0.04	0.01 ± 0.00	0.03 ± 0.02	0.10 ± 0.00	0.32 ± 0.14

a - Mean ± Standard deviation

It is clear that the relative humidity (around 33%) in severe cold (SC) region and Cold area is significantly lower than that of buildings in hot summer and cold winter (HSCW) area (52%), since high temperatures correspond to a higher partial pressure of saturated vapour and result in the low relative humidity. The indoor air velocity is within a reasonable range (< 0.2 m/s) in a majority of regions, except for the temperate region where an adverse indoor environment exists with low relative humidity and high air velocity. Since interviewees were recommended to stay in the room for at least 15 min before they filled in the survey questionnaire, light physical activity (metabolic rate around 1.1 met) was recorded for the majority of occupants.

3.2 Distribution of clothing insulation

Figure 4 illustrates the distribution of clothing insulation in all climatic zones. The mean clo-value concentrated around 1.0 clo in the majority of climatic zones and that (around 1.06 clo) in cold zone was slightly higher. A wide distribution of clothing insulation was found in HSCW zone and the mean clo-value is 1.36 clo, due to the slightly cold indoor climates. A comparison of clo-value was conducted between the neutral state and all conditions. As shown in Figure 4, there is a similar distribution of clothing data in the neutral state. However, a significant difference was found between the two distributions in most climatic zones, except for HSWW zone. This indicates that clothing insulation plays an important role in the judgment of thermal neutrality. The majority of the interviews were carried out in air-conditioned rooms in hot summer and warm winter (HSWW) zone where the thermal environments were in a narrow range and occupants seldom changed clothes.

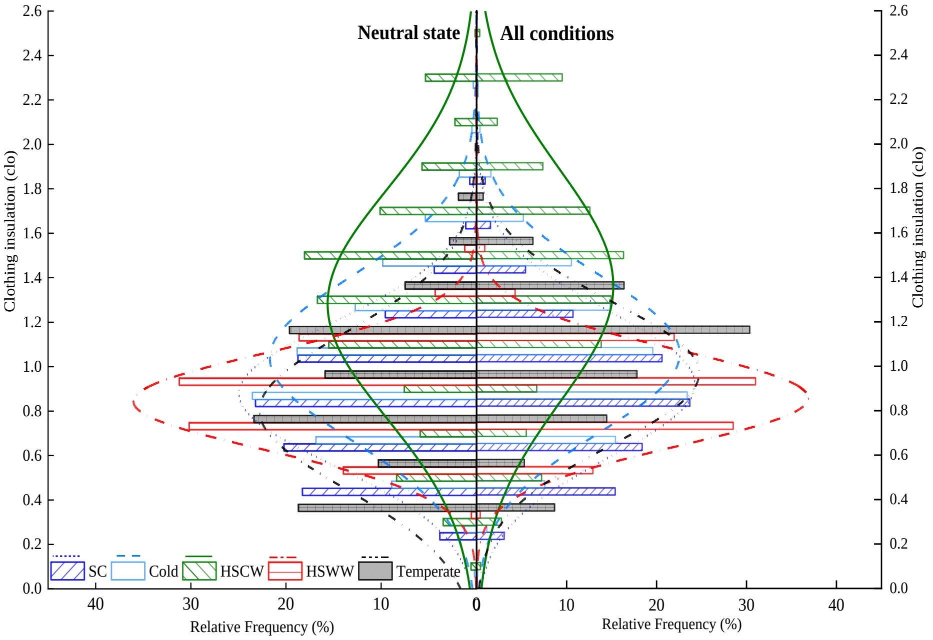


Figure 4. Distribution of clothing insulation between neutral state and all conditions

3.3 The influence of clothing insulation on thermal comfort

Clothing data in HSCW area were further selected to study the influence of clothing insulation on occupants' thermal comfort. Figure 5 shows the variation of mean thermal sensation (MTS) with operative temperatures at different clothing levels and Table 4 gives the regression details. The range of t_o varied at different clothing level. As shown in Table 4, I_{clo} at 0.4-clo level corresponds with higher operative temperatures while I_{clo} at 2.2-clo level is related with lower operative temperatures. The regressions are only applicable within the limited range of operative temperature.

