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Research on Summer Indoor Air Conditioning Design Parameters in Haikou City: A Field Study of Indoor Thermal Perception and Comfort

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Abstract: Escalating global climate change and the intensification of urban heatwaves have led to an increase in summer air conditioning cooling energy consumption. This phenomenon is particularly critical in tropical regions, as it may trigger an energy crisis. The rational setting of indoor thermal design parameters can help conserve energy to the maximum extent while ensuring thermal comfort for occupants. This study selected Haikou City, a unique tropical city in China, as the research location. Indoor environment measurements and a questionnaire survey were conducted with participants, and the outdoor thermal environment sensitivity, population attributes and differences in thermal sensation, thermal neutral temperature, and comfort range were calculated and analyzed. The following results were obtained. Based on the overall population, long-term residence, and temporary residence classification, the indoor thermal comfort needs of residents in tropical cities in Haikou were effectively identified. The actual thermal neutral temperature of the overall population is 25.7 °C, and 90% of the acceptable thermal comfort temperature range is 23.2 °C–28.0 °C. The actual thermal neutral temperature of the regular residents is 27.3 °C, and 90% of the acceptable thermal comfort temperature range is 23.3 °C–31.4 °C. The actual thermal neutral temperature of the temporary population is 25.5 °C, and 90% of the acceptable thermal comfort temperature range is 23.0 °C–28.0 °C. These research results have an important reference value for improving the setting of the temperature of air conditioning in tropical areas in summer and further reducing energy consumption, which is conducive to sustainable development.

Keywords: indoor environment; global environmental warming; energy consumption; thermal comfort; thermal sensation; thermal neutral temperature

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1. Introduction

The operation phase of buildings is the largest contributor to carbon emissions in the construction sector [1]. According to data of the China Building Energy Efficiency Association, carbon emissions from the operational stage of buildings reached 23.0 billion tons of CO_2 in 2021, accounting for 21.6% of the national carbon emissions and representing 56.6% of the total carbon emissions throughout the entire building process [2]. The energy consumption and carbon emissions from heating and cooling constitute the primary sources of energy consumption and carbon emissions during the operational stage of buildings. There are significant variations in the total carbon emissions from building operations, driven by diverse heating and cooling demands during winter and summer across different cities. Outdoor temperature and indoor temperature setpoints are crucial factors influencing the energy consumption of air conditioning systems during the summer. In recent years, the global urbanization process has accelerated, global climate warming, urban heat waves and heat islands have led to the increase of outdoor temperature, and the impact of these factors has led to the median increase of refrigeration energy consumption of 19% [3]. Particularly in tropical regions, the common use of air conditioning systems has accentuated the positive correlation between outdoor temperatures and electricity demand [4]. Unreasonable temperature settings not only decrease the comfort of indoor occupants but also escalate cooling energy consumption. However, this type of research is less focused on tropical regions.

A comfortable indoor environment makes people happy and helps improve work efficiency. There are many indicators to evaluate the comfort of an indoor thermal environment in the early stage, such as effective temperature (ET), new effective temperature (ET*), standard effective temperature (SET), thermal stress index (H.S.I.), predicted thermal scale (PMV), etc. [5]. However, the most authoritative index is Predicted Mean Vote, proposed by Professor Fanger of Denmark [6], which represents the thermal comfort feeling of most people, but cannot reflect the difference of people's feelings among different groups. Therefore, the PPD index has been proposed to accurately express people's satisfaction with the environment. Based on different evaluation indicators, thermal comfort standards (ASHRAE-1992 [7], ISO7730 [8], and CIBSE Guide1986 [9]) conforming to different national and regional conditions were also born. On the basis of the research results of ISO7730, according to local climate conditions, thermal comfort, and energy consumption of personnel, China has put forward the standard "Determination of PMV and PPD index and thermal comfort conditions in Moderate thermal Environment" (GB/T18049-2000) [10]. Under the guidance of thermal comfort standards, different climate zones and provinces in China have introduced heating and cooling time and interior design parameters according to climatic conditions, such as the Tianjin Public building energy saving design standard (DB29-153-2014) [11], Xi'an Public building energy saving design standard (DBJ/T 61-60-2011) [12], Beijing Public building air conditioning heating indoor temperature energy saving monitoring standard (DB11/1005-201) [13], etc. The relevant standards of Haikou City have not been established.

PMV and the PPD index are a comprehensive evaluation of six factors that affect human thermal comfort, including air temperature, air humidity, air flow rate, radiation temperature, activity intensity, and clothing and other factors. So far, they are the most comprehensive indexes for the evaluation of an indoor thermal environment. Air temperature is an important parameter of an indoor thermal environment. Air temperature is determined by the heat balance, composed of indoor heat gain and heat loss, the temperature of the inner surface of the envelope, and ventilation. In the process of life activities, the human body keeps its body temperature constant by constantly building and dissipating heat. The response of the human body to the increase of environmental temperature is mainly manifested by the increase of skin temperature and the increase of perspiration rate. The change level of relative humidity is not as significant as that of temperature. When the relative humidity changes in the range of 40–70%, the human body is not sensitive [14]. Usually, the discomfort of a wet environment to the human body comes from the sticky feeling of the skin's surface, which is caused by the increase of skin wetness. Air flow velocity can directly affect the heat transfer efficiency between the human body and the surrounding environment, but for different environments, the influence of wind speed on the human body is also different. In summer, when the temperature of the human skin is higher than the air temperature, the air flow can strengthen the heat dissipation of the human body so as to cool it down. On the contrary, the air flow can make the human body absorb heat from the environment, making people feel heat uncomfortably. In winter, air flow also speeds up the heat exchange between the body and the environment, making people feel cold. The average radiation temperature refers to the average temperature of each indoor surface that has an effect on the radiation heat exchange of the human body. Under normal circumstances, the body's radiation heat dissipation accounts for 42–44% of the total heat dissipation. When the average ambient radiation temperature rises, the radiation heat dissipation of the human body decreases. In order to maintain the heat balance, the proportion of convective heat dissipation and evaporation heat dissipation must be increased. The basic function of clothing is to maintain the human body in a state of thermal balance and thermal comfort; that is, clothing is an important means of supporting body temperature regulation so that its temperature is maintained within the range of the median value, even if the external environment changes. The changes brought about by the activity level of the human body will also be significantly reflected. The level of human activity is not only closely related to the metabolic rate, but also directly related to the body's moisturization. When the intensity of human activity increases, the metabolic rate of the human body also increases. At this time, the heat dissipation on the surface of human skin and the heat taken away by sweat increase, and the local airflow disturbance caused by this temperature difference will produce the "chimney effect" at the garment opening [15].

