Study on Human Thermal Comfort in Asymmetric Radiant Heat Environment in Large Space

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Abstract. In order to study indoor temperature distribution in a large space and thermal comfort of human, an environmental test and questionnaires were carried out at an airport in Xi'an in summer. The results show that the temperature distribution in the space is asymmetric. The room temperature increases from cooling floor to 0.1m high, but then it has little change within 1.5m high. However, the temperature fluctuation in horizontal is significantly influenced by internal equipment, lighting, elevator and etc. According to the environmental parameters and subjective voting, 55% of the PMV values are greater than 0.5, and more than half of the thermal feelings near the heat source and glazing curtain wall are "warmer". Properly increasing the wind speed of air vent could effectively improve the environmental comfort.

1 Introduction

As a large space, the airport needs to carry a large number of people. With the continuous growth of the number of domestic terminals, how to make most passengers satisfied with the indoor environment of the terminal is the focus of some current research. Geng et al. [1] Conducted environmental measurement and questionnaire survey on the indoor environmental quality of eight major airport terminals in China. It is found that there is a high correlation between subjective satisfaction and objective environmental measurement. Based on the analysis of Kano model, it is found that "thermal comfort" and "space layout" are the basic factors affecting the overall satisfaction of passengers. and the research on thermal comfort of three airports in Brazil by Jacqueline elhage Ramis et.al [2]. is to find out the main causes of passenger complaints through on-site temperature measurement. Kotopouleas et al. [3,4] A field measured was conducted in three airport terminals in the UK, and a questionnaire survey was conducted carried out among 3087 personnel. The average sensitivity of staff to temperature change is 1.6 times that of passengers. Passengers and staff demonstrated a high level of thermal tolerance and acceptable temperature range, with an average of 6.1 °C in summer and 6.7 °C in winter. Jia et al. [5] Through the field study of several terminals, it is concluded that the passenger can withstand the temperature change in a wide range, and the adaptability to indoor thermal environment tends to be same as the residence time increased.

A radiant cooling/heating systems was first attempt to be applied in Terminal 3 of Xi'an airport in China, and it has been put into operation in 2012. The indoor thermal environment controlled by the cooling floor should attract the attention of many researchers and engineers. With the consideration, an environment test and questionnaires were carried out in summer. The key environmental parameters that have significnt impacts on comfort level can be determined through analyzing the measured data.

2 Methodology

The terminal adopts independent temperature and humidity control technology in some large spaces. Radiant heating/cooling floors are responsible for partial sensible load, and a displacement ventilation system mainly treat fresh air and room latent load. In this test, relevant parameters of thermal environment are tested in a certain area of terminal 3 of Xi'an Xianyang International Airport. In order to observe the impacts of internal source and glazing curtain wall on indoor thermal environment, the testing region (Fig. 1) is divided into three parts. The first part is close to the heat sources such as shops and elevators, and the air vent is placed not far away. The second part is the area without any heat source. The third part is near to glazing curtain wall.

(a) Real scene of testing region.

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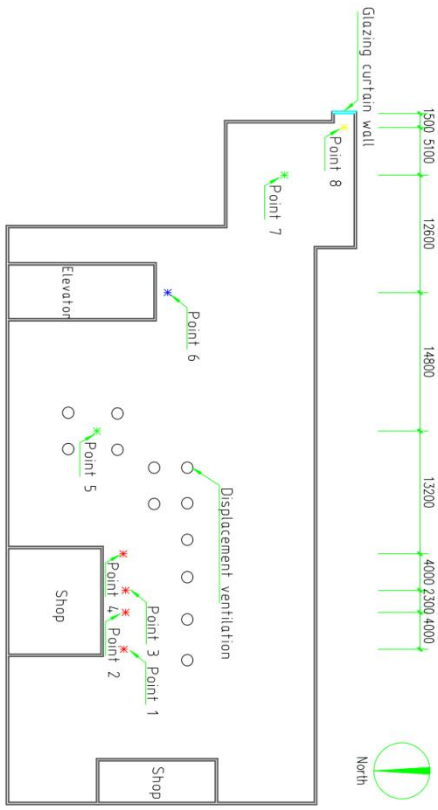

(b) Layout of testing region and measuring points.

