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Study on Thermal Comfort for University Classrooms in Pre-Heating Season in Xi'an

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ABSTRACT

Thermal comfort of students in university classrooms during transition season in Xi'an, before heating, is studied. Indoor thermal environment parameters and outdoor weather parameters of seven typical classrooms are measured. At the same time, the subjective questionnaires are used to know students' satisfaction and expectation with various environmental factors. 992 valid questionnaires are received. Based on the data collected, the thermal comfort of occupants in classroom is discussed and a thermal comfort adaptive model is established. The results show that the range of thermal comfort acceptable to students is broader than that defined in the ASHARE standard, indicating that students have some adaptability to indoor air environment. The measured indoor thermal neutral temperature is lower than the theoretical one. There is difference between the thermal sensation vote (TSV) and the predicted mean vote (PMV). The slope of TSV cure vs. operative temperature is greater than that of PMV, indicating that under actual condition, students are more sensitive to air changes. The proposed adaptive model provided a reference for understanding the thermal comfort of university buildings under natural ventilation environment in Xi'an, helpful to improve the thermal comfort and save energy for university buildings in Xi'an.

1. INTRODUCTION

PMV and PPD model (Fanger P. O., 1973) is currently adopted in the international thermal comfort evaluation standards ASHRAE 55 (2013) and ISO 7730 (1994) in the steady-state environment with air conditioning. However, the models have deviations in predicting human comfort in natural ventilated spaces. Busch (1992) conducted a field survey of the human body's thermal comfort conditions in naturally ventilated buildings and air-conditioned buildings in Bangkok and found that the comfortable ambient temperature in naturally ventilated buildings was significantly higher than the usual air-conditioning design temperature. Ealiwa et al. (2001) conducted a similar survey in Libya and found that the unmodified PMV model cannot be used to predict the thermal comfort of occupants in naturally ventilated buildings. Then Fanger and Toftum (2001) summarized the results of field surveys of non-air-conditioned buildings in Bangkok and Singapore and found that the higher the temperature of the environment, the more the people's actual thermal sensation vote deviating from predicted values of the PMV model. The thermal sensation value predicted by the PMV model is warmer than the actual feeling of residents.

During pre-heating transition seasons, natural ventilation is used for creating indoor environment for high density occupants in university classrooms in Xi'an, China. Because thermal comfort in the classrooms is different from steady-state environment with air conditioning and is also different from general residential or office buildings with low density, the thermal comfort of students in classrooms with natural ventilation during the pre-heating transition season is studied in this paper. Additionally, a thermal adaptation model for the classrooms in Xi'an before heating season is presented to provide a general understanding of the thermal comfort of university buildings under natural ventilation environment in Xi'an.

2. METHODS

2.1 Site Description

Figure 1 shows the building group of a university campus for the study in Xi'an. Four teaching buildings are around a tall office building, marked A, B, C and D, in different orientation. During the study, the state of doors and windows of classrooms in the teaching buildings, opened and closed, is completely determined by students. It is in a natural ventilation state. The information of the classrooms is listed in Table 1.

(a) Overlook (b) Office building (c) Building group

Figure 1: Views of buildings and surrounding

Table 1: Architectural features of the classroom

Classroom	N. of seats	Floor area(m^2)	Height (m)	Volume (m^3)	Windows exposition	Ventilation style
1	250	213.75	3.5	748.125	South	Natural ventilation
2	250	213.75	3.5	748.125	South	Natural ventilation
3	96	92.04	3.5	322.14	North	Natural ventilation
4	250	213.75	3.5	748.125	South	Natural ventilation
5	250	213.75	3.5	748.125	South	Natural ventilation
6	96	92.04	3.5	322.14	North	Natural ventilation
7	250	213.75	3.5	748.125	North	Natural ventilation

2.2 Climate Background

The study is carried out from November 1st to November 15th in 2017, in autumn or a transition period before heating. Large temperature difference of approximately 26.7℃ is between morning and evening. The minimum of outdoor temperature is 8.7℃ and the maximum temperature is 35.4. The highest relative humidity is up to 79.8%, while the minimum of relative humidity of outdoor air is 15.1% with a difference of 64.7%. The daily average of outdoor temperature and relative humidity distribution are shown in Figure 2 and Figure 3.