Thermal comfort and building energy efficiency are closely related. Reducing a building's energy consumption cannot be done at the expense of significant human thermal comfort. The research fields of zero energy building design [16], envelope optimization [17,18], and intelligent building control [19] are largely aimed at reducing building energy consumption or shifting the peak load of buildings under the premise of human-oriented design and satisfying human needs for their environment. Usually, these studies will consider the thermal comfort feeling of indoor personnel as one of the indicators to evaluate the performance of the system. In turn, many studies improve the thermal comfort of indoor personnel by changing environmental parameters under the premise of maximizing energy saving. In winter, better insulation performance of the envelope structure, phase change flooring, and so on can raise the indoor temperature to improve the thermal comfort of the human body. In air-conditioned rooms in the summer, fans make people feel cooler by speeding up the flow of air around people inside [20–23]. Indoor personnel will also take the initiative to adapt to the environment by increasing or reducing the level of activity and adding or reducing clothing, so as to reduce heating and cooling energy consumption. These means fit with the factors affecting human thermal comfort in PMV and PPD indicators. This is well known.

The contributions of this paper are as follows: (1) The thermal comfort conditions of different types of residents in Haikou city under an air-conditioned environment in summer were clarified through field research; (2) the indoor thermal neutral temperature and the thermal comfort interval in Haikou City were determined using a linear fitting data processing method; and (3) the recommended setting values of indoor environmental design parameters for different types of buildings in Haikou City were presented.

2. Materials and Methods

In this study, 11 buildings that are located in the central area of Haikou for relatively high occupancy in Haikou were selected to carry out on-site environmental parameter measurements and questionnaire surveys, and the relevant data of the human thermal comfort of the permanent and temporary populations in the cooling season were obtained. Permanent population means the population living in the city for more than six months throughout the year [24]. Populations living in the city year-round for more than six months were considered permanent.

2.1. Study Site

Haikou (108°37′ E–111°15′ E, 3°30′ N–20°18′ N) is a city located in the south of China, with a hot summer and warm winter climate [25], which is the provincial capital city of Hainan Island with the largest population and highest urbanization. Therefore, it ought to be taken as the first city to carry out thermal demand research for the purpose of reducing the cooling load and carbon emission to a relatively large extent in Hainan Island. The location of Haikou City is shown in Figure 1. Summer is long and hot and humid. According to meteorological data collected from the Chinese Standard Weather Database (CSWD), which is one of the most widely adopted typical year files [26], the average annual temperature in Haikou is between 22.50 °C and 25.60 °C and the annual and daily temperature differences are small. The average temperature in January, the coldest month, is above 10 °C, the average temperature in July is between 25 °C and 30 °C, and the extreme maximum temperature can reach about 40 °C. The annual average relative humidity is about 80%, and there is no obvious difference between the four seasons. At noon, the solar height angle is large, the annual total solar radiation illuminance is 130–170 W/m^2, and the annual sunshine percentage is 35–50%. The total rainfall is large, and it is common for the area to have windy weather and rainstorms. The annual rainfall days are 120 d–200 d, and the annual precipitation is between 1500 mm–2000 mm. The annual average wind speed is relatively large, higher than 1.50 m/s. The detailed meteorological data of Haikou are shown in Figure 2.

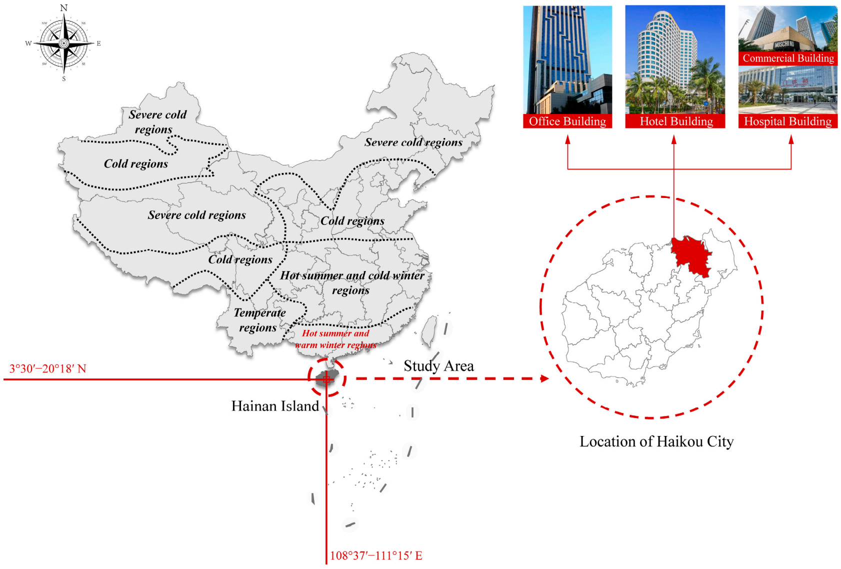
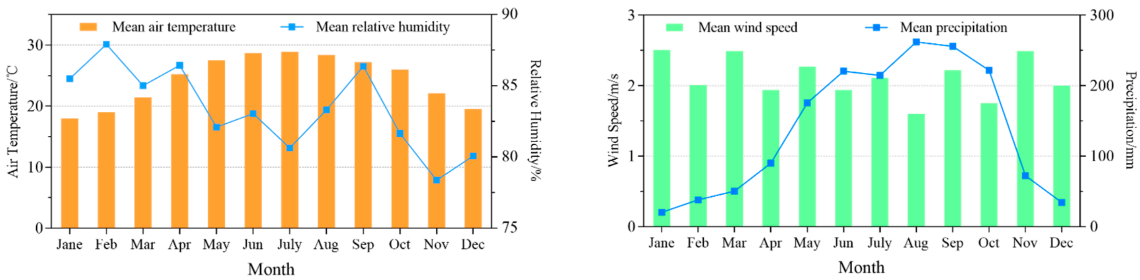


Figure 1. The location of Haikou City.



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

Figure 2. The detailed meteorological data of Haikou City; (**a**) Mean air temperature and relative humidity; (**b**) Mean wind speed and precipitation.

2.2. Field Measurement

In addition to office buildings, hotel buildings, and shopping malls, public buildings also include education buildings, hospital buildings, and transportation hub buildings, all of which are air-conditioned buildings. The contents of the survey were mainly environmental parameter measurements and questionnaire filling.

The main indoor environmental parameters that affect the thermal comfort of indoor personnel are air temperature, relative humidity, indoor air flow velocity, and wall radiation temperature. Since the indoor environment usually has low wind speed, the surrounding wall temperature does not differ much from the air temperature, and the influence of radiation temperature also decreases accordingly. Therefore, indoor air temperature and relative humidity are important indicators to determine body perception [27,28]. The data of the indoor thermal environment field test in this paper include the air temperature, relative humidity, and air flow velocity in the indoor rooms of the building. Based on the above parameters, the measurement team selected instruments such as automatic recording thermometers and anemometers, and each experimental instrument was checked before the field test to ensure the accuracy of the data. Before the measurements, special and unified training was carried out for the testers to avoid the impact of human factors on the data in the measurement process. The parameters of the utilized instruments are shown in Table 1. All instruments utilized in the measurement process complied with the requirements of the International Organization for Standardization (ISO) 10551 standards [29].