At both ends of clothing level (0.4-clo and 2.2-clo levels), the mean thermal sensation (MTS) of occupants was sensitive to the change of operative temperature with the high slope of 0.118 and 0.140, respectively. The slopes of other linear regressions were in the range between 0.008 and 0.009, indicating a slight decrease of the sensation sensitivity to the variation of t_o.

Neutral temperature (t_n) was regarded as the temperature when people votes “0”. There was a similar t_n among a wide range of clothing (0.4 - 1.9 clo), as the regression lines of the six clothing levels intersected with the reference line “MTS = 0” at the range from 20 °C to 22 °C. However, t_n for 2.2 - clo level (the calculated value is 25.4 °C) is unreasonable since the regression is built on the condition of to less than 22 °C. The correlation between MTS and t_o will change at a higher temperature when occupants wear such thick clothes.

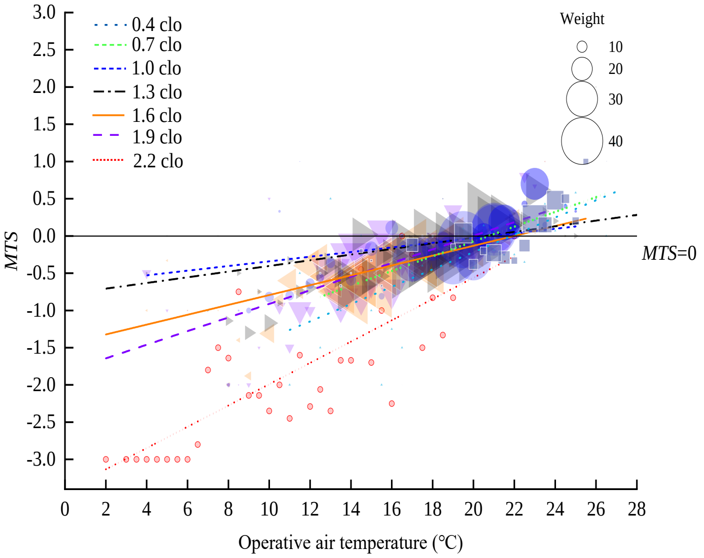


Figure 5. Mean thermal sensation (MTS) along with operative air temperature in different clothing insulation

Table 4. Weighted linear regression in different clothing insulation

I_{clo}	t_o (°C)	Coef. ^{a}	Int. ^{b}	R^2	t_n (°C)	Sig. ^{c}
0.4	[11.0-27.0]	0.12	-2.62	0.55	22.2	**
0.7	[12.5-26.5]	0.09	-1.82	0.49	20.9	**
1.0	[8.0-25.0]	0.09	-1.70	0.62	20.0	**
1.3	[4.0-31.5]	0.08	-1.66	0.69	20.0	**
1.6	[4.0-25.5]	0.08	-1.73	0.64	21.1	**
1.9	[4.0-23.5]	0.09	-1.83	0.49	20.1	**
2.2	[2.0-22.0]	0.14	-3.56	0.51	-	**

