doi:10.11835/j.issn.1671-8224.2016.02.04

To cite this article: ZHU Pei-gen, WANG Chun-wang, KONG Wei-tong, SONG Hua. Thermal comfort evaluation of people in subway station [J]. J Chongqing Univ Eng Ed [ISSN 1671-8224], 2016, 15(2): 72-82.

Thermal comfort evaluation of people in subway station

ZHUI Pei-gen †, WANG Chun-wang ‡, KONG Wei-tong, SONG Hua
National Defense Engineering Institute, PLA University of Science & Technology, Nanjing 210007, P. R. China

Received 11 December 2015; received in revised form 23 March 2016

Abstract: We analyzed the characteristics of subway station environment and the change of thermal comfort for passengers when they are in and out of the station. The dynamic thermal comfort evaluation model RWI (relative warmth index) and HDR (heat deficit rate) were built on the distinguishing features of public area in subway station. Taking one representative subway station in Nanjing as the research object, the thermal comfort conditions in different seasons and different parts were studied by field tests, questionnaires and model-evaluating. The calculated RWI shows that although the thermal comfort in Nanjing metro is relatively acceptable, ideal thermal comfort has not been achieved. And it is found that associated with predicted mean vote (PMV), using RWI can evaluate the thermal comfort more precisely.

Keywords: subway station; thermal comfort; evaluation; questionnaire; RWI/HDR

CLC number: U231+.4  Document code: A

1 Introduction

In recent years, the development of city and the sharp-increase of population promote the booming of transportation systems in many countries, especially rapid transit systems, such as metro lines. As more and more passengers take the subway as their means of transport, the number of passengers increases rapidly within a subway. Thus, it is a crucial issue to evaluate the thermal comfort level for subways to ensure different thermal comfort conditions within acceptable limits. Surveys and mathematical models are two main methods that are used to assess the degree of thermal comfort among occupants of a building and the expected comfort temperature. Wang et al. [1] conducted a study about underground-temperature’s changing rules of a subway station in Beijing. Air temperatures around platform and in tunnel, as well as that of tunnel wall and ticket lobby were measured respectively. It was found that when the train was getting through the tunnel, temperatures of the air and the wall would increase instantly and changed with a large extend. The temperature of the ticket lobby was affected by surface temperature and piston wind at the same time. Utilizing the relative warmth index (RWI), Yin et al. [2] evaluated people’s thermal comfort at a subway station in Tianjin. The advice on optimum air temperature set point in
Tianjin subway station was also proposed. Yang et al. [3] proposed that it was necessary to run chilled-water pumps, air handing unit (AHU) fans and back/exhaust fans with frequency conversion technology (FCT) to reduce the energy consumption with temperature and velocity fields distribution both in the comfortable range. Transportation Air Conditioning Committee of American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) proposed RWI for thermal comfort design and investigation in metro environment. The RWI is a function of various parameters, including temperature, relative humidity, air velocity, individual clothing, and metabolic rate. Now, the application of RWI in design process of metro systems is a common practice but it has not been widely used to evaluate thermal conditions in operating underground railway systems. Abbaspour et al. [4] used RWI to evaluate the thermal comfort at Tehran metro stations and carriages of lines 1 and 2. The research was carried out during September 2006 and July 2007 at different zones of stations. And it was found that the measurements in September 2006 did not exceed the thermal limit while it did exceed in July 2007. Ampofo et al. [5] reviewed published work on thermal comfort for the underground railway environment in UK and got a conclusion that the acceptable underground thermal comfort criteria differed from those of normal buildings in the ground. Based on the passenger percentage of dissatisfying to the thermal conditions, they defined ‘acceptable’ thermal comfort criteria for an underground railway environment. An European project called EPIQR (energy performance, indoor air quality and retrofit) is used to assess and determine the energy performance of buildings, indoor air quality and possible replacement/maintenance actions. The developed tool allows the user to answer a questionnaire related to index of environmental quality (IEQ) in his/her facility associated with the facility information (e.g. address and age of persons living in the apartment). Bluysen [6] considered that it acted as a diagnosis and analysis tool for the complaints and it took corrective actions. Marzouk et al. [7] presented an application that utilized the wireless sensor network (WSN) and the building information modeling (BIM) to monitor thermal conditions within a subway in Cairo. BIM-based model was used to visualize the readings of air temperature and humidity levels in the subway spaces, and WSN was used to measure air temperature and humidity at different spaces within the subway via a group of transmitter nodes attached with different sensors. Through the formation of the database containing air temperature and humidity readings, it was possible to track thermal comfort problems in the subway. Kim et al. [8] monitored and predicted indoor air quality (IAQ) of subways. Air pollutants, air temperature and humidity were measured at one underground subway station in Korea.

