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A Field Investigation on Summer Thermal Comfort of Occupants of Rural Houses in the North Area of Hot Summer and Warm Winter Zone, China

Xinzhi Gong [1], Yilei Yu [2], Sha Lai [3], Xingping Wang [3], Xuman Duan [3], Jing Liu [4] and Wei Wang [5,*]

[1] Guangxi Key Laboratory of Green Building Materials and Construction Industrialization, School of Civil Engineering, Guilin University of Technology, Guilin 541004, China; gxinzhi@glut.edu.cn
[2] School of Geographical Sciences and Urban Planning, The College of Liberal Arts and Sciences, Arizona State University, Tempe, AZ 85281, USA; yileiyu@asu.edu
[3] School of Tourism & Landscape Architecture, Guilin University of Technology, Guilin 541004, China
[4] School of Civil Engineering, Guilin University of Technology, Guilin 541004, China
[5] School of Business, Guilin University of Technology, Guilin 541004, China
* Correspondence: wwlg@glut.edu.cn

Abstract: Human thermal comfort presents noticeable variation across urban and rural areas. Among previous studies, only a few field investigations focus on thermal comfort experienced by rural houses within hot summer and warm winter (HSWW) zones, especially across the north area. The existing thermal environment and energy-saving standards in China make it difficult to provide accurate guidance for building performance design in this area due to the lack of thermal comfort information for humans. This study undertook a field-based survey in rural houses in Hezhou, located in the northern part of an HSWW zone in China. Both on-site environmental data collection and subjective surveys were performed at the same time. Subsequently, this study examined the correlation of operative temperatures with subjects' perceptions of the thermal environment. Our findings indicate that the actual neutral temperature in summer was 25.34 °C, whereas the predicted value was 25.17 °C. Temperatures within the range of 21.69~30.55 °C were considered acceptable during the operation. The elderly had a higher thermal tolerance than the adults. There was no significant statistical difference between males and females. Our findings contribute to the ongoing development of thermal comfort research for rural housing.

Keywords: thermal comfort; field survey; thermal environment; rural house; the north area of hot summer and warm winter zone

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1. Introduction

The study of thermal comfort has gained significant attention in recent times [1]. As society advances and living standards rise, the demand for better indoor thermal conditions and greater comfort has grown. The high demand for a living thermal environment has led to a rapid increase in energy consumption for maintaining indoor temperatures, resulting in a significant rise in the operational energy usage of buildings [2]. During 2019, building operational energy consumption represented 21% of China's overall energy usage, and 43% of that energy was directed towards enhancing indoor thermal conditions [3]. Moreover, in China, rural housing energy usage contributed to 22 percent of the total energy used by buildings [4]. A significant increase could be expected with the development of the rural economy and the growth of the housing area. In the countryside, the majority of homes are self-constructed with a lack of scientific design, which causes high energy consumption

and poor indoor thermal conditions. Zhang [5] and Xiong [6] examined how indoor thermal conditions varied between buildings in both urban and rural regions of China. These studies found that rural buildings had an indoor temperature fluctuation of 8.0 °C, exceeding that of urban buildings by about 2 °C. The study also concluded that many rural structures did not adhere to the Chinese indoor environment standards [7]. Several findings have indicated influences on thermal comfort with obvious differences between urban and rural areas [8,9]. Rural residents are more adaptable than urban residents, as their tolerance for varying temperatures is generally broader. Wang [10] studied the thermal comfort of a coastal town in Qingdao, where people were found to be well-adapted to humid and hot conditions. Xu [11] and Fan [12] discovered that rural occupants who spend extended amounts of time in houses with inadequate thermal conditions may have a greater range of acceptable temperatures. However, assessing thermal comfort in rural locations lacks established standards [13]. This absence of standardized criteria in rural regions makes it difficult to apply the conclusions on thermal comfort from urban housing studies to rural homes [14]. Adopting thermal comfort criteria directly for rural houses could lead to significant energy inefficiencies [15]. Therefore, greater focus is needed to improve indoor thermal comfort and rural living conditions.

At present, the predicted mean vote (PMV) model, introduced in 1967 through Fanger's work, has been the predominant method for measuring and estimating thermal comfort perceptions [16]. To access indoor thermal conditions, global standards such as ISO 7730 [17], ASHRAE 55 [18], and EN16798 [19] have implemented the PMV. According to the model [20], the neutral temperature represents the ideal thermal comfort level when the human body feels no need for a change in temperature. At this time, the value of PMV is 0. However, it is a predictive model derived from laboratory data. It overlooks the human capacity to actively adjust to surroundings, along with the influence of some factors (geographic location, cultural variations, aging, etc.) on thermal comfort. Numerous researchers argue that residents' thermal comfort is influenced by factors such as local climate, building typology, and indoor conditions [21,22]. Additionally, variations in residents' thermal sensations differ across various age groups and genders [23,24]. Previous research has frequently demonstrated that the PMV differed from the observed thermal sensation vote (TSV). Residents tend to tolerate a broader temperature range in natural ventilating spaces compared to those in air conditioning spaces [25–28]. In rural areas, most households rely on natural ventilation, allowing residents to maintain their thermal comfort by either adjusting the window positions or modifying the clothing layers. For this reason, a PMV model has limitations in the study of rural houses. Over the past few years, there has been a growing body of studies on thermal comfort models applicable to Chinese structures utilizing natural ventilation. These have led to the development of new models and the publication of standards informed by national thermal comfort field survey data conducted in China. GB/T 50785–2012 [29] established thermal comfort evaluation guidelines for buildings across various climate regions; however, it did not consider rural occupants [14]. Pang et al. [30] demonstrated that the permissible temperature threshold obtained during the research process for rural residents within hot and humid regions in China became wider than those specified in the standards of GB/T 50785–2012 and ASHRAE 55-2020 [18].