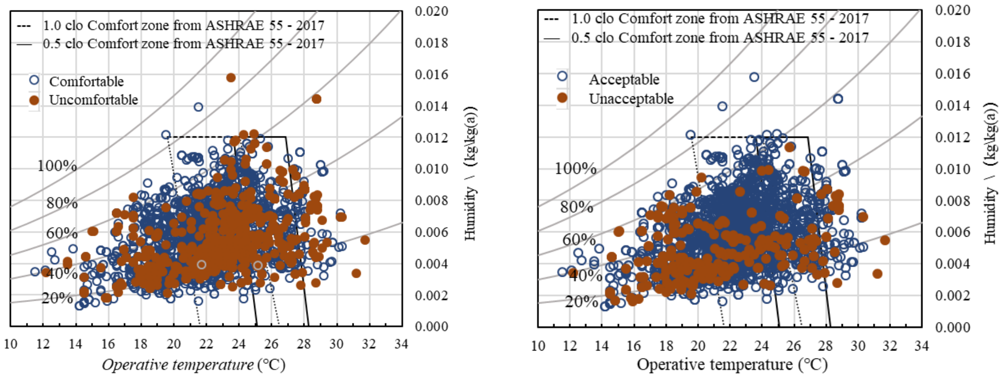
a. Coefficients of the weighted linear regression.
b. Intercept of the regression.
c. Significance of the model. ** means “$p \leqslant 0.01$”.

3.4 Thermal preference in different climatic zones

There are many uncertainties that differentiate thermal comfort from thermal sensation, such as cultural and psychological factors. In such a case, there may be a discrepancy of thermal environment required by thermal sensation vote and thermal comfort vote. A comparison between the required environments was conducted to study the influence of non-thermal factors.

It is suggested that comfort shall be evaluated using votes on the thermal sensation (TSV) and/or acceptability (TAV) scales in ASHRAE-55 standard. Moreover, thermal sensation votes on seven-point scale between -1.5 and +1.5, inclusive, shall be regarded as “comfortable” observed during the survey period. Acceptability votes between 0.1 (slightly acceptable) and 1 (very acceptable), inclusive, shall be labelled as “acceptable”. Under the division principle, the maps of “comfortable” and “acceptable” points were drawn in the graphic 0.5/1.0-clo comfort zone of ASHRAE-55 standard. The result of the severe cold (SC) zone was taken as an example due to the limited space, as shown in Figure 5. Except for the points out of the 0.5/1.0-clo comfort zone, there are still plenty of “uncomfortable” points located in the comfort zone. However, there were less amounts of “unacceptable” scatters and they mainly concentrated in the region below the comfort zone. From the opposite view, it can be indicated that people accept a wider range of thermal environments than that required by thermal sensation. That is, even though people vote “warm” which is out of the comfort range, they may accept the current environment. This again shows a high tolerance to the environment in the field situation, for people have adjustable methods when they feel “cool” or “warm”.

It can be also seen that there are a large number of “comfortable” scatters that stayed in the “0.5-clo comfort zone” (solid line frame) with relatively high operative temperatures. It is an energy waste to sustain the winter thermal environment in the summer comfort zone, since more heating supply was required. Accordingly, it is recommended to lower the temperature for heating in winter in SC zone to maintain the points at 1.0-clo comfort zone. The scatter map illustrates a considerable overlap of points between “comfortable/acceptable” and “uncomfortable/unacceptable” status, indicating that people vote differently when they are exposed to the same thermal environment. To eliminate the interferences of individual characteristics, thermal environments should be evaluated through a certain voting proportion by a group of people rather than an individual vote.



(1) Thermal sensation (2) Thermal acceptability

Figure 6. Operative temperature distinguished by (1) Thermal sensation, (2) Thermal acceptability in SC zone

4. Discussions

4.1 Neutral thermal environments in different climatic zones

As shown before, there were significant discrepancies in both indoor and outdoor thermal environments as well as the daily clothing of people between climatic zones. The various external surroundings cause different physiological and psychological responses inside the human body. The preferred thermal environments were different for occupants in different climatic zones.

To obtain the thermally neutral range of operative temperature, transition curves with “neutral and cooler” and “neutral than cooler” were drawn based on the logistic regression. Since the clothing level may influence the preference of indoor air temperature, the regression was only established within 1.0-clo garment. Figure 7 presents the transition curves delineating the neutrality zone of operative temperature (t_o) in national zones and individual zone respectively. The samples in the Hot summer and warm winter (HSWW) region and temperate region were small, where indoor air temperatures of the investigated rooms varied in a narrow range. The neutral temperature ranges of the two climatic regions were not presented.