Table 1. The parameters of utilized instruments.

Manufacturer (City, Country)	Instrument	Measurement Item	Accuracy	Resolution	Range
Shenzhen Jumaoyuan Science and Technology Co., Ltd. (Shenzhen, China)	GM1365	Air temperature	±0.3 °C	0.1 °C	−30–80 °C
		Relative humidity	±2%RH	0.1%RH	0–100%
Testo SE & Co. KGaA (Schwarzwald, Germany)	Testo405v1	Air velocity	±0.1 m/s	0.01 m/s	0.01–30 m/s
Shenzhen Laiyuan Instrument and Equipment Co., Ltd. (Shenzhen, China)	GM8902+	Air velocity	±3%	0.01 m/s	0.01–45 m/s

2.3. Questionnaire Survey

2.3.1. Questionnaire Design

The questionnaire survey is a method that has been widely adapted in the research of indoor thermal comfort in the tropics and other climate zones in the world [30–36]. The questionnaire in this study was designed based on the ASHRAE Standard 55 [37], containing the environmental parameters of the on-site measurement, the environmental sensation of the subjects (thermal sensation, thermal comfort, humidity sensation, and blowing sensation), and the expectations of the subjects for the change of environmental parameters (temperature, humidity, and wind speed). The environmental parameters include the measurement of ambient temperature and humidity. Thermal Sensation Vote (TSV) and Thermal Comfort Vote (TCV) were evaluated by the ASHRAE 7-point sensation scale, and Thermal Preference Vote (TPV) was evaluated by a 3-point scale [38,39], as shown in Figures 3 and 4.

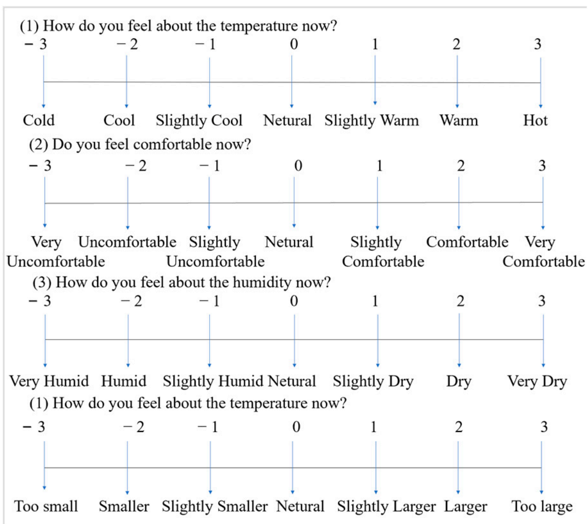


Figure 3. The environmental sensation of the subjects.

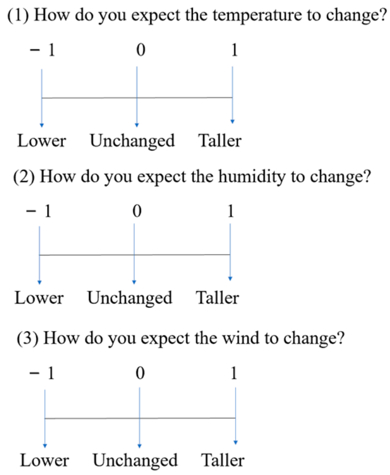
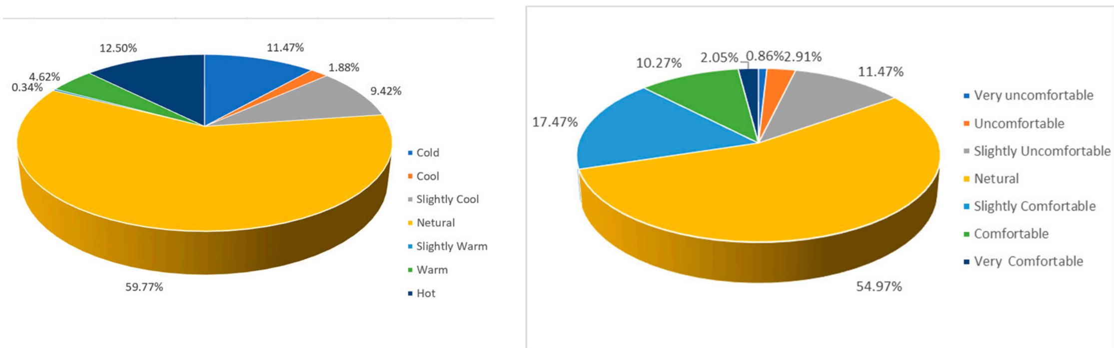


Figure 4. The expectations of the subjects for the change of environmental parameters.

2.3.2. Questionnaire Survey Method and Process

In the questionnaire survey, 2–3 people were in groups, and they were selected to enter the room during the normal operation time of the building and randomly questioned by the personnel in the room. During the survey, the questionnaire filling was carried out simultaneously with the measurement of environmental parameters, and the team carried thermometers and anemometers into the room where the respondents were. One to two members of each group were responsible for the measurement of environmental physical parameters, and one member was responsible for asking questions, as shown in Figures 3–5. The questionnaire was a paper questionnaire, and all the questionnaires were filled in by the investigators themselves according to the answers of the respondents. At the same time, the meaning of each variable in the questionnaire was explained to each respondent in the process of questioning, so as to facilitate understanding and answering. While recording the answers of the subjects, the indoor thermal environment parameters at this moment were filled in the questionnaire.



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

Figure 5. Indoor thermal perceptions of respondents; (**a**) TSV; (**b**) TCV.

2.4. Data Analysis

All data collected by questionnaire survey were input into IBM SPSS firstly, and then invalid samples, including those with essential indexes that were abnormal or missing like indoor environmental parameters or thermal votes, were cleared. After that, all data were converted into numerical parameters, such as "1" and "2", and symbolized "Male" and "Female" respectively, for the aim of making comparison.

In addition to IBM SPSS, Python was used for the visualization and analysis. As for analytical methods, the linear regression function in Python was used to fit the temperature interval divided by the temperature frequency method (bin method) to the thermal voting, and the corresponding thermal comfort model was obtained. Consequently, a series of mathematical models were set up to calculate the thermal neutrality and thermal comfort zone to find the difference between the thermal comfort demand of the permanent populations and temporary populations.

