Evaluation on Human Thermal Comfort in the Cabin Environment of Shanghai Passenger Ship

Ankang Kan,1,* Wenbing Zhu1 and Yu Wu2

Abstract

Human thermal comfort on ships is an important factor in the efficiency and quality of life of personnel. A year-long human thermal comfort survey is conducted in Chinese ship cabins environment. A field questionnaire is taken to obtain the human subjective thermal responses, including three groups: winter, summer and transitional seasons. The data for each group are collected from the residential cabins, the dining room and cockpit. The thermal neutral temperature, the thermal acceptance temperature and thermal preference temperature are presented to adequately express on the human subjective thermal response. The results indicated that the thermal acceptance temperature and thermal preference temperature are higher than the thermal neutral temperature of the interior spaces in all three seasons. In the dining room, the thermal preference temperature in winter, summer and transition seasons are 3.0 °C, 0.4 °C and 1.2 °C higher than the thermal neutral temperature. People prefer a warmer environment in interior spaces on the ship. The thermal neutral temperature and thermal acceptance temperature of the ship's cockpit exhibited small differences in the three seasons. Cockpit crew are more adaptable to the temperature fluctuations resulting from seasonal changes. This research contributes to enhance the human thermal comfort by improving marine cabins thermal environment.

Keywords: Thermal comfort; Field questionnaire; Marine cabins; Interior spaces; Season.

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1. Introduction

Global crises such as energy shortages, environmental pollution and global warming have become common problems that need to be addressed urgently.1-3 Ships serve as one of dominant transportation from the past to the present. The crew and passengers spend the majority of their time in the interior spaces on the ship, including the residential cabins, the dining room, the cockpit and the entertainment areas, etc.4-6 During voyages lasting several weeks or months, the investigation on human thermal comfort is an inevitable focus.7-10 Further research has indicated that numerous ship accidents occurred in relation to personal factors.11 Human thermal comfort plays a vital influence on the subjective behavior of individuals.12-15 This has prompted that we effort to create a more comfortable and acceptable thermal environment on ships for crew and passengers.16-18

Over the last few decades, considerable research efforts have been devoted to investigating human thermal comfort in buildings on land, including interior spaces and semi-open spaces.11-15 Nematchoua et al.15 conducted the field questionnaire survey in four Cameroon regions during two seasons, including a long rainy season and a short rainy season. They investigated the effects of air temperature, relative humidity and air speed on human thermal comfort in both traditional buildings and modern buildings. Chen et al.16 carried out a large-scale questionnaire survey in combination with experimental measurements on residential buildings in Hangzhou, China. They revealed the effects of various individual subjective behaviors on indoor human thermal comfort and proposed a modified adaptive coefficient suitable for the actual thermal conditions of Hangzhou residents. Chang et al.17 conducted a one-year survey on the thermal environment and residents' thermal comfort in interior spaces and semi-open spaces of vernacular buildings in the arid climate region of Turpan. It was found that the thermal comfort in interior and semi-open spaces is substantially different. Similarly, Zhang et al.18 conducted a one-year survey on thermal comfort in rural residential buildings in Guangdong Province, a humid and hot region of southern China.

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China. They obtained the subjective thermal responses of humans by questionnaire in indoor spaces and semi-open spaces. They concluded that the thermal comfort temperature in semi-open spaces is 0.6 °C-1.3 °C lower than that of interior spaces. This finding was contrary to previous studies which have suggested that semi-open spaces had the higher thermal neutral temperature than interior spaces.