Fig. 1. Testing region in T3 terminal.

PMV index is generally used to analyze the environment. The thermal comfort index PMV (predicted mean vote) reflects the deviation degree of human thermal balance. It is a comprehensive comfort index prposed by Professor P.O. Fanger [6] , which represents the feeling of most people in the same environment. These evaluation criteria are summarized into the temperature index to obtain the thermal comfort equation.

$$\begin{aligned} PMV &= [0.303exp(-0.036M)+0.0275] \\ &\times\{M-W-3.05[5.733-0.007(M-W)-P_a] \\ &-0.42[(M-W-58.2)-0.0173M(5.867-P_a) \\ &-0.0014M(34-t_a)-3.96\times10^{-8}f_{cl} \\ &\times\left[(t_{cl}+273)^4-(t_{mrt}+273)^4\right]-f_{cl}h_c(t_{cl}-t_a)\} \end{aligned} \quad (1)$$

$$PPD=100\text{-}95*exp\text{-}(0.03353*PMV^4+0.2179*PMV^2) \quad (2)$$

Where,

t_{cl}: Outer surface temperature of clothes, ℃, from reference, [6]

t_a: Air temperature around human body, ℃, testing value.

P_a: Partial pressure of water vapor around human body, kPa, from reference. [6]

h_c: Convective heat transfer coefficient W / (m^2 · K), from reference. [6]

f_{cl}: Area coefficient of clothing, clo，from reference. [6]

RH: Relative Humidity, %, testing value.

v: Speed, m/s, testing value.

MRT: Mean radiant temperature, ℃, calculating value by equation

$$T_m=[T_g{}^4+\frac{h_c}{\sigma_e}(T_g\text{-}T_a)] \quad (3)$$

T_g: Globe temperature, ℃, testing value.

MET: Metabolic equivalent, met, calculation value.

Therefore, the testing parameters and corresponding instruments list in Table. 1 and Figure.2 . The RC-4HC and AZ-8778 is placed at each measuring point. To observe the vertical temperature gradient changes, the instruments are respectively placed 0.1m, 0.6m, 1.1m and 1.5m off the ground.In the sitting position, 0.1m corresponds to the foot, 0.6m corresponds to the waist and knee, and 1.1m corresponds to the neck. When standing, 0.1m corresponds to the foot, 0.6m corresponds to the waist, 1.1m corresponds to the knee and 1.5m corresponds to the neck. Floor temperature is measured with a thermometer gun and averaged by multiple readings. Use AR866A to measure the wind speed at 1.1m for each measuring point.

Table 1. Measured range and accuracy of the instruments.

Instrument	parameter	Accuracy
Temperature and humidity self recorder RC-4HC	*Ta*(℃) RH(%)	±0.5℃
Black Ball Temperature RecorderAZ-8778	*Tg*(℃)	±0.6℃
Anemometer AR866A	*v*(m/s)	0.01m/s
Thermometric F566-2	*Ta*(℃)(0m)	±1%

Fig. 2. Instrument diagram of Jingchuang RH-4HC, AZ-8778 and AR866a

TSV is used as an index to evaluate human thermal sensation in the environment, The subjective investigation contents of human psychological thermal response include: local thermal sensation and thermal comfort of forehead, back, arm, hand and lower leg, overall thermal sensation and thermal comfort, etc. ASHRAE 7 continuous scale [7] is used to evaluate local and overall thermal sensation, and intermittent scale is used to evaluate local and overall thermal comfort.

2.1 Environmental parameter analysis

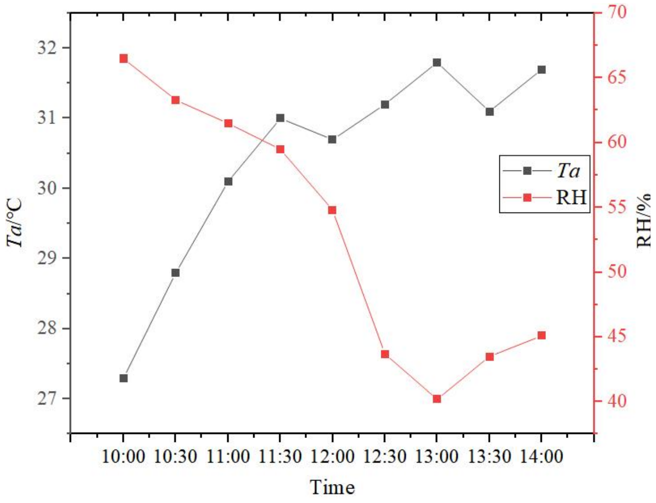

Fig. 3. Weather conditions during testing period

The test time is 10:00-14:00, and outdoor air temperature and relative humidity duiring the testing period are shown in Figure. 3. The outdoor temperature increases with time, while the relative humidity decreases.