Air temperature in underground stations is higher than that in the outdoor environment and as a result subways require an efficient ventilation system or heating, ventilation and air conditioning (HVAC) system. If the HVAC system is not running and maintained properly, the energy consumption increases, the passengers thermal comfort decreases and the rate of satisfaction between passengers decreases. Therefore, a major way to save energy for the HVAC systems is to design optimal control strategies to minimize the overall energy consumption while still maintain the satisfied indoor thermal comfort and healthy environment [9]. Freire et al. [10] has examined the indoor thermal comfort control problem in buildings equipped with HVAC systems. He proposed different strategies to reduce energy consumption and maintain acceptable indoor air conditions related to thermal comfort. Therefore, in terms of energy saving, it is necessary to evaluate the
thermal comfort of people in subway station and make thermal comfort conditions in acceptable limits.

2 Overview of subway environment and the thermal comfort of people

2.1 Characters of subway environment

Nowadays, most cities possess giant and complete metro system together with underground stations, above ground stations and elevated stations. Most of the stations are deeply underground, so the outside air gets in only through the passageway and the ventilating shaft. As a result, the underground environment is much different from that of the above ground. There are four main characters of subway environment: 1) Being less affected by the outside air parameters, subway environment has good thermo stability. However, the environment is not always comfortable for different seasons. For instance, the environment is still too warm in summer. This is because the heat generated by people, equipment and the train’s operation cannot be extracted timely and efficiently. 2) The air relative humidity is high in a subway station as it is in other underground works. 3) The nature ventilation is not good, so the association with mechanical ventilation is needed to remove redundant heat. 4) As previously mentioned, air flow in subway is disturbed greatly by piston wind coming with the train, which would make people feel uncomfortable.

2.2 Thermal comfort of people in subway station

There are two kinds of people in a subway: the staff and passengers. The staff generally spends most of their time in office areas while a few of them (such as security and sales personnel) stay in ticket lobbies and the platforms. As for passengers, they often take the subway station as a transition space. There are three main activities they perform in a subway: buying a ticket, moving from level to another and waiting for the train, indicating that they just stay for a little while. In terms of thermal comfort, the staff’s is considered steady, while the passenger’s is dynamic.

2.3 Impact by adaptability of body on thermal comfort

The adaptability theory of body on thermal comfort has significant influence on the feelings of people about the thermal conditions. De Dear et al. [11] proposed that, to a great extent, adaptive comfort standard for naturally ventilated buildings was impacted by the outdoor air temperature. So the theory was taken into consideration when we presented the evaluation model.

Auliciems et al. [12] obtained the linear regression relationship between comfortable temperature under air-conditioned buildings and average outdoor air temperature, resulting in naturally ventilated buildings adaptive model as

\[
t_{\text{comf}} = 0.31 t_{\text{out}} + 17.8,
\]

where \( t_{\text{comf}} \) is the neutral temperature based on mean outdoor temperature and \( t_{\text{out}} \) is the outdoor air temperature. The neutral temperature in subway influences people’s comfort; more importantly, it determines the ventilation rate of air conditioning systems and the heat load of the station. As a result, the investment on relative equipment and operating cost can be assessed. By analyzing energy consumption of subway station in Beijing, Lu et al. [13] found that the HVAC system can consume more than 40% of the total power. Consequently, to reduce the energy consumption, the neutral temperature under the acceptable limits (for people’s comfort) should be set as high as possible.
3 Materials and methods

3.1 Physical model of subway environment

A typical subway station consists of parts like exit/entrance, lobby hall, platform, connection channel, and office area, where the factors contributed to level of thermal comfort varies in different parts. To facilitate the study, we divided the subway station into five evaluation parts according to factors such as the temperature, humidity, velocity and performance of people: exit/entrance, lobby hall, ticket vendor area, platform, and office area. The connection channel was not considered since the passengers’ stay duration is short and its environment is largely affected by lobby hall and platform. Though in the lobby hall, the ticket vendor needs to be studied as an individual part, on the account that its performance of people differs from other parts by prolonged stay duration. The office area is a space that staff work in for a long period and most of them keep walking, so their thermal comfort is dynamic. Therefore, we used RWI and HDR (heat deficit rate) \[^{[15]}\] to evaluate the comfort level. RWI is applicable to a warm environment and is calculated from an empirical formula relating metabolic rate, insulation of clothing, insulation of air boundary, dry bulb air temperature, mean incident radiant heat and vapor pressure of water, and HDR is applicable to a cold environment. Table 3 shows the summary of index.