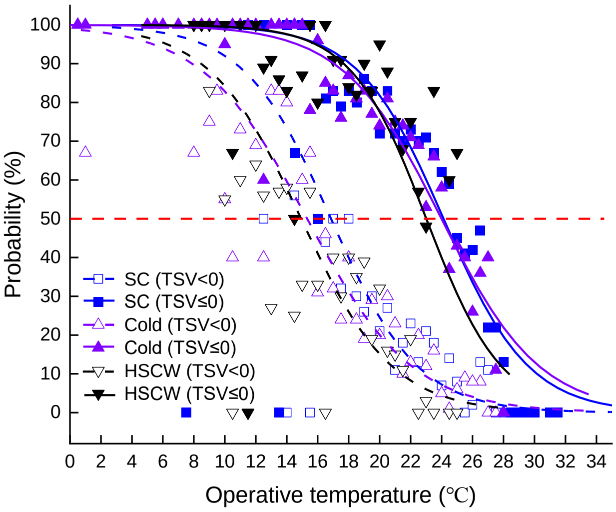


Figure 7. Transitional curves for neutral range of operative temperature in 1.0-clo garment in three climatic zones

As shown in Figure 7, the distance between the “cooler than neutral” curve (TSV < 0) and the “neutral and cooler” curve (TSV ≤ 0) at the probability of 50% was considered as the neutral temperature range. The width of a neutral range could be conceived as an indication of the extent of tolerance, which may vary between the various climatic regions. It is noticeable that there are considerable data from rural areas of the cold region, where individual private heating was adopted and indoor air temperature varied greatly. Thus the neutral scope of t_o (15.4 - 24.0 °C) was also expanded. The upper limit of the neutral range (23.1 °C) in HSCW zone was a bit lower than that of the other climatic zones. The temperature difference of 1 °C indicates the occupants’ adaptability to coldness when there is no indoor central heating system. The “cooler than neutral” curves of Cold and HSCW zones were almost identical and the threshold of the transaction from “cooler than neutral” to “neutral and warmer” was around 15 °C in both climatic zones. The lower threshold (17°C) for SC zone was slightly higher as occupants are living in heated rooms. In this perspective, it is reasonable for the heating design temperature of 18 °C when people were in 1.0-clo garments. However, the value was below the comfort region in ASHRAE-55 standard. In the surveyed buildings, occupants could take measures to adjust themselves to the thermal environment, e.g., drinking hot water, doing warming exercises, etc. They accept a relatively cool environment. It is suggested for building designers to provide chances for residents’ self-adaptability to the environments, e.g., set the value of t_a at the lower limit of the thermal comfort zone to actuate occupants to actively adapt to the environment. It was found (Ning et al., 2016) that 8% of heating energy would be saved in winter, if the indoor air temperature was modified from 24.3 °C to 20.7 °C. Therefore, a lower heating design temperature could not only improve human adaptability, but could also help reduce carbon dioxide emission.

4.2 Thermal preference in different clothing insulation

As mentioned before, occupants adjusted their clothing to maintain comfort states and they may have different preferences of thermal environments in different clothing levels. Variance analysis was conducted on the operative temperature between a thermally neutral state and all conditions. As shown in Table 5, there is no significant difference of operative temperature between the low clothing level of “1” and “2”. This suggests that the operative temperature played a little role in the neutral thermal sensation at this state. However, when people were dressed in higher clothes (levels of “3-7”), operative temperature for neutral states was significantly higher than that in all conditions, indicating that increasing operative temperature contributes to the thermal neutrality. A significant decrease of t_n was found at clothing level “7” (2.2 clo), with the mean value of 13.4 °C. When the t_n of all clothing level was reordered, the median value was 18.6 °C. The number of t_n exceeding 18.6 °C declined sharply with the increase of clothing. People can achieve the thermal neutrality in the cold environment by wearing thick clothes. This indicates a behaviour adjustment and psychological adaption in the field environments.

