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Thermal responses of the elderly in naturally ventilated dwelling houses during winter in rural Xi'an, China

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Abstract. A well-designed indoor thermal environment in winter not only meets the thermal comfort demands of the elderly, but also reduces their health risks. However, the thermal performance of residential buildings for the elderly in rural Xi'an, China, is poor, with no central heating system, and the quality of the thermal environment needs to be improved. Due to the lack of thermal comfort benchmarks that meet the thermal preferences of the elderly in rural areas, this study will address this issue through conducting a field investigation. 161 elderly people from 8 villages volunteered to participate in the survey. A clothing regulation model was established, which found that the sensitivity of the thermal resistance of their clothing to temperature changes was low. Additionally, a thermal sensation model was established, and the neutral temperature was calculated to be 11.3°C. The 80% and 90% acceptable lower limits were calculated to be 6.5°C and 8.2°C, respectively. When the indoor operative temperature was lower than 11.3°C (neutral temperature), an average of 78% of the elderly expected a slightly warmer environment, and when it was higher than 11.3°C, an average of 72% expected no change. The results of the study can be used as a basis for the design and improvement of the thermal environment of rural elderly living in cold regions of China.

1 Introduction

With aging, the elderly generally begin to deteriorate in terms of body functions, which is more obviously manifested in organ aging, body regulation, resistance, etc. [1], and reduced sensitivity to environmental hot and cold changes. There is a clear relationship between the health of the elderly and the hot and cold changes in the environment, especially those suffering from cardiovascular and cerebrovascular diseases are most susceptible to the effects of environmental temperature [2]. Since elderly people spend at least 80% of their time indoors, those with limited mobility even spend up to 95% of their time indoors [3]. Therefore, well-designed indoor thermal environments in winter can not only meet the thermal comfort requirements of the elderly, but also reduce their health risks.

According to the data of the seventh population census, the proportion of the population aged 60 and above in China is 18.7% of the total population, and nearly 60% of the elderly live in rural areas. It is expected that in 2050, the proportion of the elderly population in China will account for 35.1% of the total population [4]. The development of China's rural areas is relatively backward. With the change of the traditional family structure in rural areas, the degree of aging continues to deepen, making the traditional rural living environment can not keep up with China's economic and social development. Rural housing construction is mainly spontaneous, there is no unified construction design standards, its own spatial layout, structural features can not meet the high quality of life of the elderly home care needs [5], the quality of the thermal environment of residential life is poor. Compared with urban residents, rural residents have been living in rural environments for a long time, with higher thermal tolerance [6] and lower psychological expectations [7]. However, most of the established studies on the thermal environment and thermal comfort of residential living for the elderly are mostly focused on addressing urban elderly care institutions, and there is an extreme lack of relevant studies for rural elderly, resulting in unclear adaptation patterns to the thermal environment and thermal comfort needs of the elderly.

Therefore, this study takes the elderly in rural areas of Xi'an, China, as the research object, and carries out on-site research on the indoor thermal environment and thermal comfort of the elderly in winter, and intends to establish the relationship between the subjective responses of the elderly such as thermal sensation, thermal acceptability, and thermal expectation, and the objective parameters of the thermal environment, so as to obtain the adaptive thermal comfort law and thermal comfort needs of the elderly in winter. The research results can provide data support for the creation of a comfortable and healthy thermal environment for the elderly in rural areas, and promote the sustainable development of rural pension buildings.

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2 Methods

2.1 Climatic context of Xi’an, China

The city of Xi'an has a warm-temperate semi-humid continental monsoon climate with four distinct seasons, a mild climate and moderate rainfall, with an average annual temperature of about 15°C and an annual precipitation of 500-750 mm. Xi'an has cold, foggy winters with little rain or snow, with an average temperature of 2.3°C and an average relative humidity of 65%.

2.2 Field investigation

This study was conducted in January-February 2024 in eight villages in Chang'an District, Xi'an City, including Guo Village, Song Village, Shangcao Village, Xiacao Village, and so on .The thermal comfort and winter indoor thermal environment of the elderly were investigated using a combination of subjective thermal comfort questionnaires and on-site measurements of objective thermophysical environmental parameters, with the elderly aged 60 years or older in rural areas of Xi'an as the study subjects.