3. Results

3.1. Basic Information of Respondents' Attributes and Votes

A total of 600 subjects were interviewed and 584valid questionnaires were collected, with an effective rate of 96.83%. According to the different natures of the population, it can be divided into permanent residents and temporary population. Under normal circumstances, the former refers to the people who live in the area for more than 6 months a year. The specific conditions of the subjects are shown in Table 2. It can be seen that the subjects are mainly regular residents, and the ratio of the subjects to the neighboring residents is about 2:1. In terms of gender, the number of female subjects in the total population is more than that of male subjects.

Table 2. The specific conditions of the subjects.

Category	Total Count	Sex	Count
Temporary	195	Male Female	100 95
Permanent	389	Male Female	145 244
Total	584	Male Female	245 339

The main physiological factor that influences thermal comfort is metabolism. Apart from genders, another physiological attribute that can play a key role on it is age [40]. The age composition of permanent respondents is shown in Table 3, of which distribution is similar to census result of Haikou city published by Hainan provincial bureau of statistics [41]. The age numbers of temporary respondents were also concentrated in the range from 15 to 59 because all of them were tourists during this field study. Therefore, the samples in this study generally represent the demographic state in Haikou city.

Table 3. The comparison of age composition between respondents and Haikou city.

Category		Age Range			
		0–14	15–59	≥60	≥65
Respondents in this study	Number Proportion	68 17.48%	274 70.44%	47 12.08%	39 10.03%
Haikou city [41]	Number Proportion	2,013,725 19.97%	6,590,908 65.38%	1,476,599 14.65%	1,051,500 10.43%

Besides metabolism, clothing is another important subjective aspect that affects thermal comfort [42]. Tables 4 and 5 illustrate the proportion of different clothes in all samples. To facilitate the calculations, the Appendix C, recommended in Chinese local standard GB/T50785 [43], was used to estimate the thermal resistance of a single set of clothing. It is obvious that the clothing status varied slightly among respondents in this questionnaire survey owing to Haikou City's unique climatic conditions in summer and special geographical location.

Table 4. Clothing distribution of male respondents.

Body Position		Clothing Category			
		Short-Sleeve T-Shirt	**Long-Sleeve T-Shirt**	**Short-Sleeve Shirt**	**Sleeveless Vest**
Upper Body	Thermal resistance (clo)	0.09	0.12	0.15	0.06
	Proportion	87.40%	7.32%	3.25%	2.85%
Lower Body		Shorts		Thin Pants	
	Thermal resistance (clo)	0.06		0.12	
	Proportion	44.31%		55.69%	
Socks		No Sock	Short Sock	Long Sock	
	Thermal resistance (clo)	0.00	0.02	0.05	
	Proportion	31.30%	57.32%	11.38%	
Shoes		Sandals		Shoes	
	Thermal resistance (clo)	0.02		0.04	
	Proportion	36.99%		73.01%	

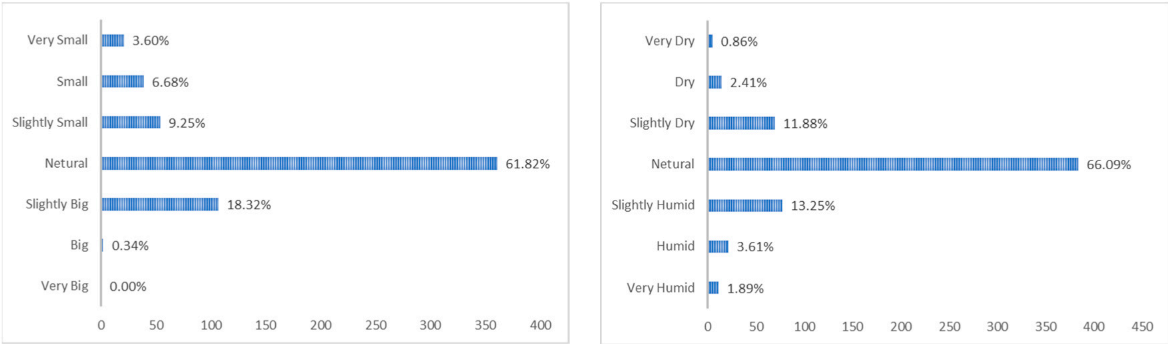
Table 5. Clothing distribution of female respondents.

Body Position		Clothing Category				
		Short-Sleeve T-Shirt	**Long-Sleeve T-Shirt**	**Short-Sleeve Shirt**	**Sleeveless Vest**	**Thin Dress**
Upper Body	Thermal resistance (clo)	0.09	0.12	0.15	0.06	0.09
	Proportion	80.56%	9.03%	5.56%	1.39%	5.56%
Lower Body		Shorts		Thin Pants		Skirt
	Thermal resistance (clo)	0.06		0.12		0.09
	Proportion	7.74%		77.46%		14.80%
Socks		No Sock	Short Sock	Long Sock		
	Thermal resistance (clo)	0.00	0.02	0.05		
	Proportion	38.89%	55.56%	5.56%		
Shoes		Sandals		Shoes		Boots
	Thermal resistance (clo)	0.02		0.04		0.10
	Proportion	49.24%		38.06%		12.70%

3.2. Respondents' Attributes and Votes

Figure 5 shows the voting distribution of all respondents' thermal sensation vote (TSV) and thermal comfort vote (TCV). As for TSV, the respondents who felt "neutral" (60%) accounted for the largest part, approximately 1/3 of the respondents answered "slightly warm" (11.47%), "warm" (4.62%), or "hot" (12.50%), and only a few respondents felt "slightly cool" (9.42%), "cool" (1.88%), or "very cool" (0.34%). On the TCV, the number of respondents' votes was concentrated in "neutral" (n = 59.76%), "slightly comfortable" (n = 17.47%), and "comfortable" (10.27%), accompanied by a relatively small proportion at "slightly uncomfortable" (11.47%), "uncomfortable" (2.91%), "very comfortable" (n = 2.05%), and "very uncomfortable" (0.86%). In general, this result indicates that, overall, people have various responses to TSV and TCV under the Hainan Island climate in the summer and have good adaptability to warm indoor environments.

The results of respondents' sensation of other environmental parameters, including humidity and wind speed, are shown in Figure 6. It can be concluded from this figure that respondents' acceptance rates for humidity and wind speed were both above 60%. Respondents who had the sensation of low wind speed and dry environment were 19.53% and 15.15% in proportion, respectively, lower than those who had opposite sensations.