With its extensive landmass, diverse climates, complex landforms, and huge economic and cultural disparities across regions, the thermal design code for civil buildings [31] categorizes China's climate across five zones: a hot summer and warm winter zone (HSWW), a hot summer and cold winter zone (HSCW), a severe cold zone (SC), a cold zone (C), and a mild zone (M). An HSWW zone refers to the area in which the average outdoor temperature of the coldest month exceeds 10 °C, while the hottest month's average outdoor temperature

ranges from 25 to 29 °C. It consists of northern and southern areas. The heating degree day based on 18 °C (HDD18) ranges from 500 to 700 °C in the north area, while it is below 500 °C in the south area of the HSWW zone. The HSWW zone usually experiences high temperatures and humidity in summers all year around, as well as short, cold winters (not even cold). Residential buildings in this zone need effective safeguarding against summer heat but no consideration for insulation in winter [32]. Cities and countryside in an HSWW zone are crucial to the economic transformation and liberalization of China. However, rural houses have serious power waste and uncomfortable indoor thermal environments because their envelopes perform poorly.

Studies regarding thermal comfort in residential buildings across China have covered multiple climate zones, such as SC zones [33–35], C zones [36–38], HSWW zones [39,40], HSCW zones [41–43], and M zones. Rural houses, in contrast to urban residences, feature a unique layout, spatial structure, cooling methods, and the ability to adapt to thermal conditions. At present, in HSWW zones, only a few studies have focused on rural dwellings, one of which is Sun et al. [44], undertaking a thermal evaluation of volcanic-rock dwellings in Haikou and comparing the thermal mechanism differences between volcanic-rock houses and modern houses. Yan et al. [45] also performed an on-site survey in a rural community in Beihai to investigate how temperature, humidity, and airflow collectively impact human thermal perception during summer.

In summary, thermal comfort surveys of buildings in HSWW zones in China are rare and mainly focus on public buildings and urban residential buildings. Current field studies on rural houses in HSWW zones have mainly concentrated on its southern areas, leaving the thermal comfort of rural homes within the northern part of HSWW zones unexamined. The existing thermal conditions and energy optimization standards of China make it difficult to provide accurate guidance for building performance design in this area, with a lack of thermal comfort information of local residents.

Hence, to deepen the understanding of the summer thermal comfort levels of rural residents within the northern region of an HSWW zone, this study conducts an on-site field investigation of contemporary rural homes in Hezhou, a typical city in this climate area. By exploring the indoor thermal conditions and comfort levels of residents in rural houses in this region, this research provides valuable references for evaluating and designing naturally ventilated rural housing within the north area of an HSWW zone. The findings contribute to the necessary theoretical framework for energy-efficient building design.

2. Methods and Materials

2.1. Study Area and Climates

The investigation was carried out in the naturally ventilated residential buildings in a rural region of Hezhou city, which is located in the east of the Guangxi Zhuang Autonomous Region (as shown in Figure 1), between E 111°05′–112°03′ and N 23°39′0″–25°09′0″. The location is in the northern area of an HSWW zone [32]. Hezhou experiences a subtropical monsoon climate characterized by strong solar radiation, a long frost-free period, and abundant rainfall. From 1981 to 2010, Hezhou experienced an average air temperature reaching 20.2 °C annually. The hottest month was July, averaging 28.6 °C, whereas January was the coldest, with an average of 9.3 °C. The annual mean rainfall recorded was 1561.7 mm. The monthly mean relative humidity is typically above 70% throughout the year. The monthly average outdoor relative humidity can reach as high as 81% in July and August, and the lowest relative humidity typically stands at 72% from October to December. During summer, with elevated heat levels, substantial humidity, sultry weather, and regular rainfalls, Hezhou's climate is well-defined. Figure 2 provides an overview of the meteorological data reflecting an average year for the region.

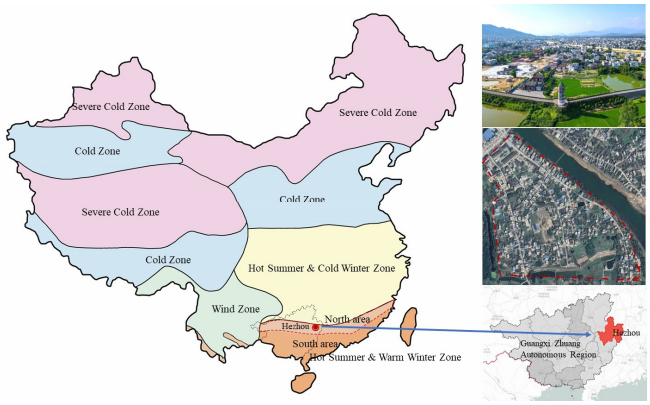


Figure 1. Research region.

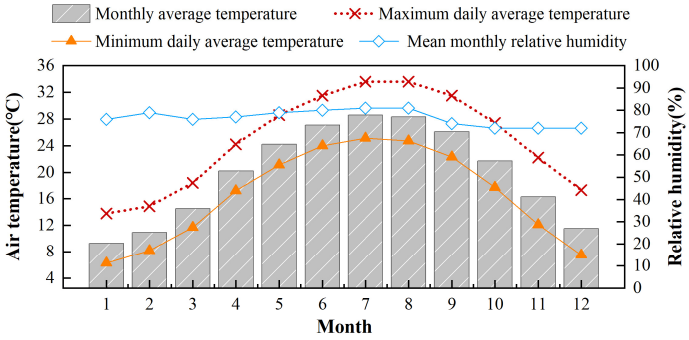


Figure 2. The meteorological data reflecting an average year of Hezhou.