When the steam partial pressure is higher than 2 269 Pa, it can be expressed as

\[
RWI = \frac{M(I_{cw} + I_s) + 6.42(t - 35) + R \times I_s}{65.2 \times (5858.44 - P)/1000},
\]

where \(M\) is metabolic rate, \(I_{cw}\) is the insulation of clothing based on wet cloth assumption, \(I_s\) is the insulation effect of air boundary layer, \(t\) is the dry-bulb air temperature, \((t - 35)\) is the difference between dry-bulb temperature and average skin temperature just before a person feels uncomfortably warm, \(R\) is the mean incident radiant heat from sources other than walls at room temperature, and \(P\) is the vapor pressure of water in air.

When the steam partial pressure is equal to or lower than 2 269 Pa, it is expressed as

\[
RWI = \frac{M(I_{cw} + I_s) + 6.42(t - 35) + R \times I_s}{234},
\]

and \(M\) can be expressed by

\[
M = M_t - T(M_t - M_f)/6.
\]

where \(M_t\) is metabolic rate in the beginning, \(M_f\) is the index at the end, and \(T\) is the time.

Saturated vapor pressure \((P_r)\) and vapor pressure \((P_v)\) at \(t\) were estimated using Eqs (2) and (3). \(P_v\) was higher than 2 269 Pa at the station in summer, Nanjing. Thus, RWI in the study came from Eq. (2), while in the transition season RWI came from Eq. (3).

3.2 Thermal comfort evaluation of subway public area

As mentioned above, the office area has relatively steady factors for people’s thermal comfort. Therefore, it can be evaluated by the PMV-PPD model \[^{[14]}\]. In other parts, people are in a progress of taking a train and most of them keep walking, so their thermal comfort is dynamic. Therefore, we used RWI and HDR (heat deficit rate) \[^{[15]}\] to evaluate the comfort level. RWI is applicable to a warm environment and is calculated from an empirical formula relating metabolic rate, insulation of clothing, insulation of air boundary, dry bulb air temperature, mean incident radiant heat and vapor pressure of water, and HDR is applicable to a cold environment. Table 3 shows the summary of index.

When the steam partial pressure is higher than 2 269 Pa, it can be expressed as

\[
RWI = \frac{M(I_{cw} + I_s) + 6.42(t - 35) + R \times I_s}{65.2 \times (5858.44 - P)/1000},
\]

where \(M\) is metabolic rate, \(I_{cw}\) is the insulation of clothing based on wet cloth assumption, \(I_s\) is the insulation effect of air boundary layer, \(t\) is the dry-bulb air temperature, \((t - 35)\) is the difference between dry-bulb temperature and average skin temperature just before a person feels uncomfortably warm, \(R\) is the mean incident radiant heat from sources other than walls at room temperature, and \(P\) is the vapor pressure of water in air.

When the steam partial pressure is equal to or lower than 2 269 Pa, it is expressed as

\[
RWI = \frac{M(I_{cw} + I_s) + 6.42(t - 35) + R \times I_s}{234},
\]

and \(M\) can be expressed by

\[
M = M_t - T(M_t - M_f)/6.
\]

where \(M_t\) is metabolic rate in the beginning, \(M_f\) is the index at the end, and \(T\) is the time.