Table 5. Difference of operative temperature between thermally neutral state and all conditions

Clothing level	1	2	3	4	5	6	7
	0.4 clo	0.7clo	1.0 clo	1.3 clo	1.6 clo	1.9 clo	2.2 clo
Δ t_o (°C)	0.0	0.2	0.5	0.6	0.9	1.0	1.4
Significance	-	-	*	**	**	**	**

In addition, a comparison of TSV and TAV was made between different clothing levels. The results were shown in Figure 8.

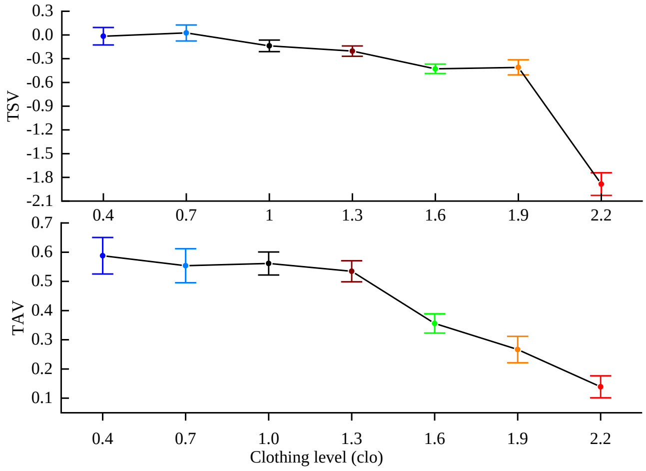


Figure 8. Comparison of TSV/TAV in different clothing

Although a significant decline of the thermal sensation was merely found in clothing level of “2.2 clo”, the thermal acceptability decreased significantly when the clothing level exceeded the level “4” (1.3 clo). This indicates that adding clothing insulation compensates for the decrease of indoor temperature, but the thermal acceptability still decreases. The compensation is limited when clothing insulation exceeds 1.3 clo. It is inconvenient for occupants to do indoor tasks in thick clothes, which causes the discomfort. However, the mean votes in all clothing levels were more than 0.1 (slightly acceptable), indicating an acceptability of the environments as a whole. Based on the analysis above, a maximum clothing insulation of 1.9 clo is suggested for winter conditions.

5. Applications

For engineering purposes, the “comfort” sensation should be converted to and expressed in measurable, physical quantities. This is facilitated using the acceptable limit of operative temperature. Neutral temperature ranges at 1.0 - clo garments were shown in the three climatic zones. This provides recommendations for indoor environment design in heating seasons. The acclimation of human beings to the environments should be considered and lower temperature for heating supply is encouraged. People actively adapt to the environment. Though adding clothes is effective for occupants to protect themselves from cold, the effect is missing when clothing insulation exceeds 1.9 clo. Allowing the adjustable range of clothing can not only improve occupants’’ thermal states, but also contribute to building energy efficiency.

6. Conclusions

This study discussed the thermal environment, thermal comfort and clothing behaviours of occupants based on the Chinese thermal comfort database in the five zones: Severe cold (SC), Cold, Hot summer and cold winter (HSCW), Hot summer and warm winter (HSWW) and Temperate areas. Conclusions can be drawn as follows.

(1) Indoor operative temperatures (t_o) in Severe cold area and Cold area were much higher than that in Hot summer and cold winter zone (HSCW) and Temperate zone in winter, while the difference of neutral operative temperature between climatic zones became smaller. The neutral operative temperature in HSCW (17.8 °C) zone and Temperate (15.8 °C) area were significantly higher than the mean operative temperature for all conditions (HSCW: 16.7 °C, Temp: 13.6 °C).