2.2. Building Information

Han et al. [46] indicate that a house featuring 2 or 3 levels is the most common housing type in rural Hezhou. Through our on-site investigation, detached houses and townhouses (as shown in Figure 3), typically featuring 2 or 3 stories, were the predominant housing types in rural Hezhou, which aligns with the findings of the previous study [46]. These structures are mainly built with brick-concrete structures, with fired common brick walls measuring 240 mm in thickness. To enhance ventilation and airflow, these houses were designed with a relatively large number of doors and windows, which are often left open. The first floor generally has a height between 3.3 m and 3.6 m, with a living room, a dining room, a kitchen, and a bedroom for the old. The second floor's height is approximately 3 m, with some bedrooms. The top floor is mostly used for storage or remains unused.



(**a**) (**b**)

Figure 3. Typical rural houses in Hezhou. (**a**) Detached house; (**b**) Townhouse.

2.3. Time and Respondents

According to China's four seasons division method [47,48], a mean temperature exceeding 22 °C over five consecutive dates was considered the threshold for defining summer. Under these criteria, the period from 30 April to 29 October was defined as summer in Hezhou. The surveys were conducted during the hottest time of summer (from 28 July 2020 to 3 August 2020) and the dates before autumn beginning (from 25 October 2020 to 28 October 2020). The surveys were conducted every day between 8:00 AM and 8:00 PM.

Local residents in houses were randomly selected, ensuring they were in good health, had a residency for no less than 4 years, and were well-adjusted to the climate conditions. In this survey, older people were defined as 60 years or above. A total of 251 respondents from 98 households, ranging in age from 18 to 83 years, took part in the study, with a gender distribution of 55.4% female and 44.6% male. Among these 98 households, 38.78% were families with 3~4 members across two generations, while 39.8% consisted of three-generation families with 5~7 individuals. Smaller households of 1~2 members accounted for 15.31%, whereas only 6.12% comprised larger families with 8~10 individuals. Income distribution showed that 22.4% of families had a per capita annual income below CNY 6000 (USD 800), 63.3% earned between CNY 6000 and 15,000 (USD 800~2000), and 14.3% exceeded CNY 15,000 yuan (USD 2000). The respondents included 47 elderly males and 54 elderly females, alongside 65 adult males and 85 adult females aged 18~59. Due to higher engagement in household work, females had a metabolic rate 0.07 MET above that of males 20 min leading up to the questionnaire survey. Table 1 provides an overview of the participant's demographics. While conducting the questionnaire surveys with the selected residents, the indoor thermal conditions of houses were observed. In total, 98 rural houses were surveyed, of which 55 were townhouses, and 43 were detached houses. Among the respondents, 107 lived in detached houses, while 144 lived in townhouses.

Table 1. The overview of the participant's demographics in our study.

Gender	Total	Adult	Elderly		Age (Years)	Weight (kg)	Height (cm)	Living Time (Years)	Metabolic Rates (20 min Before Questionnaires) (met)
Male	112	65	47	Maximum	81.00	80.00	185.00	80.00	1.60
				Minimum	18.00	40.00	160.00	4.00	1.00
				Mean	51.79	67.63	173.58	52.92	1.22
				S. D.	17.23	7.52	5.11	17.48	0.28
Female	139	85	54	Maximum	83.00	70.00	175.00	90.00	1.60
				Minimum	18.00	40.00	150.00	22.00	1.00
				Mean	50.76	58.29	161.73	51.38	1.29
				S. D.	18.24	7.66	3.31	14.04	0.29

The questionnaire surveys and thermal assessments were conducted under naturally ventilated conditions, ensuring that air conditioning remained turned off. Participants received pre-survey guidance from the research team, which included explanations about the questionnaire format and the subjective evaluation scale. Those with higher education levels completed the survey independently, whereas respondents with less formal education or older participants received assistance through interviews. Each respondent was required to fill out the longitudinal questionnaire twice at minimum, ensuring an interval of more than 20 min between each attempt. Respondents were also instructed to stay indoors for a minimum of 15 min before answering questionnaires. The summer study yielded 502 valid responses. The survey was conducted by a group of graduate students who were well-versed in thermal-comfort-related theories and techniques and were led by college professors.

2.4. Questionnaires and Instruments

The questionnaire comprised

(1) Fundamental data regarding buildings and respondents, including aspects such as environmental surroundings, floor area, electric equipment, the thermal load, sunshading, solar energy utilization, demographic information (such as age, gender, weight, height, health status, clothing habits, and activity level), the duration of residence in Hezhou, household size, household earnings, and usual cooling strategies.
(2) Subjective assessments related to thermal conditions, including perceptions of temperature, humidity, air velocity, acceptability, and preference, with response scales ranging from 2 to 7 levels (Table 2).

Table 2. Survey questionnaire options.

Voting Scale	Thermal Sensation	Humidity Sensation	Wind Sensation	Thermal Preference	Wind Preference	Acceptability
−3	Cold	Very humid	Very still			
−2	Cool	Humid	Moderately still			
−1	Slightly cool	Slightly humid	Slightly still	Cooler	Less air movement	Unacceptable
0	Neutral	Neutral	Neutral	No change	No change	
+1	Slightly warm	Slightly dry	Slightly draughty	Warmer	More air movement	Acceptable
+2	Warm	Dry	Moderately draughty			
+3	Hot	Very dry	Very draughty			

This field study aimed to explore the thermal comfort in Hezhou's climate by monitoring outdoor environmental factors, including the outdoor air temperature (t_a) and relative humidity (RH), using a HOBO MX2300 series data logger with a resolution of 0.05% RH, 0.04 °C. Indoor conditions were assessed with an AZ8829S data logger (resolution RH 0.1%, 0.1 °C) and a ST733 anemometer. A globe thermometer with a 150 mm diameter and a 0.1 °C resolution was used to measure the globe temperature (t_g). Table 3 presents details of the measured parameters and the corresponding equipment following the ISO 7726 standard for physical measurements [49].