Saturated vapor pressure \((P_r)\) and vapor pressure \((P_v)\) at \(t\) were estimated using Eqs (2) and (3). \(P_v\) was higher than 2 269 Pa at the station in summer, Nanjing. Thus, RWI in the study came from Eq. (2), while in the transition season RWI came from Eq. (3).
Table 2 Summary of evaluation parts in subway station

<table>
<thead>
<tr>
<th>Area</th>
<th>Serial number</th>
<th>Temperature/°C</th>
<th>Humidity/%</th>
<th>Standing time/s</th>
<th>Performance</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exit/entrance</td>
<td>1</td>
<td>20 to 50</td>
<td></td>
<td></td>
<td>Up and down stairs</td>
<td>High wind speed</td>
</tr>
<tr>
<td>Lobby hall</td>
<td>2</td>
<td>29</td>
<td>60</td>
<td>50 to 90</td>
<td>Walking</td>
<td></td>
</tr>
<tr>
<td>Ticket vendor area</td>
<td>3</td>
<td>29</td>
<td>60</td>
<td>0 to 120</td>
<td>Standing</td>
<td>High passenger density</td>
</tr>
<tr>
<td>Platform</td>
<td>4</td>
<td>28</td>
<td>60</td>
<td>30 to 300</td>
<td>Standing</td>
<td></td>
</tr>
<tr>
<td>Office area</td>
<td>5</td>
<td>26</td>
<td>60</td>
<td>Long-term</td>
<td>Sit</td>
<td>Staff</td>
</tr>
</tbody>
</table>

Table 3 Summary of index in all evaluation parts where PMV is predicted mean vote, RWI is relative warmth index and HDR is heat deficit rate

<table>
<thead>
<tr>
<th>Location</th>
<th>Character of thermal condition</th>
<th>People</th>
<th>Evaluation model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Office area</td>
<td>Stable</td>
<td>Staff</td>
<td>PMV</td>
</tr>
<tr>
<td>Exit/entrance, lobby hall, platform, and ticket vendor area</td>
<td>Unsteady</td>
<td>Passenger</td>
<td>RWI, HDR</td>
</tr>
</tbody>
</table>

Table 4 shows the comparison between RWI index and ASHRAE criterion.

Table 4 Comparison between RWI(relative warmth index) index and ASHRAE(American Society of Heating, Refrigerating and Air-conditioning Engineers) criterion

<table>
<thead>
<tr>
<th>Thermal sensation</th>
<th>ASHRAE</th>
<th>RWI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warm</td>
<td>2</td>
<td>0.25</td>
</tr>
<tr>
<td>Slightly warm</td>
<td>1</td>
<td>0.15</td>
</tr>
<tr>
<td>Neutral</td>
<td>0</td>
<td>0.08</td>
</tr>
<tr>
<td>Slightly cool</td>
<td>−1</td>
<td>0.00</td>
</tr>
</tbody>
</table>

HDR is expressed by

\[
\text{HDR} = \frac{D}{\Delta r} = 28.39 - M(r) - 6.42(r - 30.56) + RI_a + I_{cl},
\]

(5)

where \( D \) is the heat deficit (integral of current times) in terms of J/m³, \( \Delta r (s) \) is the exposure time in terms of s, and \( I_{cl} \) is the thermal resistance of clothes.

\( \text{HDR} \leq 0 \) is required to avoid the absence of heat deficit. When \( D \) is getting to about 100 kJ/m², namely, \( \text{HDR} \leq -100 \text{ W/m}^2 \), people will feel uncomfortably cold. While the heat storage capacity of body is about 100 kJ/m², people will feel uncomfortably warm. So it can be concluded that in the transit space the appropriate \( \text{HDR} \) is inversely proportional to people’s hanging time. Therefore, we used the average stay time to calculate people’s thermal comfort index. Tables 5 and 6 show the key values for calculating.

Table 5 Insulating effect of clothing at various activity levels where \( M \) is the metabolic rate and \( I_{cw} \) is the the insulation of clothing based on wet cloth assumption

<table>
<thead>
<tr>
<th>Activity</th>
<th>( M/(\text{W/m}^2) )</th>
<th>( I_{cw}/(\text{m}^2\text{KW}^{-1}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basal</td>
<td>15</td>
<td>0.09</td>
</tr>
<tr>
<td>Seated at rest</td>
<td>20</td>
<td>0.09</td>
</tr>
<tr>
<td>Seated vending fares</td>
<td>25</td>
<td>0.06</td>
</tr>
<tr>
<td>Standing vending fares</td>
<td>28</td>
<td>0.08</td>
</tr>
<tr>
<td>Standing or occasional stroll</td>
<td>39</td>
<td>0.06</td>
</tr>
<tr>
<td>Walking, 3.0 km/h</td>
<td>39</td>
<td>0.06</td>
</tr>
<tr>
<td>Walking, 5.0 km/h</td>
<td>54</td>
<td>0.05</td>
</tr>
<tr>
<td>Walking, 6.0 km/h</td>
<td>71</td>
<td>0.04</td>
</tr>
</tbody>
</table>
Table 6  Key values for calculating where \( M \) is the metabolic rate, \( I_{cw} \) is the the insulation of clothing based on wet cloth assumption, \( I_a \) is the insulation effect of air boundary layer, and \( R \) is the mean incident radiant heat from sources other than walls at room temperature