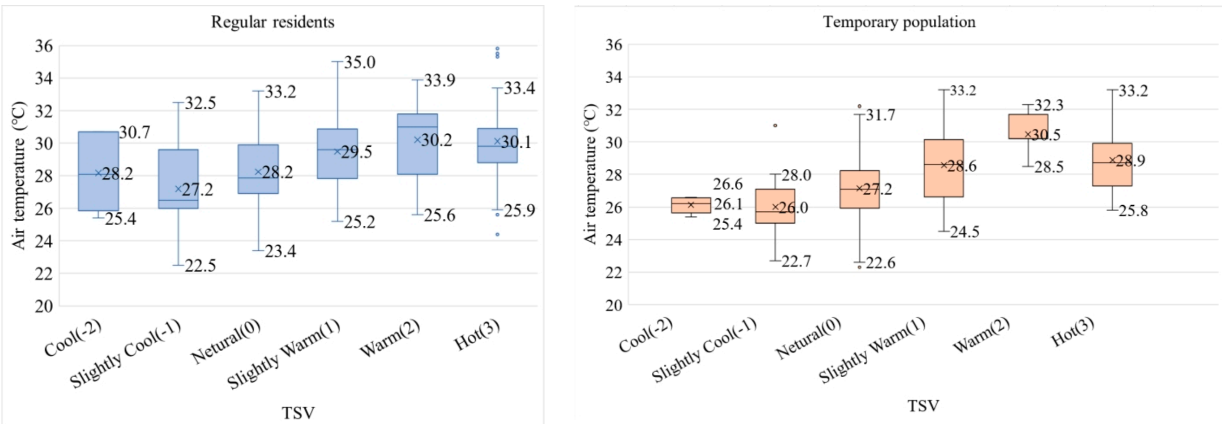
(**a**) (**b**)

Figure 6. Thermal sensation votes to wind velocity and humidity: (**a**) Wind velocity; (**b**) Humidity.

3.3. Thermal Sensation and Comfort of Different Respondents

3.3.1. Thermal Sensation

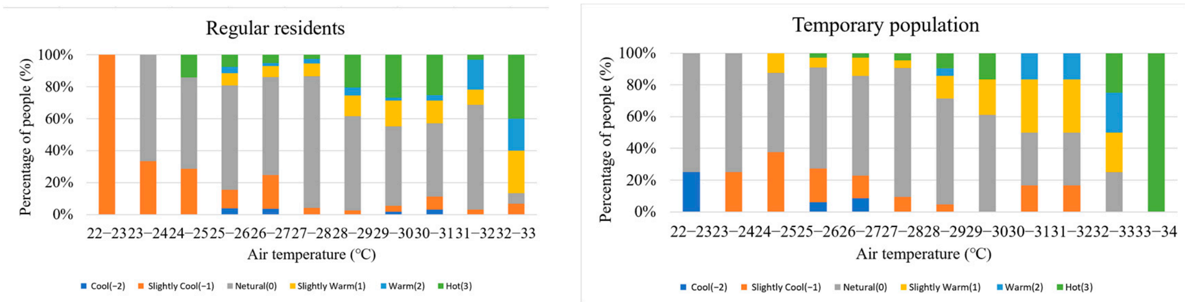
Figure 7 reflects the relationship between TSV and air temperature. The common tendency is that a higher air temperature is in correspondence to a larger thermal sensation vote value. However, it can be found that the responding temperature to vote was different between the permanent population and temporary population. Generally, the average responding temperature of the permanent population was about 1.0 °C higher than that of the temporary population, which indicates that the two kinds of respondents' bodies showed variation in their thermal sensation of the ambient temperature during the field study.



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

Figure 7. The relationship between TSV and air temperature: (**a**) Regular residents; (**b**) Temporary population.

The distribution of measured TSV in different air temperature scales is displayed in Figure 8. In general, with a growing air temperature, the proportions of samples with TSV = 1, TSV = 2, and TSV = 3 in the two kinds of respondents increase gradually. The most obvious difference can be seen is that the percentage of people selecting "warm" and "hot" in the permanent population was less than that of the temporary population in the range of 29.0 °C–30.0 °C and higher. In addition, the temporary population's thermal sensation results were greater than the permanent population's in the range of air temperature less than 26.0 °C. It was particularly true that the permanent population's sensitivity to high ambient temperature was weaker than the temporary population's sensitivity in the period of testing.

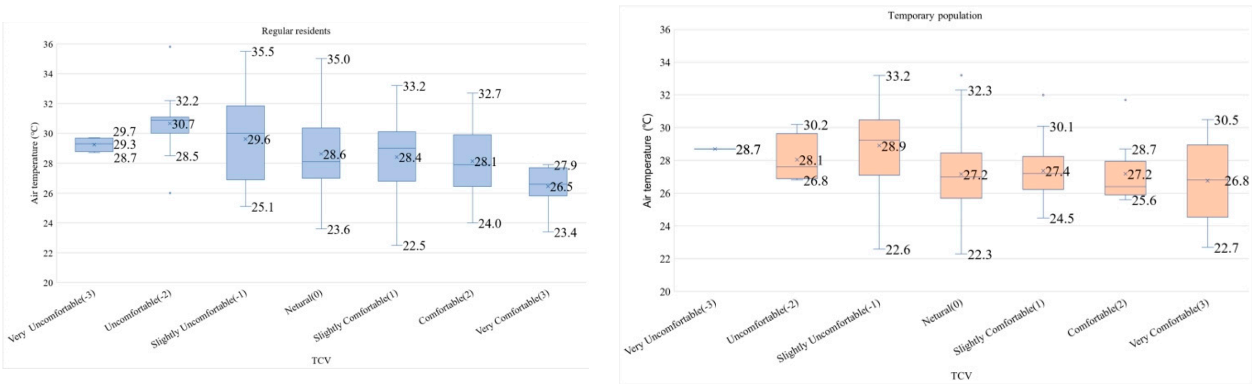


(**a**) (**b**)

Figure 8. The distribution of measured TSV in different air temperature scales: (**a**) Regular residents; (**b**) Temporary population.

3.3.2. Thermal Comfort

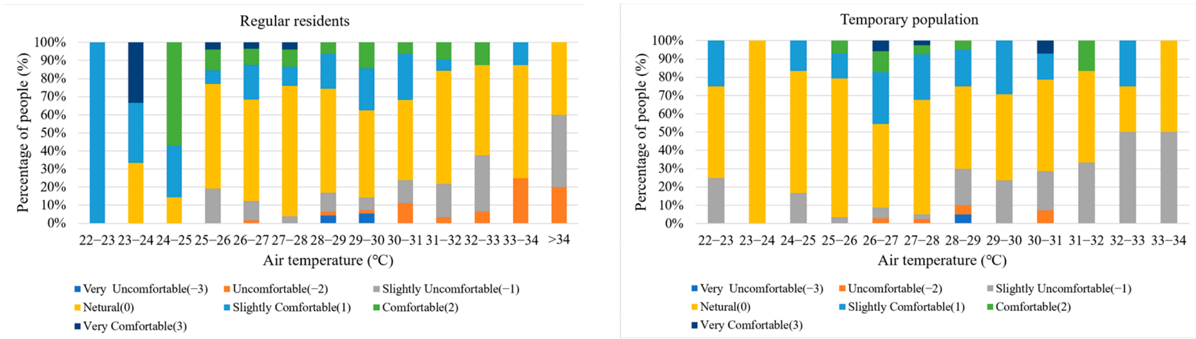
Figure 9 shows the thermal comfort distribution box plots. As can be seen in this figure, different TCV values corresponding to indoor air temperatures have a remarkable variance. Overall, there were some differences in the average temperature of the two groups in all voting scales. The average temperature for the permanent population to reach a state of comfort was approximately 1.2 °C higher than the temporary population's, which indicates that permanent population in Haikou City prefer warmer environments to work and live.