Table 3. Survey tools for monitoring.

Measurement Instrument	Parameter	Measuring Range	Accuracy	Resolution	Sampling Interval	Illustration
HOBO MX2300, USA	Outdoor temperature	−40 to +70 °C	±0.2 °C	0.04 °C	1 min	
	Outdoor RH	0 to 100%	±2.5%	0.05%	1 min	
AERMANDA AZ8829S, Taiwan, China	Indoor temperature	−40 to +85 °C	±0.6 °C	0.1 °C	1 min	
	Indoor RH	0 to 100%	±3%	0.1%	1 min	
SENTRY ST733, Taiwan, China	Air velocity	0 to 40 m/s	±0.03 m/s	0.01 m/s	1 min	
Juchuang JTSOFT-Meter JTR04, China	Globe temperature	−20 to 125 °C	±0.5 °C	0.1 °C	1 min	

The assessment for the indoor thermal conditions was conducted in accordance with ASHRAE 55 and GB 50785 standards. Measurements were carried out at a single location in an area under 16 m^2, while two location points were used for an area between 16 m^2 and

30 m^2, dividing the diagonal line into three equal sections. Larger areas exceeding 30 m^2 required measurements at three distinct location points. Equipment was properly calibrated before measurements and positioned away from heat sources, with measurements taken at 1.1 m above the floor at one-minute intervals [50]. To maintain accuracy, measuring devices were positioned in predetermined locations for 10 min to allow the readings to stabilize before being recorded.

2.5. Evaluation Index

Thermal comfort assessment is impacted by fluctuations arising from the mean radiant temperature (t_{mrt}) and the air temperature (t_a), as indicted by References [51,52]. Reference [53] highlights the inconsistency in the distribution of radiant temperatures across globe thermometers. To enhance accuracy, the use of an operative temperature (t_{op}), which synthesizes the impact of ta and t_{mrt} on human thermal experience, is advised. Equation (1) [18] provides the formula for calculating t_{op}:

$$t_{op} = A \times t_a + (1 - A) \times t_{mrt} \quad (1)$$

where t_{op} represents the operative temperature (°C); t_a denotes the air temperature (°C); t_{mrt} indicates the mean radiant temperature (°C); with A representing the average weighting coefficient between t_a and t_{mrt}.

On the basis of ISO 7726 [49], using the standard globe (D = 0.15 m, and ε_g = 0.95) under natural convection conditions, the t_{mrt} was calculated as in Equation (2):

$$t_{mrt} = \left[(t_g + 273)^4 + 0.4 \times 10^8 |t_g - t_a|^{\frac{1}{4}} \times (t_g - t_a) \right]^{\frac{1}{4}} - 273 \quad (2)$$

where t_{mrt} represents the mean radiant temperature (°C); t_g denotes the globe temperature (°C); t_a indicates the air temperature (°C).

The quantitative relationship of the thermal sensation vote (TSV) and indoor operative temperature is calculated as Equation (3). Weighted binned linear regression (binning t_{op} values into 0.5 °C intervals with weighting determined by the sample size of each group) is adopted in the present paper [54].

$$TSV = at_{op} + b \quad (3)$$

where a represents the degree of fluctuation in thermal sensation influenced by t_{op}, while b remains as constant value.

To determine whether clothing insulation distributions and thermal sensation votes remain consistent across various groups, a nonparametric Mann–Whitney U test is employed. To assess the association between two independent variables, with R^2 indicating the strength of linear regression models, the Pearson correlation analysis is conducted. The results confirm that all regression equations achieve statistical significance ($p < 0.001$) and exhibit a satisfactory fit ($R^2 > 0.5$). The SPSS 27.0 software is used for all statistical computations in this study.

3. Results

3.1. Thermal Environmental Conditions

The recorded indoor and outdoor parameters measured over the questionnaire periods are summarized in Table 4. The statistical data include the mean, minimum, and maximum values, as well as the standard deviation. The indoor air temperature ($t_{a,in}$) varied between 22.9 °C and 34.3 °C, with an average of 28.38 ± 2.97 °C. The maximum indoor relative

humidity (RH_{in}) was 89.1%, while the maximum outdoor relative humidity (RH_{out}) was 93.5%. Rural residents usually open windows to save air-conditioning electricity, resulting in unbearable indoor humidity. The outdoor air temperature ($t_{a,out}$) was between 23.46 °C and 34.5 °C during the survey period, with a mean value of 29.37 ± 2.59 °C. Most of the time, residents were in calm air, with the highest indoor air velocity of 0.6 m/s.

Table 4. Thermal physical variables during the questionnaire periods.