<table>
<thead>
<tr>
<th>Location</th>
<th>( M/(\text{W/m}^2) )</th>
<th>( I_a/(\text{m}^2\text{K}^{-1}) )</th>
<th>( I_{cw}/(\text{m}^2\text{K}^{-1}) )</th>
<th>( R/(\text{W/m}^2) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entrance</td>
<td>54</td>
<td>0.04</td>
<td>0.05</td>
<td>10</td>
</tr>
<tr>
<td>Ticket sale hall</td>
<td>54</td>
<td>0.05</td>
<td>0.05</td>
<td>0</td>
</tr>
<tr>
<td>Platform</td>
<td>39</td>
<td>0.06</td>
<td>0.06</td>
<td>0</td>
</tr>
<tr>
<td>Wagon</td>
<td>28</td>
<td>0.07</td>
<td>0.08</td>
<td>0</td>
</tr>
</tbody>
</table>

4  Results and discussion

4.1 Analysis of questionnaire results in different seasons

Base on the model mentioned above, a case study in one representative station in Nanjing was developed. Taking seasonal variances into consideration, we selected August 20 as the representative for summer, November 10 for transition season and December 20 for winter. Air temperature, humidity and air flow velocity were measured. The passengers were invited to answer the questions and vote for thermal sensation in each evaluation part. The questions consist of three main contents: 1) volunteer background information; 2) thermal sensation level in investigation time according to ASHRAE thermal sensation scale, namely, “hot (3)”, “warm (2)”, “slightly warm (1)”, “neutral (0)”, “cool (1)”, “slightly cool (2)” or “cold (3)”. However, 7-scale thermal sensation makes it hard for people to distinguish them exactly and the statistic difficulty is accordingly increased. So we simplified the 7-scale thermal sensation into 5 (cold, slightly cold, neutral, slightly hot, hot); 3) the most uncomfortable part and time in the station. Fig. 1 illustrates the process of a passenger entering and leaving a station, and Fig. 2 shows summary of thermal-comfort-level evaluation in the station.

From the survey results, it can be found that on August 20, 60% passengers expressed satisfaction with the thermal environment; on November 10, 72% passengers were satisfied with thermal environment; and on December 20, 66% passengers felt comfortable under the thermal conditions. ASHRAE has made a frequency distribution of the percentage of test subjects who feel comfortable when exposed to the nominal ASHRAE comfort classifications. A quantitative relationship among ASHRAE comfort designations, the frequency distribution and RWI is shown in Fig. 3, which gives the percentage of people not feeling comfortable and desiring a cooler condition [5].

Fig. 1  Process of a passenger entering and leaving a station

4.2 Result-comparison of 3 surveys

Data gathered by the questionnaires was logged to convert into diagrams as is shown in Fig. 4.
to the comparison chart, conclusions are as follows.

1) The ratio of passengers feel comfortable is the biggest in summer, falls to the smallest in transition season, and turns up in between in winter;

2) Subway environment at present in Nanjing as a whole, generally makes people feel hot or slightly hot, the proportion of which is much larger than that of passengers feel “cold” or “slightly cold”;

3) In the transition season and winter, the phenomenon that passengers feel “hot” and “slightly hot” appears much more frequently than that in summer.

To explain the above results, with the thermal comfort evaluation index, we assessed the station thermal environment. Taking field test data of August 20 and November 10 as the basis, RWI values correspond to a passenger before entering and after entering the station were calculated in the three days. The key values are shown in Tables 5 and 6. It needs to be mentioned that in winter (December 20), the outside air temperature is low, RWI index cannot be used to evaluate the comfort of the passengers and HDR based
on Eq. (5) should be used. Table 8 shows the results.