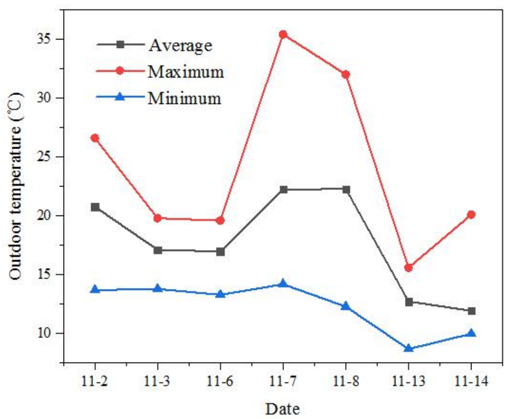


Figure2: Outdoor daily temperature

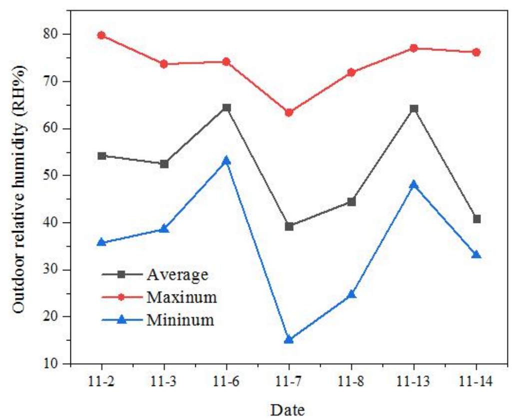


Figure 3: Outdoor daily relative humidity

2.3 Methods

Both measured and questionnaire method were performed.

2.3.1 Measurements: The instruments used in this study included a SWEMA03 omnidirectional hot-wire anemometer, a temperature-humidity self-recording instrument and a SWEMA05 black globe thermometer. The metabolic rate of participants could not be measured directly. Since they have sat in classroom for at least 20 minutes before filling questionnaires, it was given 69.84 W/m^2 (1.2met) according to the international thermal comfort standard ISO 7730 (ISO, 1994), which was the metabolism level of those who were sitting lightly. During the study, the students' clothes were recorded in detail. According to the ASHRAE standard, the thermal resistance of clothes was in units of clo (1clo=0.155 $m^2\cdot$℃/W).

The number of measuring points was determined according to the area of room. Five measuring points were selected and arranged at the front, the middle and the back of classroom in a type of plum blossom, 1.1m away from the ground and 0.5m away from wall and the window. In order to prevent the influence of solar radiation, the measuring points for outdoor air were set on the north side of the buildings without any sunshine.

2.3.2 Questionnaire: Assessment of thermal comfort for a classroom was given based on the responses of students or the questionnaires filled by students in the classroom and the data of measurement which was carried out simultaneously. 992 valid questionnaires were collected. The students were about 20 years old and took about 15 mins to answer their questionnaires which included four parts, namely the basic information on age and gender, the clothing information, the thermal sensation on seven-point scale (-3 cold, -2 cool, -1 slightly cool, 0 neutral, +1 slightly warm, +2 warm, +3 hot) and thermal preference responses (+1 warmer, 0 constant, -1 cooler). According to the seven-point thermal sensation scale, seven-point scale for relative humidity sensation (-3 too dry, -2 dry, -1 slightly dry, 0 just right, +1 slightly humid, +2 humid, +3 too humid) and air movement sensation (-3 too small, -2 small, -1 slightly small, 0 just right, +1 slightly big, +2 big, +3 too big) were created respectively, correspond to the humidity perception vote and draft perception vote.

3. RESULTS

3.1 Parameters and Votes

The statistical results of indoor environment parameters and questionnaires are shown in Table 2, including air temperature (t_a), relative humidity (φ), average radiant temperature (t_r), operative temperature (t_{op}), air velocity (v), cloth insulation (I_{cl}), predicted mean vote (PMV), predicted percentage of dissatisfied (PPD), thermal sensation vote (TSV), humidity perception vote (HPV), air movement perception vote (AMPV). The operating temperature and relative humidity are shown in Figure 4 and Figure 5. In Figure 4, it is seen that high percentage of operating temperature is between 21℃ and 24℃, accounting for 85% of the total sample number. In Figure 5, it is shown that the relative humidity of the classroom is moderate, and the relative humidity of about 85% of the samples is from 40 RH% to 50 RH%.