The research subjects were the elderly aged over 60 years old in rural areas of Xi'an, and a total of 161 valid data were obtained in the winter research, of which 84 were males and 77 were females. The statistical results of the basic information of the interviewed elderly , such as gender, age, height, weight, clothing thermal resistance, and metabolic rate, are shown in Table 1.

Table 1. Background information of respondents.

Gender	Parameters	Min.	Max.	Mean	S.D.
M: 84	Age / yr	60	85	71.86	7.39
	Height / cm	160	187	169.49	5.99
	Weight / kg	50	95	67.79	8.07
F: 77	Age / yr	60	78	67.07	4.92
	Height / cm	150	170	159.49	3.52
	Weight / kg	46	81	64.55	9.82

The Thermal Comfort Questionnaire included not only basic information such as gender, age, height, weight, metabolic rate, and clothing thermal resistance of the older adults interviewed, but also thermal sensation (TSV), thermal acceptability (TA), and thermal expectation (TP) of the thermal environment in which the respondents were located. These subjective thermal responses were tallied according to Table 2.

Indoor thermal environment parameters were tested using a Delta HD32.3 thermal index meter, in parallel with the subjective thermal comfort questionnaire survey. The instrument was placed at a height of about 1.5 metres above the ground and within 1 metre of the respondent during the test. Air temperature (t_a), relative humidity (RH), black globe temperature (t_g) and air velocity (v_a) were recorded simultaneously during the questionnaire. The testing apparatus complied with ISO7726-2002 sensor measurement range and accuracy requirements. In addition, observations and recordings were made of the heating measures in the spaces where the interviewees were located, which included the use of electric blankets, Chiese kang, electric fans, and so on.

The statistical results of indoor air temperature (t_a), relative humidity (RH), black globe temperature (t_g) and air flow rate (v_a) during the survey period are shown in Table 3, including the results of statistical analyses of the minimum, maximum, mean and standard deviation of each parameter.

Table 2. Occupants’ subjective sensations rating scales.

Scale	Thermal sensation	Thermal acceptability	Thermal preference
+3	Hot	-	-
+2	Warm	Very acceptable	-
+1	Slightly warm	Just acceptable	Want warmer
0	Neutral	-	No change
-1	Slightly cool	Just unacceptable	Want cooler
-2	Cool	Very unacceptable	-
-3	Cold	-	-

Table 3. Summary of indoor thermal environmental parameters in survey period.

Parameters	Min.	Max.	Mean	S.D.
t_a /℃	3.9	15.9	9.58	3.43
RH / %	26.2	84.0	53.38	15.92
t_g/ °C	4.0	23.7	9.90	4.19
v_a/ m/s	0.00	0.45	0.04	0.07

3 Results and analysis

3.1 Clothing adjustment

Clothing regulation is one of the behavioural modifications to maintain human thermal comfort in different climatic conditions [8]. During the research, the thermal resistance of a single garment was taken according to ISO9920 [9], and the thermal resistance of the full set of garments was calculated according to the relevant formulae. The statistical results show that the average clothing thermal resistance of the elderly in rural Xi'an in winter is 1.53 clo. Figure 1 demonstrates the relationship between I_{cl} and t_{op}, and the linear regression equation is shown in equation (1). The slope of the linear regression equation is -0.02, indicating that when the indoor operating temperature increases by 1°C, the thermal resistance of the garment decreases by 0.02clo.

$$I_{cl}=-0.02t_{op}+1.708,\ R^2=0.567 \quad (1)$$

Compared with the clothing regulation law of urban elderly in Xi'an (I_{cl} =-0.0121t_{op} +1.7049, R^2 =0.0139) [3], the clothing thermal resistance of rural elderly is more sensitive to changes in temperature. After the field research, it was found that most of the urban areas have centralised heating or turn on the air conditioner to warm up in winter; while there is no centralised heating in the rural areas in winter, and most of their heating measures are using electric blankets and electric fans, and the

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quality of the indoor thermal environment is worse, so the rural older people are more sensitive to low temperatures, and they mostly regulate their clothing to maintain their own thermal comfort.