(2) The mean clo-value concentrated around 1.0 clo in most climatic zones. The distribution of clothing insulation was widest in Hot summer and cold winter (HSCW) zone, with the mean value of 1.36 clo. The clothing insulation in this region was studied and it was found that the neutral temperatures at the clothing level of 0.4 – 1.9 clo were all converged in the range from 20 °C and 22 °C.

(3) From the map of operative temperature distinguished by thermal sensation and thermal acceptability in severe cold (SC) zone, it is indicated that people accept a wider range of thermal environments than that based on thermal sensation. It is recommended to lower the temperature for heating in winter to maintain the thermal environments at the winter comfort zone. Since people may vote differently when they are exposed to the same thermal environment, thermal environments should be evaluated through a certain voting proportion by a group of people rather than an individual vote.

(4) The neutral temperature ranges for occupants in 1.0-clo garments were [17.0 - 24.1 °C] in Severe cold zone, [15.4 - 24.0 °C] in Cold zone and [15.0 - 23.1 °C] in Hot summer and cold winter zone. Adding clothing insulation of Hot summer and cold winter zone compensates for the decrease of indoor temperature, but the effect is missing when clothing insulation exceeds 1.9 clo. It is suggested to allow the adjustable range of clothing when designing indoor thermal environments, which can not only achieve thermal comfort of occupants, but also contribute to building energy efficiency.

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8. Appendices

Table A. Regression results of the transition curves with and “neutral than cooler” (TSV<0) and “neutral and cooler” (TSV≤0)

Zones	Formula[a]
Severe cold	$\mathbf{P(TSV < 0) = \frac{100\,exp(6.02 - 0.35}\boldsymbol{t_{op}}\mathbf{)}}{\mathbf{1 + exp(6.02 - 0.35}\boldsymbol{t_{op}}\mathbf{)}}$
	$\mathbf{P(TSV \leq 0) = \frac{100\,exp(8.80 - 0.36}\boldsymbol{t_{op}}\mathbf{)}}{\mathbf{1 + exp(8.80 - 0.36}\boldsymbol{t_{op}}\mathbf{)}}$
Cold	$\mathbf{P(TSV < 0) = \frac{100\,exp(4.54 - 0.30}\boldsymbol{t_{op}}\mathbf{)}}{\mathbf{1 + exp(4.54 - 0.30}\boldsymbol{t_{op}}\mathbf{)}}$
	$\mathbf{P(TSV \leq 0) = \frac{100\ exp(7.59 - 0.32}\boldsymbol{t_{op}}\mathbf{)}}{\mathbf{1 + exp(7.59 - 0.32}\boldsymbol{t_{op}}\mathbf{)}}$
Hot summer and cold winter	$\mathbf{P(TSV < 0) = \frac{100\ exp(5.08 - 0.34}\boldsymbol{t_{op}}\mathbf{)}}{\mathbf{1 + exp(5.08 - 0.34}\boldsymbol{t_{op}}\mathbf{)}}$
	$\mathbf{P(TSV \leq 0) = \frac{100\ exp(9.48 - 0.41}\boldsymbol{t_{op}}\mathbf{)}}{\mathbf{1 + exp(9.48 - 0.41}\boldsymbol{t_{op}}\mathbf{)}}$

Note: a - All regressions were fitted well with the R-square of more than 0.90. Moreover, coefficients of the regression models were statistically significant.

References

ASHRAE Standard 55-2017. Thermal environmental Conditions for Human Occupancy. American Society of Heating Refrigerating and Air-Conditioning Engineers. Georgia, Atlanta.

Building Energy Research Center (BERC), tsinghua University, 2018. China Building Energy Use 2018. https://berc.bestchina.org/?ky/article250/92.html.