Table 2: Indoor environment parameters and questionnaires

Parameter	Average	Highest record	Lowest record	St. deviation
t_a(℃)	22.49	25.58	17.8	1.620
φ(%)	49.17	64.63	34.63	7.191
t_r(℃)	23.71	26.18	19.49	1.501
t_{op}(℃)	23.10	25.67	18.94	1.510
v(m/s)	0.053	0.085	0.02	0.014
I_{cl}(clo)	0.114	0.12	0.11	0.004
PMV	-0.04	0.75	-1	0.356
PPD	12.08	22.45	5.01	5.309
TSV	0.79	2.20	-1.40	0.733
HPV	-0.70	-0.4	-2	0.271
AMPV	-1.21	0	-2.36	0.515

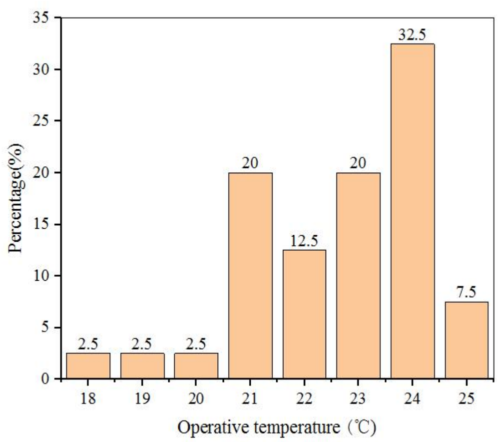


Figure 4: Frequency distribution of operating temperature

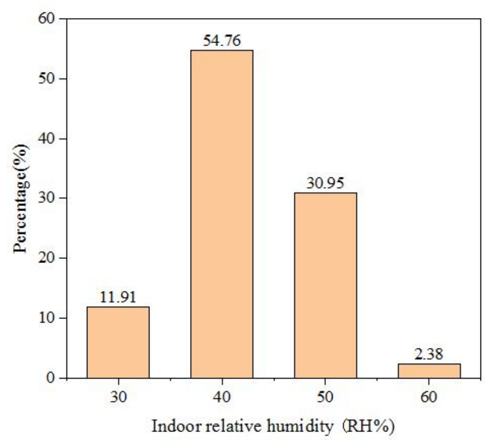


Figure 5: Frequency distribution of relative humidity

3.2 Effect of Humidity

The relative humidity recommended by the thermal comfort standard is in 25~70%RH. The relative humidity during the study fluctuates between 30%RH and 65%RH. Figure 6 shows the humidity perception votes (HPV) given by the students for the classrooms, 98% of which are between -2 and 0, indicating that the air in this season is dry. More humidity is required in the transition season before heating in Xi.an.

3.3 Effect of Wind Speed

The average wind speed during the study was 0.053m/s. Figure 7 shows the air movement perception votes (AMPV) by the students. 18.03% of the students believe that the wind speed was too small and 28.76% of them felt bad who thought that there was no wind at all. It can be seen that low wind speed decreases the students' thermal comfort in the transition season in Xi'an to a certain extent. The complains on low wind speed were often heard from students during the study. One of the reasons for this complain we found was from that some students closed doors or windows for a quiet learning environment. Moreover, the ventilation of the buildings was not very good. However, 52.89% of the students felt good, or the wind speed was moderate, indicating that students had a certain degree of adaptability to the environment.

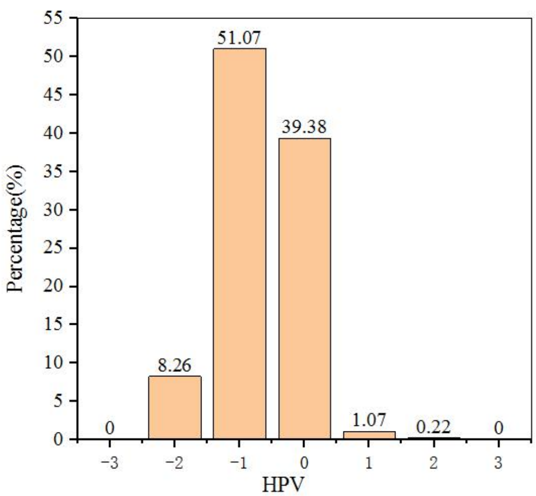


Figure 6: Humidity Perception Vote (HPV)