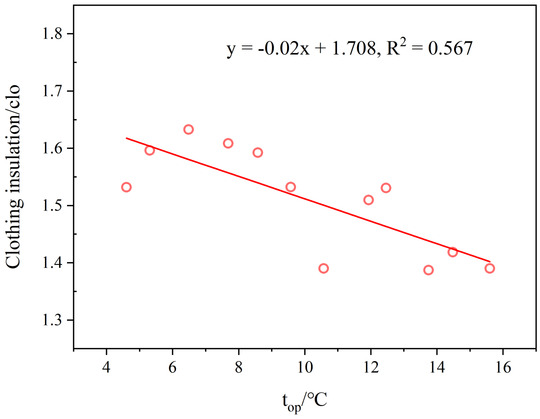

Fig. 1. Correlations between clothing insulation and indoor operative temperature.

3.2 Thermal sensation and neutral temperature

The indoor operating temperature is used as a thermal environment evaluation index to describe the human thermal sensation in the area. The thermal sensation of the elderly and the indoor operating temperature were fitted and analysed, and the result is shown in Figure 2, and the linear regression equation is shown in equation (2). The regression coefficient of the fitted equation of thermal sensation with t_{op} shows the degree of sensitivity of the human body to changes in ambient temperature, and the sensitivity coefficient of indoor is 0.186.

$$TSV = 0.186t_{op} - 2.104,\ R^2 = 0.827 \quad (2)$$

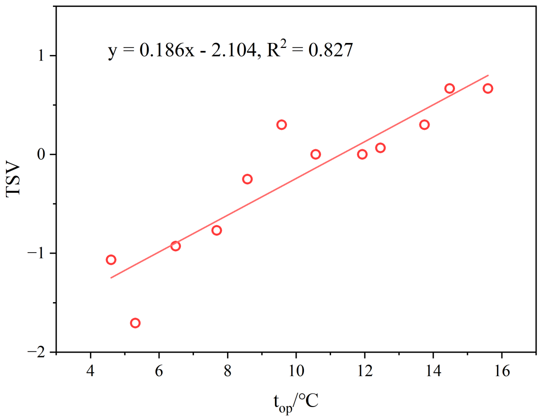

Fig. 2. Correlation between thermal sensation and indoor operative temperature.

Neutral temperature is the temperature at which the human body feels most comfortable with heat and cold, and directly responds to the thermal comfort needs of people when they feel comfortable. By making TSV = 0, the measured indoor neutral temperature in winter can be calculated to be 11.3°C. The neutral temperature in rural of Xi'an in winter is lower than that in urban Xi'an (the neutral temperature is 19.4°C) [3] and Shanghai (the neutral temperature is 16.7°C) [10]. On the one hand, this is due to the fact that rural elderly people in Xi'an have been living in unheated environments for a long time and have a low level of economic income, which leads to a lower level of psychological expectation of thermal environments; on the other hand, rural elderly people have a high thermal resistance to clothing as a whole, which leads to a high tolerance to cold. These factors result in a neutral temperature for rural older people that is both different from that of urban older people in the same region and different from that of older people in other climatic zones.

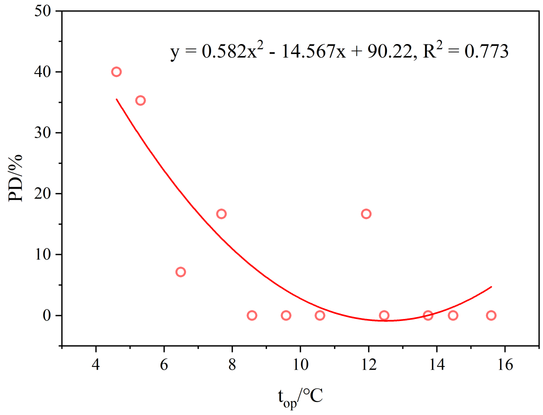

Fig. 3. Correlation between dissatisfied percentage (PD) and indoor operative temperature.