As can be seen from the results, RWI of summer (August 20) outside the subway station has a high value, which means passengers had a poor thermal comfort. But when they get in the station, RWI has significantly reduced to 0.22. The value does not meet the thermal neutral standards (RWI = 0.08). Fig. 3 shows that more than 80% people under this condition would want a cooler environment, while the present case study carried out in Nanjing metro does not prove the values well. This agrees with other studies which believe the acceptable thermal comfort criteria for an office may not be achievable in an underground railway environment.

Despite that the calculated value was high, the hot and humid environment has been significantly improved compared with outdoor environment and passengers would generate short-term comfort sensation due to a sudden improvement in hot and humid environment. So it can be concluded that using RWI to evaluate the thermal comfort in metro is feasible. Table 7 shows that in the transitional season (November 10), when passengers enter the subway from outside, RWI keeps increasing in a holistic way, which means the thermal environment is more discomfortable, resulting in passengers’ obvious discomfort. In winter (December 20), passengers add clothes because of the low outdoor temperature, which leads to clothing-insulation change. Outside the station, passengers are in a more comfortable state (HDR = −17.2 W/m²). When they enter the subway station, due to higher temperature, HDR value decreases. But it is still in an acceptable range: −56 W/m² ≤ HDR ≤ 0 W/m² [10]. So the passenger still feels comfortable.

4.3 Analysis of questionnaire results in different evaluation parts

It can be concluded from the results of questionnaires that the passenger’s thermal comfort degree in a subway is a process of dynamical changing, in other words, a passenger in the subway has a different thermal comfort degree when he/she is at different locations. For the question “Do you think which part of the subway station has the most uncomfortable thermal environment”, most passengers chose the “ticket vendor area” and “platform level”. Fig. 5 shows gathered results.

Survey results show that the temperature in the station entrance and lobby hall level is higher, though the thermal comfort level is not the worst. It is because when a passenger from the outside environment gets into the subway station, hot and humid conditions have been improved, the passenger’s thermal tensions will be relaxed and the comfort level is good. In the ticket vendor area, the wind speed is reduced and the crowd density is high, so the rate of passenger satisfaction decreases and people feel anxious and uncomfortable.

To further analyze the change rule of the thermal
comfort level when passengers enter the station from outside, buy tickets, take a train, and finally get out of the station, the thermal comfort index RWI corresponding to each evaluation unit is calculated. Assume that a passenger is walking outside in summer at a constant speed as 1.2 m/s, and then gets into the subway station. It usually takes 1 min for a passenger to arrive at the ticket vendor area and wait for buying tickets. Within about 1 min, performance of walking activity becomes occasional and in most of the time people keep standing in a line. After about half a minute, the passenger reaches to the platform and waits for the train. In this period, the performance is standing or walking around occasionally. Usually, the average waiting time is about 4 min. The time passengers spent in the train is usually long and most of them in a standing or sit-state way. When passengers get off the train, it usually costs them 3 min to get out of the station. Table 8 shows the main measuring values.

By calculating, RWI values shown in Fig. 6 reflect the whole changing process for a passenger entering and leaving the station.

![The changing process of RWI](image)

**Fig. 6** Change of RWI (relative warmth index) among the process

Fig. 6 shows that when passengers walk into the station, they are in an environment, of which the temperature is lower than that of outside, and as a result, the RWI declines. When they are waiting to buy tickets, RWI rises immediately and keeps increasing till the peak point. This is because the activity intensity changes and the metabolic rate remains at a high level. On the other hand, when passengers stop walking suddenly or walk slowly, the relative wind velocity decreases, and the air boundary layer insulation increases. RWI value then decreases with decreased metabolic rate, until the passenger gets on the train. RWI value keeps in an acceptable range in the train, which leads passengers to remain in a comfortable level. After arriving at the destination station, passengers get off on the platform and then the station hall, RWI gradually increases till passengers reach to the ground. And RWI gradually gets back to the starting extent. By analyzing the RWI and results of questionnaire in Nanjing, a quantitative relationship among them is shown in Fig. 7.