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

Figure 9. The thermal comfort distribution box plots: (**a**) Regular residents; (**b**) Temporary population.

The distribution of TCV values in different indoor air temperatures is presented in Figure 10. From the data in this figure, the most remarkable distinction can be seen in the air temperature scales over 29.0 °C. Specifically, the proportion of respondents who felt "neutral", "slightly comfortable", "comfortable", and "very comfortable" in the permanent population was significantly higher than the temporary population's and there were even a small number of the permanent population feeling acceptable in the indoor environment under a temperature of more than 32.0 °C. Based on the data analysis above, it can be said that the acceptability and tolerance to high-temperature indoor environments would be improved by living under the climate of Haikou City for a long time.

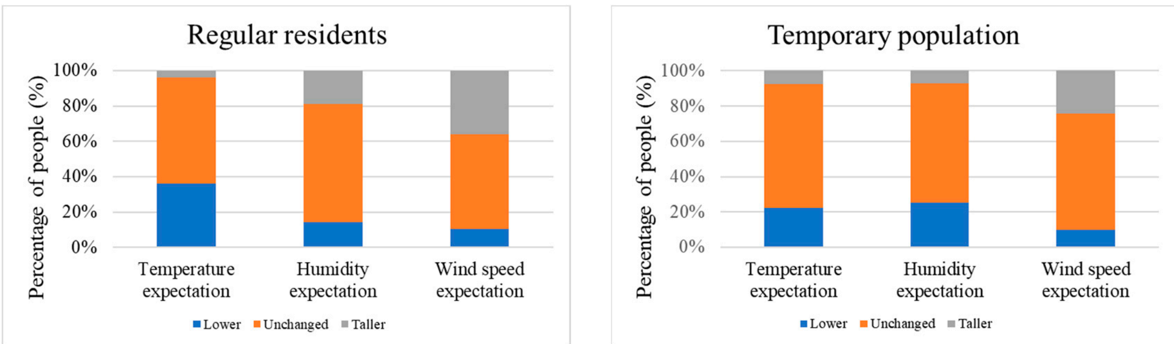


(**a**) (**b**)

Figure 10. The distribution of TCV values in different indoor air temperatures: (**a**) Regular residents; (**b**) Temporary population.

3.3.3. Preference Vote

Figure 11 displays the statistical results of TPV for changing indoor thermal environment parameters. In terms of the permanent population, 59.84% of them were satisfied with the current Ta, 3.93% of them preferred warmer environments, and 36.22% of them wanted the temperature to be lower. Proportions of preference votes for humidity were 66.93% for maintaining, 18.90% for increasing, and 14.17% for decreasing. More than half of all permanent living respondents (53.60%) selected no change in wind speed, 35.43% of them voted for enhancing, and 10.40% of them showed a preference for weakening.

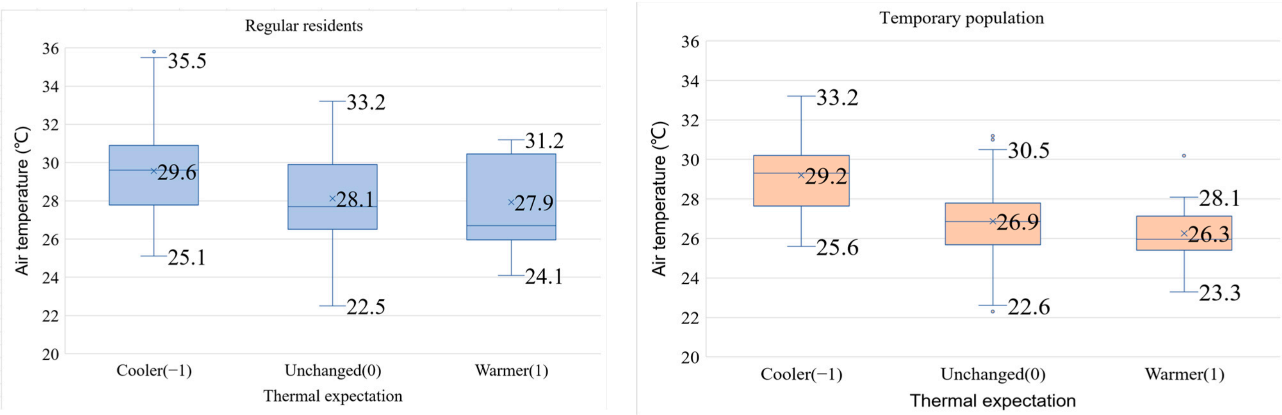


(**a**) (**b**)

Figure 11. The respondents' preferences for changing indoor thermal environment parameters: (**a**) Regular residents; (**b**) Temporary population.

As for the temporary population, 22.16% of them wanted Ta become lower, 25.27% of them were inclined to accept a drier environment, and 24.19% of them demanded stronger wind speed. A total of 70.27% of all temporary living respondents were comfortable with the current Ta, 68.11% for current humidity, and 66.13% for the current wind speed. Few temporary living respondents voted for higher Ta (7.57%), higher humidity (6.99%), and weaker wind speed (9.68%). Taken as a whole, this comparison shows that the two kinds of respondents were different in environmental preference, and the permanent population had higher proportions for improving Ta and strengthening wind speed than the temporary population. In addition, the permanent population are inclined to live in a humid environment while the temporary population are the opposite.