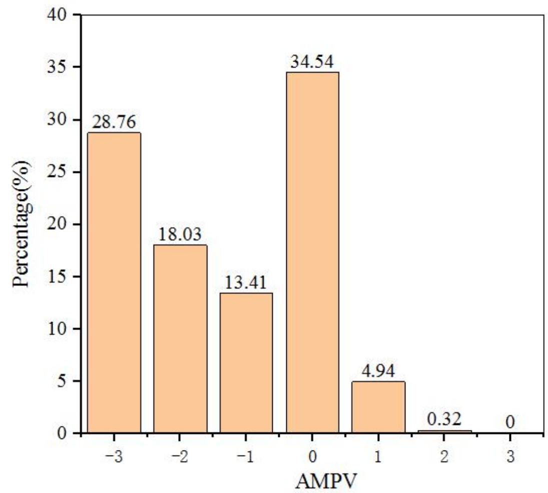


Figure 7: Air Movement Perception Vote (AMPV)

4. DISSCUSSION

4.1 Operating Temperature

When the relative humidity is in the thermal comfort range and the indoor air velocity is relatively low, operative temperature (t_{op}) is recommended as an indicator for thermal comfort (Wang Zhaojun, 2004). It reflects the combined effect of convective heat transfer between a body and air and the radiation heat transfer of the body with enclosure. It is reasonable to use t_{op} to evaluate the influence of indoor air temperature and radiation temperature on human thermal sensation. During the time of the study the indoor relative humidity is between 30~65%RH and the average of indoor air velocity is 0.053m/s. Therefore, t_{op} was used to analyze the human thermal sensation in the transition season before heating in the classrooms in Xi'an which is calculated from the average of the air temperature(t_a) and the average radiation temperature(t_r).

4.2 Analysis of Acceptability

Both direct and indirect methods are used to study the acceptance rate of the subjects for the thermal environment. The direct method is that the students are asked to answer directly in questionnaires if the environment is accepted. The statistical results show that 96.88% of the subjects can receive the thermal environment during our testing. The indirect method is that the acceptability is calculated based on the thermal sensation voting values which are also filled in the questionnaire by participants. When votes are in range of -3, -2, 2 and 3, the air environment is generally not acceptable. Dissatisfied rate at a temperature is defined as the percentage of voters who dissatisfies the air environment is unacceptable at that temperature.

In ASHRAE standard (ASHRAE55, 2013) and ISO 7730 standard (ISO, 1994) it is stipulated that the environment accepted by 80% of residents is thought as a thermal comfort environment. The temperature corresponding to the dissatisfaction rate of voting greater than 20% is an unacceptable temperature for people. Figure 8 shows the measured percentage of dissatisfied with operative temperature. During the experiment, the operating temperature is in 18~26℃. When the student's dissatisfaction rate is lower than 20%, the measured acceptable operating temperature in the study is in range of 18~25.63℃ for students in classrooms in the transition period before heating in Xi'an. Figure 9 shows the predicted percentage of dissatisfied (PPD) with operating temperature. It is clear that the acceptable operating temperature is in the range of 19.56~26℃. The lowest acceptable value for the measured acceptable operating temperature is much smaller than the lowest acceptable value for the predicted operating temperature indicating that the actual measured thermal comfort zone is different from the predicted thermal comfort zone. What's more, uncertainty in logged clothing level and metabolic rate is high. This conclusion further verifies that PMV-PPD model is not appropriate.