De Carli, M., Olesen, B. W., Zarrella, A., Zecchin, R., 2007. People's clothing behaviour according to external weather and indoor environment. *Building and Environment*, 42(12), pp 3965-3973.

De Dear R, Brager G.S., 1998. Developing an adaptive model of thermal comfort and preference. *ASHRAE Transactions*, 104, pp 1-18.

De Dear, R., Xiong, J., Kim, J., Cao, B., 2020. A review of adaptive thermal comfort research since 1998. *Energy and Buildings*, 214, 109893.

GB 50176-2016. Code for thermal design of civil building. Ministry of Housing and Urban-Rural Development of the People’s Republic of China (MOHURD). Beijing. (in Chinese)

Humphreys, M. A., Hancock, M., 2007. Do people like to feel ‘neutral’?: Exploring the variation of the desired thermal sensation on the ASHRAE scale. *Energy and buildings*, 39(7), pp 867-874.

Humphreys MA, Rijal HB, Nicol JF, 2013. Updating the adaptive relation between climate and comfort indoors; new insights and an extended database. *Building and Environment*,63, pp 40-55.

Hwang RL, Lin TP, Cheng MJ, Chien JH, 2007. Patient thermal comfort requirement for hospital environments in Taiwan. *Building and environment*, 42(8), pp 2980-2987.

IPCC. Climate Change 2007, In: Solomon S, et al., editors, The physical science basis. Contribution of the working group I to the fourth assessment report of the intergovernmental panel on climate change, Cambridge.

ISO Standard 7730, Ergonomics of the thermal environment- Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria, International Standards Organization, Switzerland, 2005.

Lancaster A, Cox DR, 2018. Analysis of Binary Data. 2nd edition. New York: Routledge.

MOHURD, Standard of test methods for thermal environment of building (JGJ/T 347-2014), Ministry of Housing and Urban-Rural Development (MOHURD), Beijing, China, 2014.

Ning H, Wang Z, Ji Y, 2016. Thermal history and adaptation: Does a long-term indoor thermal exposure impact human thermal adaptability? *Applied Energy*, 183, pp 22-30.

Nikolopoulou, M., Lykoudis, S., 2006. Thermal comfort in outdoor urban spaces: analysis across different European countries. *Building and environment*, 41(11), pp 1455-1470.

Schiavon, S., Melikov, A. K., 2008. Energy saving and improved comfort by increased air movement. *Energy and buildings*, 40(10), pp 1954-1960.

Su X, Wang Z, Zhou F, Duanmu L, Zhai Y, Lian Z, et al., 2022. Comfortable clothing model of occupants and thermal adaption to cold climates in China. *Building and environment*, 207, 108499.

Taleghani, M., Tenpierik, M., Kurvers, S., Van Den Dobbelsteen, A., 2013. A review into thermal comfort in buildings. *Renewable and Sustainable Energy Reviews*, 26, pp 201-215.

Toe, D. H. C., Kubota, T., 2013. Development of an adaptive thermal comfort equation for naturally ventilated buildings in hot–humid climates using ASHRAE RP-884 database. *Frontiers of architectural research*, 2(3), pp 278-291.

Wang, Z., 2006. A field study of the thermal comfort in residential buildings in Harbin. *Building and Environment,* 41(8), pp 1034-1039.

Winslow, C. E., Herrington, L. P., Gagge, A. P., 1937. Physiological reactions of the human body to varying environmental temperatures. *American Journal of Physiology-Legacy Content*, 120(1), pp 1-22.

Xie, Y., Liu, J., Huang, T., Li, J., Niu, J., Mak, C. M., & Lee, T. C., 2019. Outdoor thermal sensation and logistic regression analysis of comfort range of meteorological parameters in Hong Kong. *Building and Environment*, 155, pp 175-186.

Yan, H., Mao, Y., Yang, L., 2017. Thermal adaptive models in the residential buildings in different climate zones of Eastern China. *Energy and Buildings*, 141, pp 28-38.