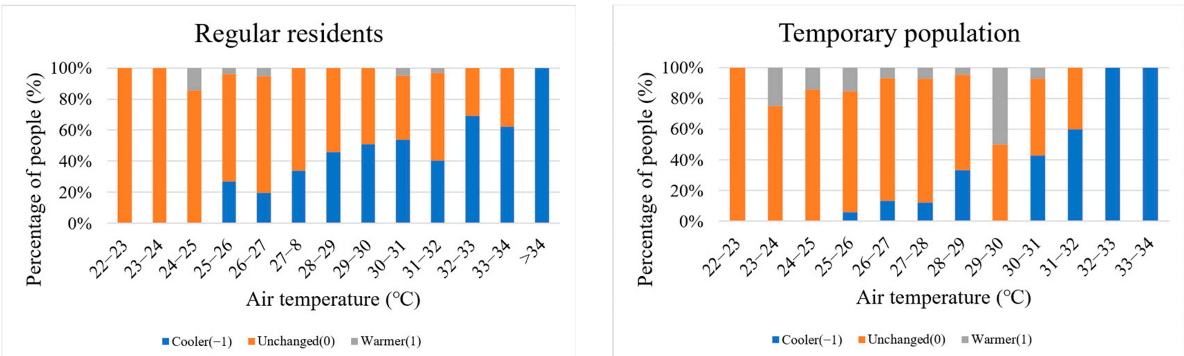
The cross-analysis results of the TPV with the thermal expectation votes can be seen in Figure 12. This figure compares the difference in the two groups of respondents' willingness to change the indoor temperature. It is noted that when sampled people who felt "cold", the proportion of people who expected the indoor temperature to remain unchanged in the temporary population was a little lower than in the permanent population. Comparatively, the permanent population's proportions of having the willingness to lower indoor air temperature when they voted for "slightly warm", "warm", and "hot" were 83.72%, 77.78%, and 93.10%, respectively, lower than the temporary population's in the same voting scales. Such a result is generally consistent with the analysis of the impact of tropical climate factors on respondents' TSV and TCV in Figures 10 and 11.



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

Figure 12. The TPV with the thermal expectation votes: (**a**) Regular residents; (**b**) Temporary population.

Figure 13 exhibits the cross-analysis of air temperature with the thermal expected votes. In general, with an increase in air temperature, the samples with the expectation of a warmer environment gradually decreased. Comparatively, the permanent population's proportion of expecting air temperature to improve was obviously higher than the temporary population's once the Ta was below 25.0 °C. This may be caused by the difference in sample size. On the contrary, when the Ta was above 30.0 °C, the ratio of people who expected the indoor temperature to remain unchanged or improve in the temporary population was much lower than in the permanent population. It can be concluded that the desired temperature is not necessarily the same in these two groups of respondents in Haikou City.



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

Figure 13. The cross-analysis of air temperature with the thermal expected votes: (**a**) Regular residents; (**b**) Temporary population.

3.4. Thermal Neutrality and Thermal Comfort Zone

Thermal neutral temperature represents the temperature at which people feel the most moderate technically in one certain environment, which is one of the most-used thermal indexes to evaluate people's thermal comfort [30,37]. Using linear regression to establish the relationship model between raw thermal vote and air temperature is the way to obtain thermal neutral temperature [30,44]. Figure 14 shows the regression equations of air temperature and MTSV obtained from the measured data. This article divides the indoor air temperature measured on site into continuous intervals of 0.5 °C [45,46], with the middle value of the data in each interval as the x-axis value and the average value of the thermal sensation vote in each temperature interval as the y-axis value, forming a scatter plot representing the relationship between the two. Then, the indoor air temperature ta and the average thermal sensation vote MTSV are fitted and analyzed.

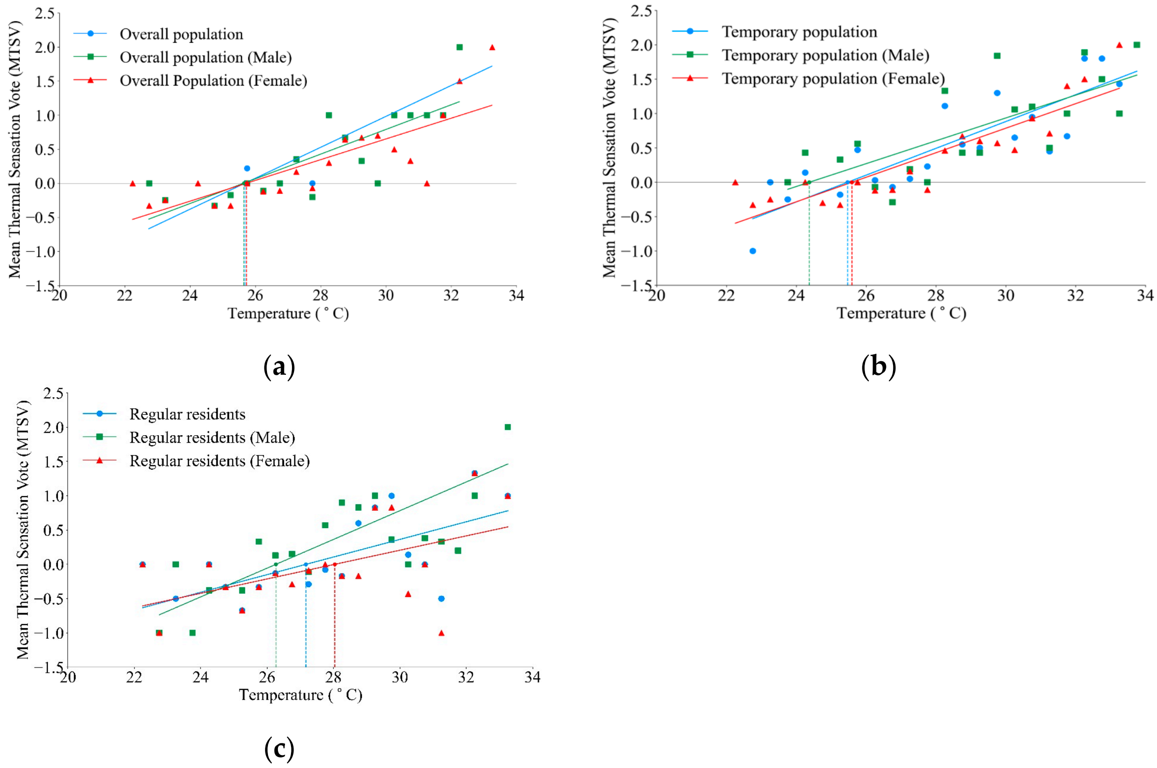


Figure 14. The regression equations of air temperature and MTSV: (**a**) Over population; (**b**) Temporary population; (**c**) Regular residents.

By setting the overall MTSV to 0, the actual thermal neutral temperature of the overall population in Haikou City during the indoor air conditioning season is 25.7 °C. When the male and female MTSV are set to 0, the actual thermal neutral temperatures of male and female respondents are calculated to be 25.7 °C and 25.8 °C, respectively. Women are 0.1 °C higher than men. According to the ASHRAE standard, 90% of people feel satisfied with the ambient temperature for the thermal comfort interval, and 80% of people feel satisfied with the ambient temperature for the thermal acceptable interval [47]. Based on Chinese local standard GB/T50785, for the thermal comfort equation PMV-PPD, when MTSV = −0.5–0.5, 90% of the indoor population can obtain an acceptable temperature range [43], which was adapted in the previous research on Hainan Island [36]. Based on the above conclusion, 90% of the overall population in Haikou City can accept a temperature range of 23.2 °C–28.0 °C during the air conditioning season in public buildings, with a range of 22.5 °C–28.7 °C for males and 21.9 °C–29.3 °C for females, respectively. It can be seen that the upper limit of acceptable temperature for female participants is not significantly different from that of males, but the lower limit is significantly higher and the range is narrower, indicating that during the air conditioning season in public buildings in Haikou City, women are less fond of cold environments than men.