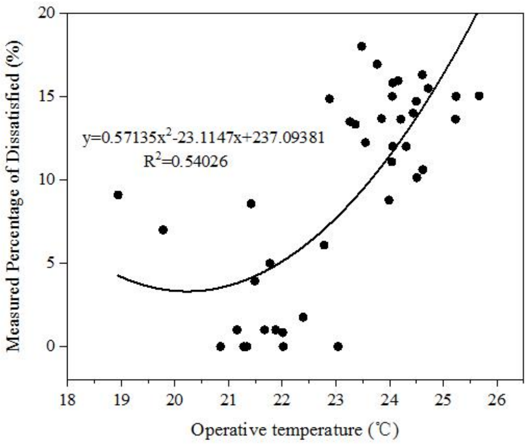


Figure 8: Measured Percentage of Dissatisfied

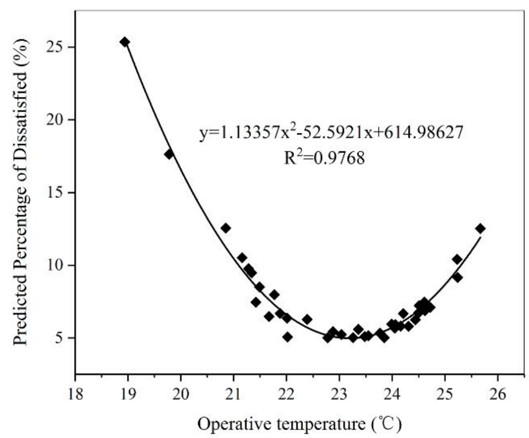


Figure 9: Predicted Percentage of Dissatisfied (PPD)

4.3 Thermal Neutral Temperature

In this paper, the operating temperature was grouped according to 0.5℃ degrees, and the average thermal sensation in each group was analyzed by regression analysis. Figure 10 shows the linear regression result of the actual average thermal sensation vote to operating temperature. The thermal neutral temperature is defined as the operating temperature when TSV=0 of the linear regression formula. Thermal neutrality is a state in which people feel neither cold nor hot. By linearly regressing the data measured in the classroom, the regression formulas for TSV, PMV and PMV_e for the natural ventilation buildings in the transition season before the heating in Xi'an were obtained. Equation (1) is the linear regression of the actual thermal sensation voting (TSV). When TSV=0, the measured thermal neutral temperature of the classrooms in the transition season before heating in Xi'an is 20.71℃. According to the slope of the equation, it is known that when the indoor temperature is changed 1℃, the thermal sensation will be changed 0.33 scales.

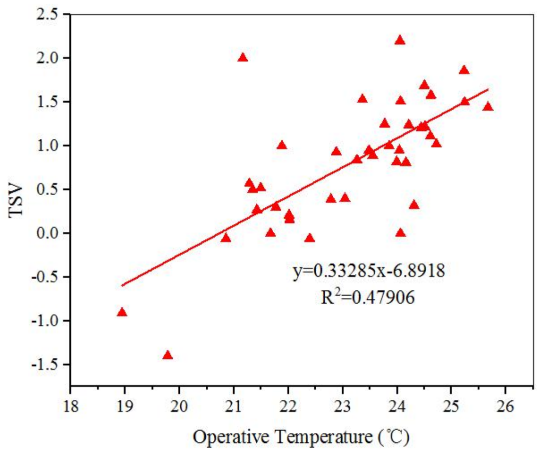
$$TSV=0.33285t_{op}-6.8918, \quad R^2=0.47905 \tag{1}$$

Figure 11 shows the predicted thermal sensation vote (TSV) which are calculated by MATLAB software with operating temperature and their regression line. Equation (2) is the linear regression of them. When PMV=0, the theoretical thermal neutral temperature obtained is 23.31℃. It is 2.6℃ higher than the measured thermal neutral temperature, indicating that the students can adapt to rather cold air in the transition season. The slope of the measured TSV is 0.33285 greater than the slope of the PMV is 0.22121, indicating that students are more sensitive to the change of temperature under actual condition. The PMV indicator is given under the consideration that the physiological and psychological response of human body to the thermal environment is the same, regardless of season effect. In fact, human physiological responses and psychological expectations are important factors affecting thermal comfort. It is probably one of the reasons for the large difference between PMV and the measured data (TSV).

$$PMV=0.22121t_{op}-5.15636, \quad R^2=91916 \tag{2}$$

Figure 12 shows the data of TSV, PMV and PMV_e. Fanger gave expected factors (e) for different regions, which were mainly used to correct PMV in non-air-conditioned environment. $PMV_e=e\times PMV$ in Fig.12. For China, the expected factor e is 0.7 (Fanger P O, 2002). Compared with TSV, PMV and PMV_e, in the range of 18.5～23℃, PMV_e revised by 0.7 is closer to the actual thermal sensation. Especially when indoor operating temperature is around 18.5℃, which is almost equal. When students feel temperature within the thermal neutral zone, the modified PMV value is -0.4. Hence, the modified PMV model cannot correctly give the prediction value of zero. PMV has a big deviation from the actual thermal comfort survey results in transition season before heating in Xi'an.