![Percentage of people who want a cooler environment in summer](image)

**Fig. 7** Percentage of people who want a cooler environment in summer in Nanjing

5 Conclusions

Taking a typical station of Nanjing metro system as a case study, we studied the thermal comfort evaluation of people in subway. The conclusions are as follows:

1) According to analysis of the thermal environment characters in different subway areas, PMV-PPD model should be used to evaluate the thermal comfort in the office, while it is more appropriate to use both RWI/HDR and PMV to evaluate the thermal comfort in the public area.
Table 8 Summary of measuring values where $M$ is metabolic rate, $V_a$ is the air speed, $V_d$ is the relative speed, $I_m$ is the insulation effect of air boundary layer, $I_c$ is the insulation of clothing based on wet cloth assumption, $P$ is the vapor pressure of water in air, $t$ is the dry-bulb air temperature, and $R$ is the mean incident radiant heat from sources other than walls at room temperature

<table>
<thead>
<tr>
<th>Area</th>
<th>$M/(W \cdot m^{-2})$</th>
<th>$V_a/(m \cdot s^{-1})$</th>
<th>$c/(m \cdot s^{-1})$</th>
<th>$I_m/(m^2 \cdot K \cdot W^{-1})$</th>
<th>$I_c/(m^2 \cdot K \cdot W^{-1})$</th>
<th>$P/Pa$</th>
<th>$t/°C$</th>
<th>$R/(W \cdot m^{-2})$</th>
<th>Time/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside</td>
<td>150</td>
<td>1.5</td>
<td>1.2</td>
<td>0.04</td>
<td>0.05</td>
<td>3213</td>
<td>33.0</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>Entrance/exit</td>
<td>150</td>
<td>2.0</td>
<td>1.2</td>
<td>0.04</td>
<td>0.05</td>
<td>2520</td>
<td>31.0</td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>Lobby hall</td>
<td>150</td>
<td>0.5</td>
<td>1.2</td>
<td>0.05</td>
<td>0.06</td>
<td>2520</td>
<td>29.0</td>
<td>0</td>
<td>1.0</td>
</tr>
<tr>
<td>Ticket vendor</td>
<td>138</td>
<td>0.5</td>
<td>0.0</td>
<td>0.08</td>
<td>0.06</td>
<td>2520</td>
<td>29.0</td>
<td>0</td>
<td>1.5</td>
</tr>
<tr>
<td>Platform</td>
<td>110</td>
<td>1.0</td>
<td>0.0</td>
<td>0.06</td>
<td>0.06</td>
<td>2520</td>
<td>28.0</td>
<td>0</td>
<td>3.0</td>
</tr>
<tr>
<td>Train</td>
<td>70</td>
<td>0.5</td>
<td>0.0</td>
<td>0.08</td>
<td>0.06</td>
<td>2520</td>
<td>26.0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Platform</td>
<td>83</td>
<td>1.0</td>
<td>1.2</td>
<td>0.04</td>
<td>0.06</td>
<td>2520</td>
<td>28.0</td>
<td>0</td>
<td>1.0</td>
</tr>
<tr>
<td>Lobby hall</td>
<td>94</td>
<td>0.5</td>
<td>1.2</td>
<td>0.05</td>
<td>0.06</td>
<td>2520</td>
<td>29.0</td>
<td>0</td>
<td>1.0</td>
</tr>
<tr>
<td>Entrance/exit</td>
<td>103</td>
<td>2.0</td>
<td>1.2</td>
<td>0.04</td>
<td>0.06</td>
<td>2520</td>
<td>31.0</td>
<td>0</td>
<td>1.0</td>
</tr>
<tr>
<td>Outside</td>
<td>150</td>
<td>1.5</td>
<td>1.2</td>
<td>0.04</td>
<td>0.05</td>
<td>3213</td>
<td>33.0</td>
<td>35</td>
<td></td>
</tr>
</tbody>
</table>

2) Applying RWI values obtained for halls and platforms to Fig. 2 shows that, more than 90% of the people in halls and platforms desire cooler environment in summer. But according to the questionnaire, it proves that the subway station thermal environment at present can meet the vast majority of passengers’ thermal comfort requirements, which means that only using RWI to evaluate the metro thermal environment in hot-humid area such as Nanjing cannot get the results as expected.

3) According to the questionnaire results and RWI values, the relationship of which adaptable for Nanjing is drawn.

4) To some extent, maximizing the subway station temperature set point in an acceptable range or making the air conditioning system partly operated (people may feel a little hot) is acceptable for reducing the energy consumption of a metro station.

References