	Parameter	Mean	Maximum	Minimum	Standard Deviation
Indoor	$t_{a,in}$ (°C)	28.38	34.3	22.9	2.97
	RH_{in} (%)	62.25	89.1	44.4	8.91
	t_g (°C)	28.48	33.5	23.9	2.79
	t_r (°C)	28.51	34.27	23.5	2.81
	v_a (m/s)	0.06	0.6	0	0.14
	t_{op} (°C)	28.45	33.46	23.66	2.83
Outdoor	$t_{a,out}$ (°C)	29.37	34.5	23.46	2.59
	RH_{out} (%)	61.97	93.5	38.11	13.43

Confirming distinctions of thermal comfort in two typical houses, the variations in indoor thermal environment in townhouses and detached houses were counted, as shown in Figure 4. Regarding the $t_{a,in}$ and the globe temperature (t_g), the nearly identical values were monitored across townhouses and detached houses, even though the $t_{a,in}$ fluctuation was greater in townhouses. The average RH_{in} in townhouses and detached houses were 61% and 58.9%, respectively. There were no substantial differences discovered in the average RH_{in} across the spaces.

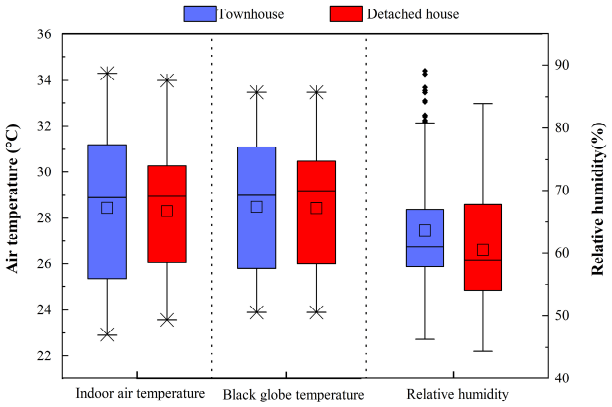


Figure 4. Variations of indoor thermal environment in townhouses and detached houses.

3.2. Clothing Insulation and Cooling Approaches

To cope with the thermal environment, rural residents commonly adjust their clothing. This study gathered clothing insulation (clo) data via surveys and computed them based on an ASHRAE 55 standard.

Figure 5 demonstrates the correlation of clothing insulation with indoor t_{op} as well as the corresponding linear regression findings. The insulation values ranged from 0.13 clo to 0.8 clo, with an average of 0.41 clo. In Figure 5, there is a clear pattern indicating that clothing insulation tended to decrease as t_{op} increased. When the t_{op} increased by 1 °C, the clothing insulation decreased by 0.0436. The Pearson correlation coefficient of 0.727 ($p < 0.001$) confirms a strong linear correlation between these two variables.

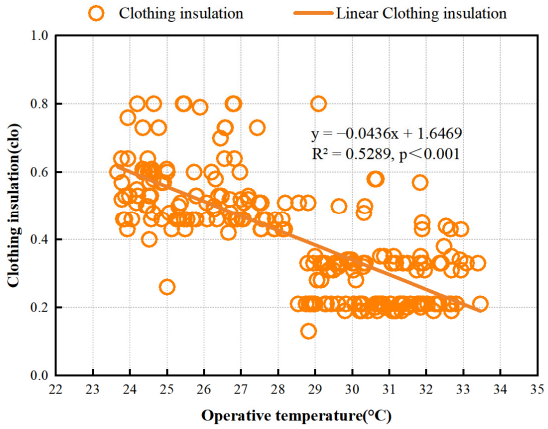


Figure 5. Correlation between clothing insulation and t_{op}.

To enhance thermal comfort, local rural residents adopt various cooling strategies to adapt to high temperatures. As shown in Figure 6, the most common cooling approaches are using electric fans (82.9%) and opening doors and windows (80.5%), indicating a strong reliance on cost-effective cooling solutions. Other strategies, in descending order, include using handheld fans (37.5%), drinking cold water (15.1%), using air conditioning (10.4%), taking cold showers (8.4%), and reducing clothing layers (3.2%). The large disparity between electric fan usage (82.9%) and air conditioning (10.4%) underscores a clear preference for cost-effective, energy-efficient cooling methods over more expensive technological options in rural Hezhou.

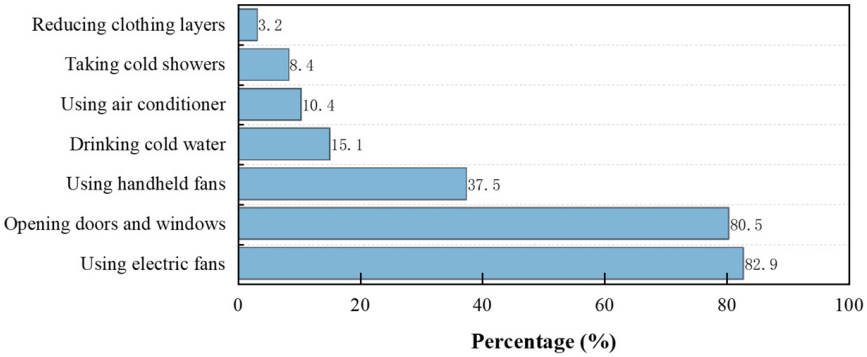


Figure 6. The percentage of common cooling approaches adopted by rural respondents.

3.3. Subjective Perceptions of Thermal Environment

This survey adopted thermal sensation votes (TSV), humidity sensation votes (HSV), and wind sensation votes (WSV) to respond to and evaluate comfortable temperatures, humidity, and ventilation that the subjects found in their houses. Table 3 shows that the ASHRAE thermal comfort scale was used here.

Figure 7 shows distributions of TSV, HSV, and WSV. Most respondents reported that a neutral thermal sensation and a neutral humidity sensation accounted for 65.5% and 79.1%, respectively. The sensation categories of (−1, 0, +1) are commonly associated with a comfortable state [55]. According to the survey findings, over 67% of the votes fell into the TSV comfort range, while only 53% fell into the WSV comfort range.