There is a large deviation between the predicted line and the measured curve and PMV cannot be used to explain the comfort of the transitional classrooms before heating. There is a big difference between PMV or PMV_e and the actual thermal comfort results in the non-air-conditioned environment. It is mainly due to people's low expectation in non-air-conditioned environment (Yangqin Ou et al, 2005).



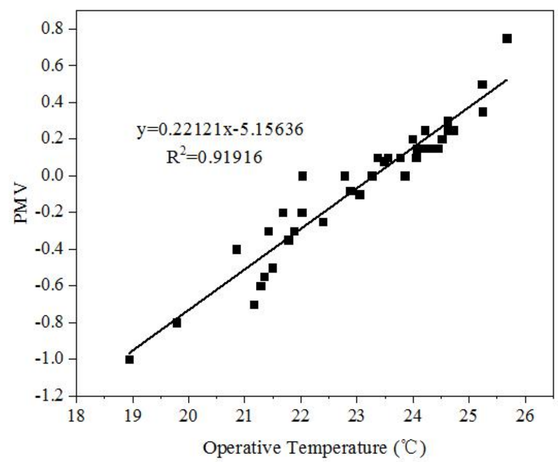


Figure 10: Regression of observed thermal sensation votes (TSV) with operation temperature
Figure 11: Regression of predicted thermal votes (PMV) with operation temperature

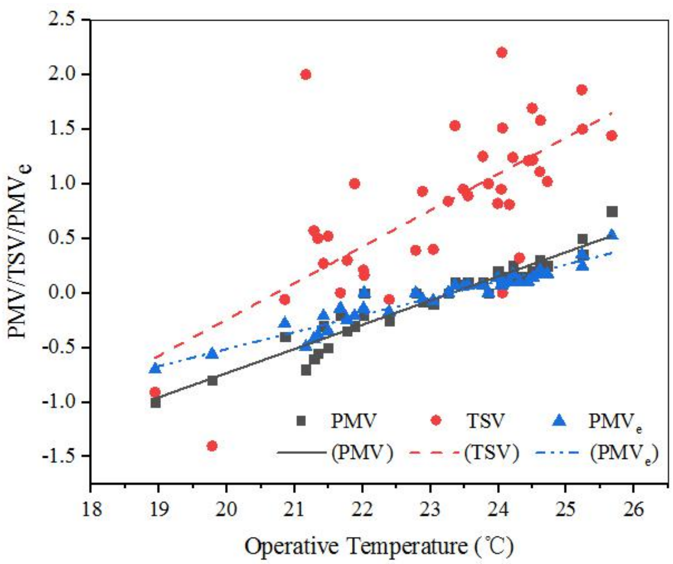


Figure 12: TSV, PMV and PMV_e with operation temperature

4.4 Expected Temperature

The thermal neutral temperature is usually not the most comfortable temperature for human body (Humphreys M A,1975). The preferred temperature that people are willing to accept often deviates from the thermal neutral temperature. Two methods can be used for the calculation of preferred temperature, namely thermal perception method and direct interrogation method. The method of direct interrogation is adopted in this paper to reflect the feelings of occupants. Taking an interval of 0.5℃, the numbers of people voting for warming (+1) and cooling (-1) are counted respectively. Figure 13 shows the percentage of both people and also the linear regression results with the operating temperature. The temperature corresponding to the intersection point of the two fitting curves is the expected temperature. The expected temperature of the university classrooms in Xi'an is 22.99℃ during the transition season. The measured thermal neutral temperature is equal to 20.71℃, which is 2.28℃ lower than the expected temperature indicating that residents are accustomed to warmer environment when the weather changes from hot to cold in autumn, i.e., people expect higher temperature subjectively.