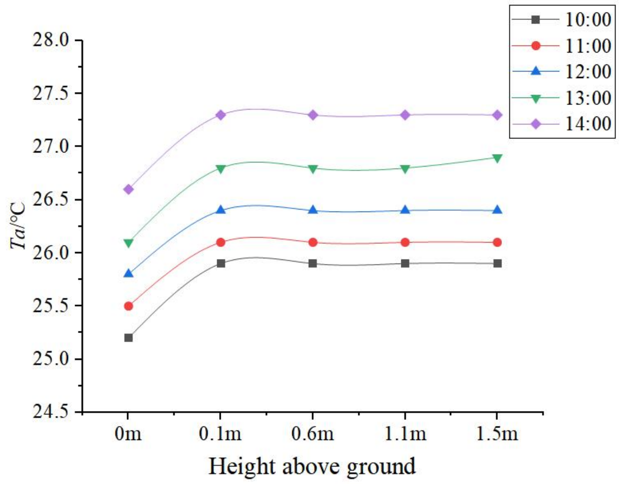

Fig. 4. Vertical Temperature Distribution at Point 1.

Fig. 4 illustrates that the air temperature at the vertical height at point 1 increases with time. The room temperature increases obviously from cooling floor to 0.1m high, but then it has little change with the height. The temperature variation law of other measuring points is similar to that of point 1. The reason is that the radiation cooling floor works terminal 3.Radiant cooling floor exchanges heat with indoor air by means of radiant and convective heat transfer. The cool air from displacement air vent (1m high) encounters other heat sources such as people, the temperature rises, and the air floats up. By inquiring and investigating the thermal sensation of the four parts of the personnel, there is no obvious discomfort with the difference in vertical temperature. This result has a similar distribution law with the previous test results of Zhao [7] et al. In the vertical height of the terminal.

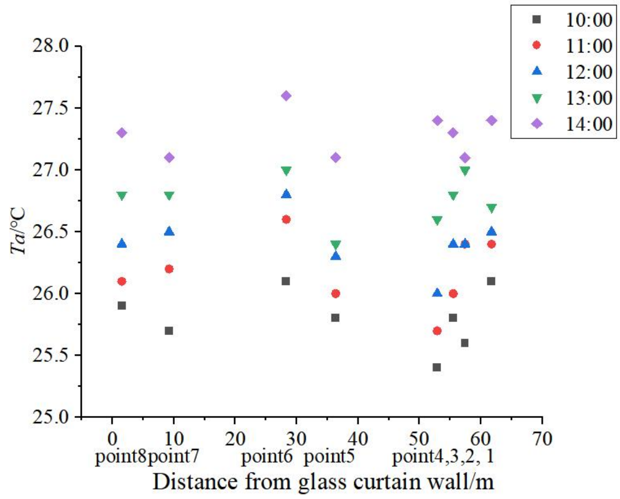

Fig. 5. Air temperature at each measuring point 1.1m from the ground.

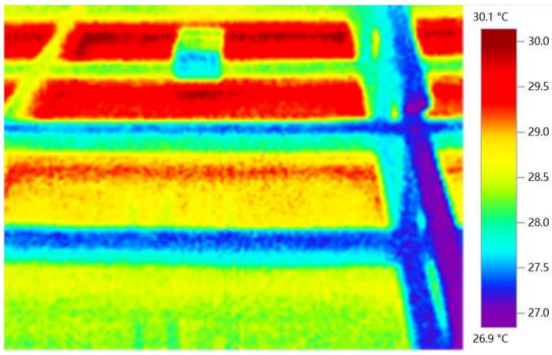

Fig. 6. Thermal imaging of glazing curtain wall at point 8 at 13:00

Since the temperature variation can be ignored in the range of 0.1m and 1.5m high, the temperatures at 1.1m height are used to present the temperature variation in horizontal direction.