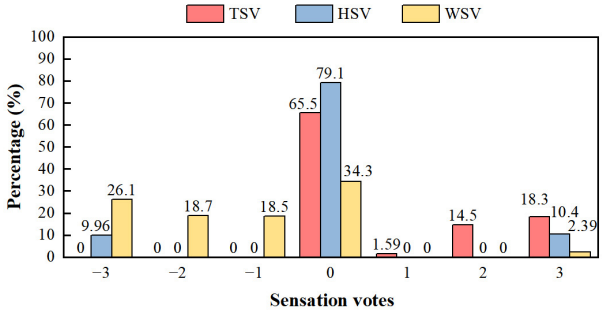
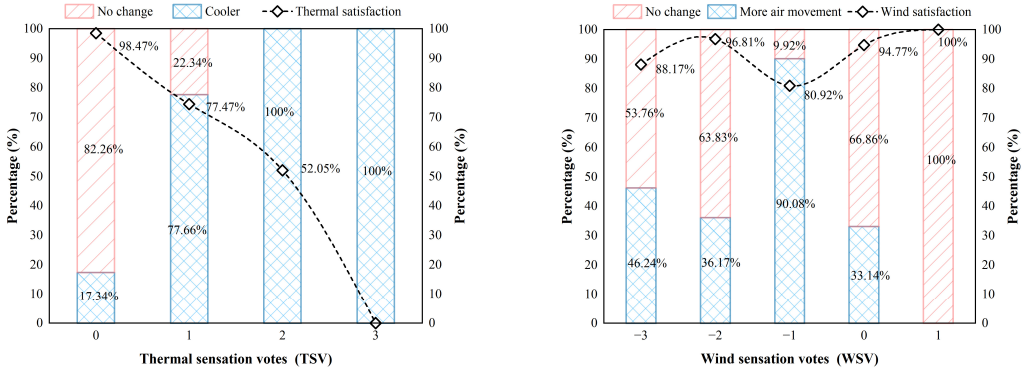


Figure 7. The percentage of respondents' TSV, HSV and WSV in rural houses in Hezhou.

Additionally, the crosstab relationships of sensation, preference, and acceptability in terms of thermal and wind sensation were analyzed, as shown in Figure 8a and Figure 8b, respectively. Figure 8a shows that among the subjects with a slightly warm thermal sensation, 77.47% accepted the current thermal environment, while 77.66% expected the current environment to be cooler, and 22.34% expected it to be warmer. Figure 8b shows that among the subjects with a very still and moderately still wind sensation, most of them accepted the current natural ventilation atmosphere.

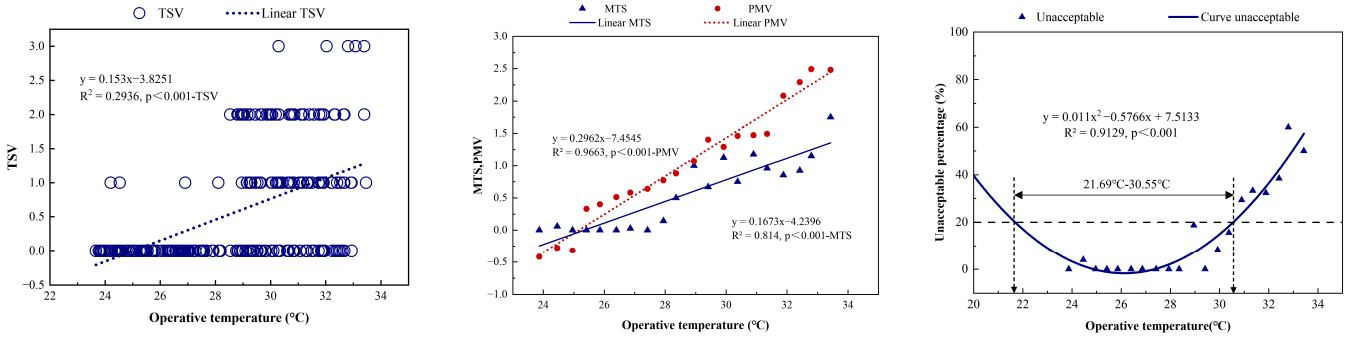


(**a**) (**b**)

Figure 8. Crosstab analysis of sensation, preference and acceptability. (**a**) Thermal; (**b**) Wind.

3.4. Thermal Comfort Evaluation Model

TSV is widely used and accepted as a field assessment of thermal comfort conditions. Figure 9a presents the findings on thermal sensation statistics and its relationship with the t_{op}. As the Pearson correlation coefficient stands at 0.544, the plot reveals a limited linear correlation between TSV and t_{op}.



(**a**) (**b**) (**c**)

Figure 9. Respondents' thermal comfort evaluation models. (**a**) TSV; (**b**) MTS and PMV; (**c**) PPD.

In this study, to obtain a high linear correlation, by employing the temperature frequency method, the t_{op} was partitioned into several intervals at 0.5 °C increments [56]. The independent variable in the analysis was the mean temperature for each interval, whereas the dependent variable was the corresponding mean thermal sensation (MTS) vote, as shown in Figure 9b. Additionally, the PMV of each response was calculated by the python3.11calculation program based on the evaluated parameters of thermal conditions, clothing insulation levels, and metabolic activity rates. Figure 9b also shows the relationship between PMV and t_{op}. By unary linear fitting of the MTS and PMV with t_{op}, the corresponding regression equations could be obtained as in Equations (4) and (5). The high Pearson correlation coefficients of 0.902 and 0.983 in Equations (4) and (5) indicate that MTS and PMV were significantly linearly correlated with t_{op}. In Figure 9b, as t_{op} increased, at the interval of t_{op} < 24.9 °C, the disparity between PMV and MTS diminished progressively. In contrast, as t_{op} increased at the interval of t_{op} > 24.9 °C, the PMV exceeded MTS, and their differences increased. In this study, actual and predicted respondents' neutral estimates and the acceptance of indoor thermal conditions were examined through the linear regression model. Respondents' neutral temperature (t_n) corresponds to the point where the regression equation results in zero. By using Equations (4) and (5), the actual t_n was 25.34 °C, whereas the predicted t_n was 25.17 °C.