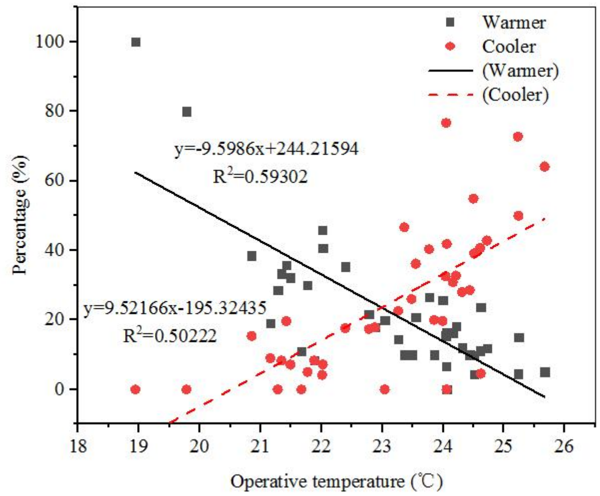


Figure13: Calculate the desired temperature

4.5 Climate Adaptability Model

Humphreys points out that indoor thermal neutral temperature is related to outdoor climate, especially in natural ventilation buildings (Humphreys M A, 2007) The establishment of climate adaptability model can solve the relationship between human thermal comfort and outdoor conditions under natural ventilation. During the transition season, the indoor comfort temperature is variable to the outdoor conditions and people need to coordinate, endure, and take adaptive measures to meet their comfort. In this paper, the outdoor temperature is grouped according to 1℃ degrees,and the thermal neutral temperature of each group is calculated. Figure 14 shows the linear regression result of the thermal neutral temperature to the outdoor temperature. By linear regression, Equation (3) is the climate adaptability model of transition season for classroom in Xi'an is obtained. It can be seen from the model that if the change of 1℃ occurs in the outdoor temperature between 10℃ and 30 ℃, the thermal neutral temperature will be changed by 0.33℃ accordingly. Further, thermal comfort model on the transition season before heating in Xi'an classrooms can be predicted the comfort zone, which is good for seeking economic operation mode of building equipment and for climate analysis in the stage of building scheme design.

$$t_n=0.32963t_o+15.01553 \quad R^2=0.84103 \tag{3}$$

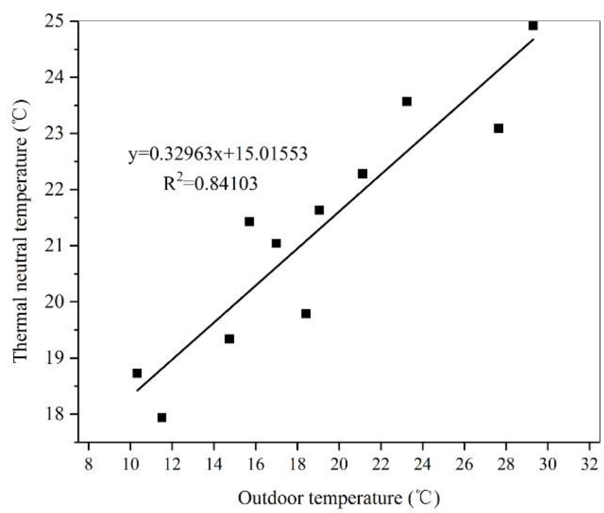


Figure 14: Linear regression of thermal neutral temperature (t_n) and outdoor temperature (t_o)

6. CONCLUSIONS

Thermal comfort in university classroom in Xi'an during transition season before heating was studied. The results showed that the range of measured acceptable thermal comfort temperature is different that calculated by PPD, indicating that PMV-PPD model is not appropriate. The measured thermal neutral temperature (20.71℃) for the season before heating is obviously lower than the theoretical one (23.3℃), which testifies that occupants have stronger adaptability to the cold air during the transition period. The revised PMV cannot correctly give the thermal neutral zone in Xi'an. Significant difference between TSV and PMV indicates that students are more sensitive to the change of air. The expected temperature (22.99℃) is 2.28℃ higher than measured thermal neutral temperature, forecasting that people expect a warmer temperature environment. The proposed adaptive model provided a reference for thermal comfort of university buildings before the heating.

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