temperatures at 1.1m height of the eight points are shown in the figure. 5. The air temperature of all measuring points increases with time. The peak temperature value of each testing point occurred at 14:00 p.m. Overall, the temperatures at points 5 and 7 are relatively low because there is no heat source surrounding and they are close to air vents. There is a charging pile next to point 1, the heat emitted by the charging pile increases the air temperature. Point 6 is close to the escalator. Point 8 is close to the glazing curtain wall. As Figure 5 illustrates, the temperature of the curtain wall is between 28-30.1 ℃, The heat source emits heat to the space through radiation and convective heat transfer (mainly radiation). The heat dissipation of elevator has the greatest impact on the indoor, followed by the heat dissipation of store lights and charging piles. The temperature of point 1 is generally higher than that of points 2-4, because point 1 is at the charging pile, more and more people use chargers. The temperature near the curtain wall is obviouly affected by the outdoor air temperature.

Inputting the measured environmental parameters *Ta,* RH, *v* (The whole process is in a static wind state, and the wind speed is recorded as 0.01m/s), The metabolic equivalent can be approximately regarded as 1met, and

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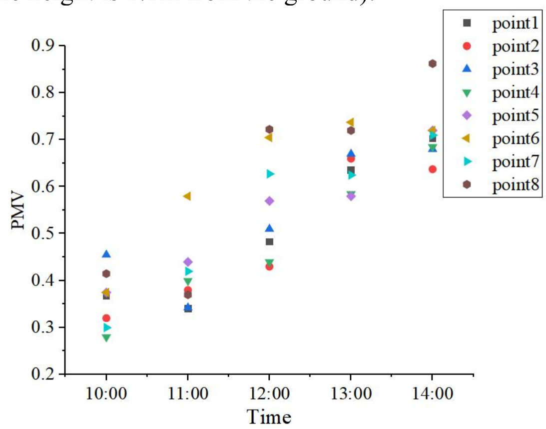
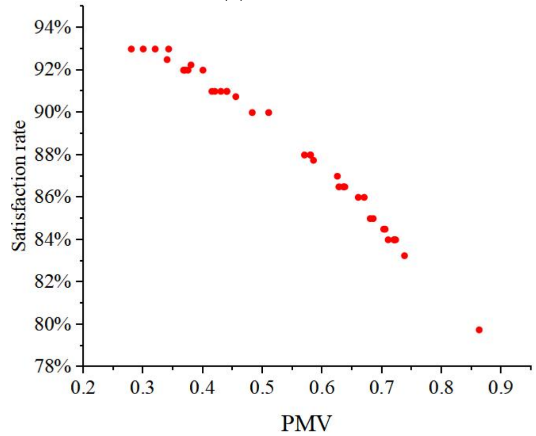
the thermal resistance of the clothing worn by the subjects can be approximately regarded as 0.6clo, which is a typical summer clothing thermal resistance.and *Tg* into the PMV to obtain the PMV value of each point (The height is 1.1m from the ground):



(a) PMV value



(b.) Relationship between PMV and satisfaction

Fig. 7. PMV value and satisfaction

The PMV value is shown in Figure. 7-a, and 55% is greater than 0.5 during testing period. According to the thermal comfort requirements of ASHRAE standard 55-2017, PMV greater than 0.5 is relatively hot.From the numerical point of view, after 11:00, the PMV value at point 6 and point 8 is the highest among all points, which is basically caused by the high air temperature and high black ball temperature at these points, implying that the heat from elevator and glazing curtain have obvious impacts on comfort level.