3.3 Thermal acceptability

Thermal acceptability (TA) refers to the psychological state of being able to tolerate a hot environment. The temperature frequency method (Bin method) [11] was used to segment the t_{op} at 1°C intervals, and the percentage of "just acceptable (-1)" and "very unacceptable (-2)" votes in each temperature band to the total number of votes in that temperature band was counted to obtain the actual dissatisfaction rate (PD). The PD was fitted to t_{op} in Figure 3, and the regression equation is shown in equation (3).

$$PD = 0.582 \cdot t_{op}^{\ 2} - 14.567\ t_{op} + 90.22,\ R^2 = 0.773 \quad (3)$$

Making the PD equal to 20% and 10%, the lower limits of the indoor 80% and 90% acceptable temperature ranges are obtained as 6.5°C and 8.2°C, respectively. The lower limit value of winter thermal acceptability for the elderly in rural Xi'an is lower than that in urban Xi'an (14.9°C for 80% and 17.1°C for 90%) [3]. This phenomenon is closely related to the built environment and living habits, and rural elderly have adapted to the cold indoor environment without heating, so the lower limit of thermal acceptability is lower and the acceptability of the thermal environment is higher.

3.4 Thermal preference

Thermal expectation (TP) refers to an individual's expectation of a change in temperature. The percentage of each vote in each temperature band in the room was counted using 1°C as the temperature interval, and the statistical results are shown in Figure 4.When the indoor operating temperature is lower than 11.3℃ (neutral temperature), 78% of the people want "slightly warmer (+1)"; when the indoor operating temperature is higher than 11.3℃, 72% of the people choose "no change (0)". According to the largest proportion of people who voted "no change" in each temperature band, the satisfactory temperature range in winter is 13℃-14℃. However, in Xi'an, the temperature range for the urban elderly is 20°C-21°C in winter [3]. In contrast, the psychological expectation of the rural elderly for winter temperature is even lower.

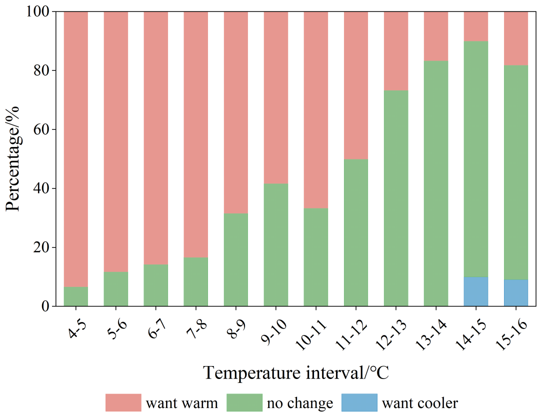

Fig. 4. Thermal preference ratio for different indoor operative temperature bins.

In summary, in view of the peculiar patterns of thermal adaptation of rural elderly, it is necessary to develop thermal comfort standards for rural elderly in order to guide the design and improvement of the thermal environment of residential buildings for the rural elderly.

4 Conclusions

In this paper, an in-depth study of winter adaptive thermal comfort for the elderly in rural Xi'an was carried out, and the following conclusions were formed:

(1) The average clothing thermal resistance of the elderly in winter is 1.52clo, which is linearly correlated with the indoor operating temperature, and when the indoor operating temperature increases by 1℃, the clothing thermal resistance decreases by 0.02.

(2) The winter thermal sensation of the elderly was linearly correlated with the indoor operating temperature, and the measured neutral temperature indoors in winter was 11.3°C, and the sensitivity coefficient of thermal sensation of the elderly with temperature change was -0.186.

(3) Indoor thermal acceptability of the elderly in winter was quadratically correlated with operating temperature, with the lower limits of the 80% and 90% acceptable indoor temperature ranges being 6.5°C and 8.2°C, respectively.

(4) An average of 78% of older people expect to be slightly warmer in winter (t_{op} < 11.3°C (neutral temperature)) and an average of 72% expect to be unchanged (t_{op} > 11.3°C).

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