The actual thermal neutral temperature of regular population in Haikou City during the indoor air conditioning season is 27.3 °C. Comparing the regular population of different genders, it can be found that the thermal neutral temperature of women is 1.8 °C higher than that of men, which is consistent with the overall situation of the respondents. In terms of acceptable temperature range, 90% of female residents can accept thermal comfort temperature ranges of 23.3 °C–33.3 °C, while for males it is 23.9 °C–31.4 °C. It can be seen that the lower and upper limits of acceptable thermal comfort temperature for male residents are lower than those for females, and the higher slope of the thermal adaptation model indicates that they are more sensitive to indoor air temperature.

It can be concluded that the actual thermal neutral temperature of the temporary population is 25.5 °C. The acceptable thermal comfort range for 80% of the temporary population in summer in Haikou City is 22.9 °C–28.0 °C. The 90% actual acceptable thermal comfort ranges for female and male are 23.0 °C–28.5 °C and 21.7 °C–27.3 °C, respectively.

Comparative analysis shows that the upper limits of the acceptable thermal comfort temperature range for 90% of the permanent population are about 3.0 °C lower than those of the regular population, and the adjustable range is also slightly narrow, indicating that after adapting to the living habits, cultural wind speed customs, and climate characteristics of Haikou City, there are differences in thermal comfort needs. This reflects the possibility of expanding the actual acceptable comfort zone of public buildings in Haikou City during summer based on current standards and regulations.

4. Discussion

Based on the data analysis result of Section 3 and existing studies, this section discusses the impact of living under the Haikou City climate on indoor thermal sensations and comfort demand. Afterwards, this section proposes indoor thermal design parameter suggestions for building spaces for different groups of people to work and live. Furthermore, in Section 4.3, the limitations of the paper and the prospects of related research in the future are pointed out.

4.1. The Influence of Heat Acclimatization on Thermal Sensation

By comparing the fitting regression results of the two groups of people, it can be found that the actual thermal neutral temperature of the permanent and adjacent populations is higher for females than males, and preferences of the permanent population of the same gender are also higher for the different populations. In terms of the actual acceptable temperature range, the upper limit value of males in the same population is lower than that of females, while the lower limit value of the permanent population is higher than that of the adjacent population. In addition, there is not much difference in the size of the range between the two male populations, while the difference is significant for females, with females residing nearby having a wider range and significantly lower limits than males, while females residing regularly have higher limits than males. From this, it can be seen that there are gender differences in the impact of human thermal adaptation on the indoor population in Haikou City. The change in thermal comfort needs of women is more significant than that of men, leading to a significant decrease in their tolerance to environmental temperature changes, especially in cold environments.

4.2. Thermal Comfort and Indoor Design Parameters Range

In Figure 14, the overall thermal neutral temperature of the permanent residents is in the middle of the male and female thermal neutral temperature, while the overall thermal neutral temperature of the temporary population is more inclined to the female thermal neutral temperature. This is caused by the fact that in the survey, the male to female ratio of permanent residents is close to 1:1, while the male to female ratio of temporary population is 3:5. According to the research results in this paper, the male to female ratio of permanent residents is 1:1 and the male to female ratio of temporary residents is 3:5. Office buildings, commercial buildings, and hotel buildings can be considered residential areas for permanent residents, residential areas for the overall population, and residential areas for the temporary population, respectively. Based on load consumption, it is proposed that the thermal comfort temperature requirement for regular residents is 23.3 °C–31.4 °C. The thermal comfort temperature requirement for the overall population is 23.2 °C–28.0 °C. The thermal comfort temperature requirement for the temporary population is 23.0 °C–28.0 °C. When the ratio of men to women is 1:1, the thermal neutral temperature of the whole population of permanent residents should adopt the data of survey linear fitting of 27.3 °C, and the thermal neutral temperature of the whole population of the temporary population should adopt the average value of male and female subjects of 25.0 °C. The thermal neutral temperature of the overall population was 26.2 °C. This result is further explained in the discussion section of this paper. In practical applications, engineers can flexibly set the cooling temperature of a building according to the conclusions of this paper and the ratio of men and women in the building.

4.3. Limitations and Future Research

This study provides guidance and reference for improving the indoor thermal environment design of green buildings in Haikou city. Although this study does not represent the population, more comprehensive studies are underway. This investigation of thermal comfort was conducted in air-conditioned circumstances. As such, the results are only applicable to the indoor parameter design of air-conditioned buildings. The results of this study may not be applicable in different climates and cultural areas. The narrow age distribution of the subjects is also a limitation, and the results should be interpreted accordingly. Moreover, in the future, the thermal comfort range of the human body in office buildings [48], medical buildings, and school buildings should be studied separately as well as the thermal comfort range and the flexibility of building energy systems.

5. Conclusions

At the end, the difference in the specific requirements for the thermal comfort of both regular residents and the temporary population in Haikou city was derived from a questionnaire survey of more than five hundred people. From these results, the conclusion has been drawn that the duration of settling has an obvious impact on the requirements of thermal conditions for satisfying comfort under the climate of tropics. Moreover, the indoor environment design parameters of spaces for the permanent and temporary populations in Haikou City need to be identified differently. Based on the overall population, long-term living, and temporary living classifications, effective identification of the indoor thermal comfort needs of residents in tropical cities was carried out. The actual thermal neutral temperature of the overall population is 25.7 °C, and 90% of their acceptable thermal comfort temperature range is 23.2 °C–28.0 °C. The actual thermal neutral temperature of the temporary population is 25.5 °C, and 90% of their acceptable thermal comfort temperature range is 23.0 °C–28.0 °C. The actual thermal neutral temperature of the regular population is 27.3 °C, their expected thermal temperature is 24.0 °C, and 90% of their acceptable thermal comfort temperature range is 23.3 °C–31.4 °C. The research results are of great significance to the setting of air conditioning design parameters in Haikou city.

This research will promote local governments to develop relevant standards to improve human thermal comfort while saving energy. More research can be conducted in the future to determine the thermal comfort of human beings in buildings of different ages and physical states (such as hospital wards, offices, schools, nursing homes, etc.) in tropical cities, and formulate indoor environmental design parameters for special buildings that meet specific requirements. Additionally, the energy savings associated with running the building according to the new comfort temperature zone should be investigated.

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