The results of thermal comfort studies in many different regions confirmed that simple linear regression could not accurately characterize human adaptive behaviors in specific environments, such as increasing or decreasing clothing, using on-demand warming devices, and engaging in exercise that changes one's metabolic rate [39]. In this study, thermal sensation Probit regression analysis was used, along with thermal dissatisfaction rate measurements for each temperature range, to determine appropriate temperatures for radiation-prone indoor situations. Figure 9c shows the 80% acceptable temperature ranges, which were based on the intersections of the Probit regression analysis regarding measured thermal dissatisfaction rates (20%) and operative temperatures. The actual t_{ac} (80%) fell within the range of 21.69 °C to 30.55 °C, which claims that individuals living in rural areas possess strong adaptive abilities.

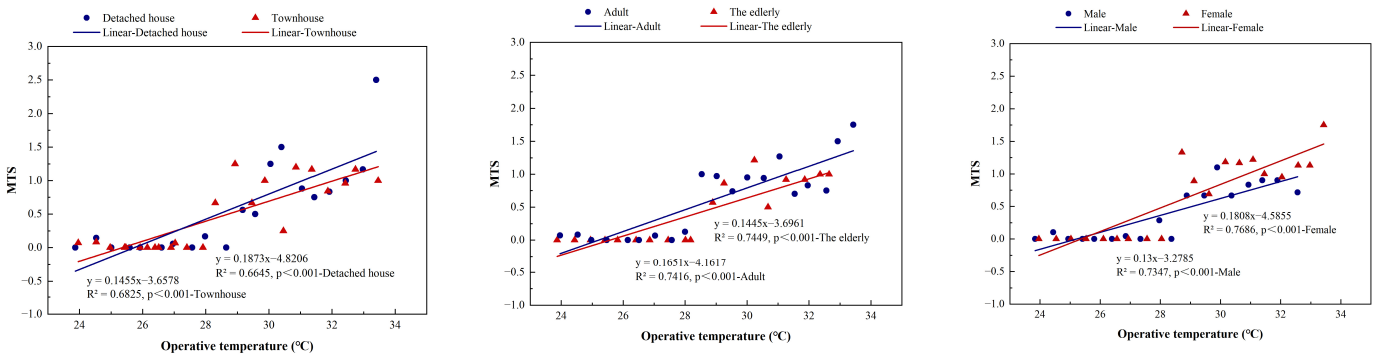
$$\text{MTS} = 0.1673\ t_{op} - 4.2396,\ R^2 = 0.814,\ p < 0.001 \quad (4)$$

$$\text{PMV} = 0.2962\ t_{op} - 7.4545,\ R^2 = 0.9663,\ p < 0.001 \quad (5)$$

4. Discussion

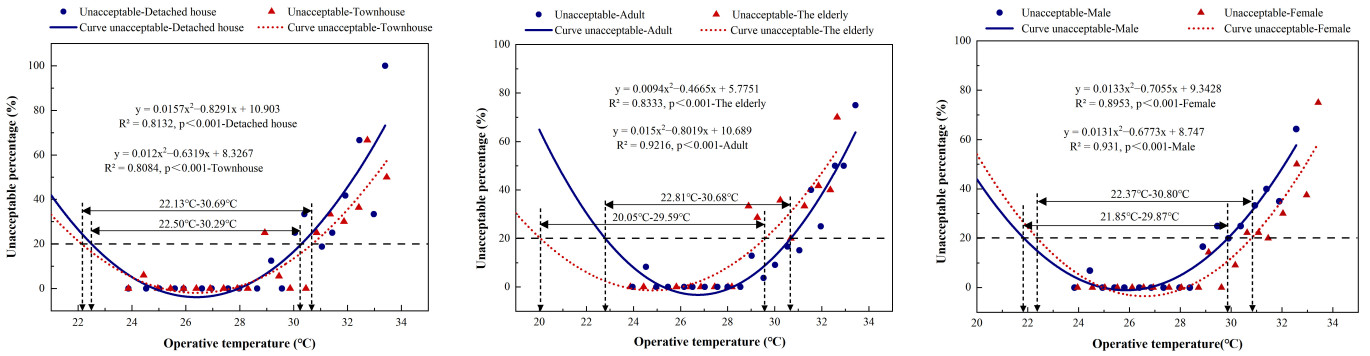
4.1. Effects of Building Types, Ages and Genders

To further investigate the effects of individual factors on the results of the actual neutral sensation and thermal acceptance, the data in terms of the building type, age, and gender were analyzed independently, as shown in Figures 10 and 11. The actual t_n and t_{ac} were derived using the regression analysis, as indicated in Table 5. The results show that the t_n in detached houses was 0.6 °C greater than the t_n in townhouses. The rural elderly were more tolerant to heat in summer than adults in the northern area of the HSWW zone, which was confirmed as the conclusion of the previous study [57]. The neutral temperature did not show a significant statistical difference between males and females.



(**a**) (**b**) (**c**)

Figure 10. Relationship between respondents' MTS/PMV and t_{op}. (**a**) Building type; (**b**) Age; (**c**) Gender.



(**a**) (**b**) (**c**)

Figure 11. The highest limit of acceptable temperature (80%). (**a**) Building type; (**b**) Age; (**c**) Gender.