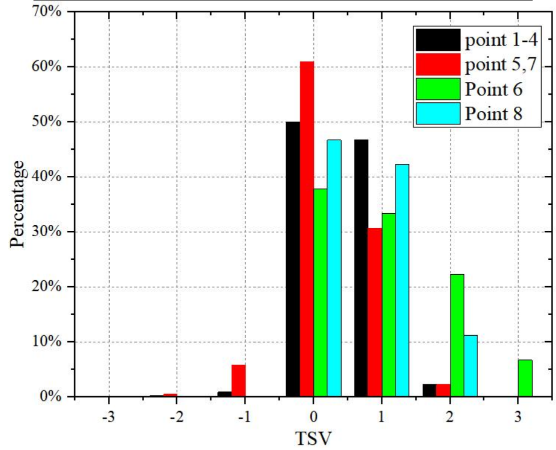
Figure.7-b shows the relationship between PMV and satisfaction. Satisfaction is calculated by PMV-PPD model. It is a predicted value, which reflects people's evaluation of the current environment. As the value of PMV increases, the satisfaction of people to the environment decreases.

2.2 Subjective questionnaire analysis

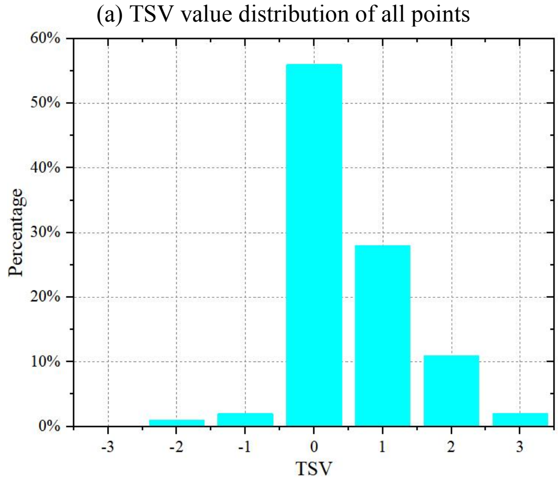
Reference [8] suggested that 100 subjects were randomly selected in an experiment, The situation of testers is shown in the table. 2. The tester is in a sitting or standing position. The sedentary time of the passengers is more than 15 minutes.

Table 2. Testers Situation.

Tester Information		Number
Gender	Male	56
	Female	44
Identity	Passenger	12
	Staff	88
Age	<18	4
	19-30	25
	31-45	32
	45-60	27
	>60	12



(a) TSV value distribution of all points



(b) Overall distribution of TSV

Fig. 8. TSV value distribution of all points

Figure. 8 shows the distribution of TSV values and overall values of all points. The environment of points 5 and 7 is considered "neutral" , more than 50%.People at points 1-4 and 6 of the heat source and point 8 of the glazing curtain wall feel "hot" more than people without heat source. Compared with the PMV value in the figure 8, TSV can also reflect the same thermal feeling of different positions in the space, and more than 80% interviewees are satisfy the thermal environment.

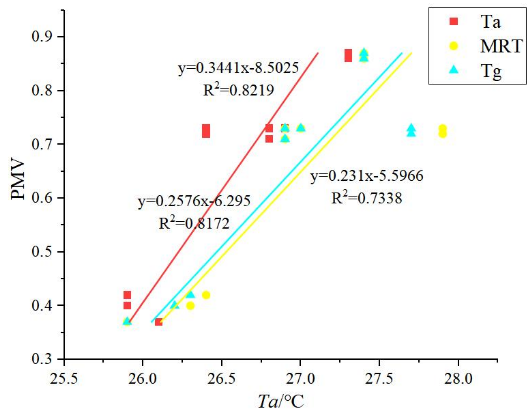


Fig. 9. Linear regression diagram of different temperature parameters and PMV

Figure. 9 shows the relationship between PMV values and *Ta*, MRT and *Tg*. It can be seen that the air temperature in the environment is most closely related to PMV. Appropriately reducing the air dry bulb temperature or increasing the wind speed could improve the environment comfort.

3 Conclusion

This paper tests the environmental parameters and subjective questionnaire survey of a space in the terminal, and obtains the following conclusions.

1.The temperature in space is asymmetric. 55% of the PMV values are greater than 0.5, and many values are greater than 0.5. Most people feel "hot" near to the heat source and glazing curtain wall, hoping that the environment will be "cold".

2.According to the fitting image and curve of PMV(Fig.9), The air temperature has the greatest impact on environment comfort level.Reducing the air temperature could significantly improve the environment.

3.During the test, the wind speed in the environment is in a static state, which is 0.01m/s. Increasing the air volume of displacement ventilation should significantly improve the environmental situation. It can also consider adding vents under heat sources or seats.

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