Table 5. T_n and t_{ac} calculated by the regression method.

Parameter	Total	Gender		Age		Building Type	
		Male	Female	Adult	The Elderly	Detached House	Townhouse
t_n (°C)	25.34	25.22	25.36	25.2	25.58	25.73	25.13
t_{ac} (°C)	21.69~30.55	21.85~29.87	22.37~30.80	22.81~30.68	20.05~29.59	22.50~30.29	22.13~30.69

4.2. Comparative Analysis of Thermal Comfort Attributes with Earlier Research

A comparison of t_n and t_{ac} (80%) from previous field studies performed in summer natural ventilated residential buildings across diverse climates and locations is provided in Table 6. A comparative analysis of the SC/C, HSCW, HSWW, and M zones indicates that as the outdoor temperature rose, both the value of residents' t_n and the maximum of t_{ac} increased. Within the HSWW zone, rural residents tended to have lower t_n values but higher t_{ac} values than urban residents. This variation arises from the reduced use of air conditioning in rural areas, which enhances their ability to adapt to heat and builds greater heat resistance. In addition, climate differences within the HSWW zone contribute to regional disparities, as the southern part, being hotter, allows rural residents to develop a higher t_{ac} limit than those living in the cooler northern region. The findings highlighted differences in the residents' t_{ac} ranges of the indoor thermal environment preferred by residents in naturally ventilated spaces within the HSWW climate zone. Therefore, tailoring the design t_{ac} range to specific locations within the HSWW zone is necessary.

Table 6. Variations in thermal comfort across different regions in summer.

References	Location	Zone	Area	t_n (°C)	t_{ac} (°C)
This study	Hezhou, China	North area of HSWW	Rural	25.34	21.69~30.55
Zhang et al. [58]	Jiangmen, China	South area of HSWW	Rural	24	up to 31.1
Yuan et al. [59]	Xiamen, China	South area of HSWW	Rural	24.78	/
Zhang et al. [39]	Guangzhou, China	South area of HSWW	Urban	27.9	22.0~29.5
Wang et al. [40]	Guangzhou, China	South area of HSWW	Urban	28.4	27.1~29.6
Yu et al. [35]	Tibet, China	SC	Rural	21.79	/
Wei et al. [38]	Xi'an, China	C	Urban	26.1	up to 28.9
Chang et al. [60]	Turpan, China	C	Rural	26.6	up to 32.2
Xiong et al. [6]	Wuhan, China	HSCW	Rural	25.15	22~28.3
Wei et al. [61]	Guangan, China	HSCW	Rural	29.33	26.76~32.06
Xu et al. [41]	Nanjing, China	HSCW	Urban	28	22~30.1
Bassoud et al. [62]	Adrar, Algeria	Hot	Urban	31.52	28.4~35.48
Cohen et al. [63]	Beer Sheva, Israel	Mild	Urban	22.8	19.4~24.5

5. Conclusions

This study presented an analysis of the thermal comfort data obtained by a field survey carried out in naturally ventilated rural houses in Hezhou, a typical area in the north of an HSWW zone in China. The findings are based on indoor and outdoor environmental measurements conducted across 98 rural houses and thermal comfort questionnaires, with 502 valid responses from 251 respondents. The findings indicate that rural populations in the northern and southern sections of this zone experience differences regarding a neutral temperature and acceptable thermal conditions. To gain a deeper understanding, future research needs to conduct extensive and long-term investigations on thermal comfort among rural communities in the northern HSWW zone of China. In the future, the changing trend of thermal comfort and adaptation throughout different seasons will be analyzed, and more influential factors related to thermal comfort will be studied. These studies will contribute to refining thermal comfort evaluation standards and improving energy efficiency guidelines for rural housing. Furthermore, such research can provide architects and policymakers with critical data for livable housing solutions and sustainable design in rural communities. The major conclusions are summarized below:

1. In the Hezhou region, the collected survey data revealed that the rural houses maintained an average indoor air temperature of 28.38 °C and an operating temperature of 28.45 °C, both of which exceeded the summer comfort threshold defined in the standards of ISO 7730 (26 °C), ASHRAE 55 (27 °C), and China's GB/T 50,785 (28 °C).
2. In summer, rural residents wore clothing with an average thermal insulation of 0.41 clo. With each unit's operating temperature increasing, the clothing insulation level decreased by 0.044 clo.
3. Approximately 79.1%, 67%, and 53% of rural residents felt comfortable with the current thermal, humid, and wind environment, respectively. Local rural residents were highly adaptable to the intense heat and humidity of summer.
4. The actual neutral temperature during summer is 25.34°C, whereas the predicted neutral temperature is 25.17°C. The acceptable temperature span ranges from 21.69 °C to 30.55 °C. The acceptable temperatures in rural Hezhou were relatively lower than regions in the south area of the HSWW zone.

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Nomenclature

$t_{a,in}$	Indoor air temperature
t_g	Globe temperature
v_a	Air velocity
$t_{a,out}$	Outdoor air temperature
t_{mrt}	Mean radiant temperature
t_{ac}	Acceptable temperature
TSV	Thermal sensation votes
WSV	Wind sensation votes
HSWW	Hot summer and warm winter zone
SC	Severe cold zone
M	Mild zone
RH_{in}	Indoor relative humidity
t_r	Radiation temperature
t_{op}	Operative temperature
RH_{out}	Outdoor relative humidity
t_n	Neutral temperature
PMV	Predicted mean vote
HSV	Humidity sensation votes
MTS	Mean thermal sensation
HSCW	Hot summer and cold winter zone
C	Cold zone

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