A comprehensive overview of previous work reveals that research on human thermal comfort in different places and seasons presents differences due to geographical location, thermal adaptation and climatic conditions. It may generate diametrically opposed results. Dili et al. investigated the subjective human thermal response questionnaire in traditional residential buildings in Kerala, India, including summer season and winter season. They concluded that traditional residential architecture was remarkably effective in providing a comfortable indoor environment, independent of the seasons. Furthermore, Gou et al. presented the qualitative analysis on human thermal comfort for rural residents in hot summer and cold winter regions of China. The results showed that the rural residential buildings were well adapted to the local summer climate, although the interior thermal comfort was not satisfactory in winter. However, this conclusion was contrary to that of Dili. A possible explanation for these results is that the two thermal comfort surveys have different location and climatic conditions. Besides, there are differences in the traditional building structures of the rural residents in the two areas. The space structure of ships and buildings on land as well as the climatic conditions present a large difference. For the research on human thermal comfort on ships and the improvement of cabin thermal environment is an urgent problem to be solved. Liu et al. studied human thermal comfort in air-conditioned Chinese ship cabins in winter reason. They presented the thermal neutral temperature, thermal preference and thermal acceptance temperature of ship cabins by field questionnaires. The results indicated that passengers preferred a temperature above that of the neutral temperature on the ship during the winter reason. The thermal acceptable temperature range was determined to be 18.54 °C-23.29 °C. Zhang et al. proposed a predicted mean vote (PMV) method to evaluate the subjective thermal response of human in submersible cabins. They revealed the thermal comfort in short warm states and long sustained cold states. To the best of our knowledge, surprisingly little attention has been devoted to human thermal comfort on ships, more in buildings on land. In addition, considering the available literatures on human thermal comfort on ships, most of them are also limited to specific seasons or specific cabins. In order to further investigate the human thermal comfort comprehensively and improve the thermal environment, we conducted a survey on human thermal comfort in different seasons and interior spaces on the ship.

In this paper, we have obtained the subjective human thermal sensation voting by the field questionnaires on the ship. Thermal environmental parameters are also measured by experiments in the different interior spaces and the different seasons. To further fully express human thermal comfort, the subjective thermal response is divided into three groups: summer, winter and transitional seasons. We adapted the thermally neutral temperature, the thermal acceptance temperature of more than 90% respondents and the thermal preference temperature to evaluate the human thermal comfort. Based on the three groups of data obtained from residential cabins, dining room and cockpit, the thermal neutral, thermal acceptance and thermal preference temperatures are analyzed by regression analysis in the summer, winter and transition seasons.

2. Methodology
2.1 Climatic conditions and geographical location
The conducted survey took place on a passenger ship sailing between Shanghai and Zhoushan in the East China Sea. Shanghai is a bustling coastal city in the eastern area of China, and Zhoushan is a coastal city in Zhejiang Province in the southeastern area of China. According to the Köppen-Geiger climate classification, Shanghai and Zhoushan are typical hot summer and cold winter areas (Fig. 1). Shanghai is situated at 120° 52’-122° 12’ E and 30° 40’-31° 53’ N, while Zhoushan is situated at 121° 30’-123° 25’ E and 29° 32’-31° 04’ N. There is little variation in climate between the two areas throughout
the year, with a mild and humid climate, shorter springs and autumns, longer winters and summers, with annual precipitation mostly in the range of 800-1600mm. The average annual temperature and relative humidity are both distributed between 15 °C-22 °C and 60%-80%. The average temperatures in winter and summer are 3 °C-5 °C and 25 °C-33 °C respectively, and 8°C-18°C in both spring and autumn. The hottest and coldest months occur in August and January, respectively. [27,28]

2.2 Time of the survey on the ship
In order to fully investigate the thermal response of the ship's crew, a field survey is taken on the short-haul passenger ship, namely ‘LuoJiaShan’. It mainly sails between Shanghai and Putuo Mountain in Zhoushan in the whole year. According to the standard (climatic seasonal classification) QX/T152 (2012),[29] we consider winter and summer occurring when the average temperature is less than 10°C and more than 22°C for more than five consecutive days, respectively. Similarly, spring and autumn occur when the average temperature is between 10°C-22°C for more than five consecutive days. The field survey was conducted in the whole 2019 year on the ‘LuoJiaShan’ ship.

Taking into account the effect of seasonal factors, the survey time was divided into three groups: July 10 (transition seasons), respectively. Because the short spring and autumn seasons and the slight temperature differences between the two areas where the ship sailed, spring combination with autumn together are called transitional seasons.

2.3 Respondents of the questionnaire
All respondents are randomly selected without considering any limitations on age, gender, height or weight. A total of 1197 raw data are obtained from the residential cabin, the dining room and the cockpit on the ship. After eliminating incomplete questionnaires, a total of 1104 valid raw data are obtained. It is divided into three groups dependent on seasons: winter, summer and transition seasons. From the data we have obtained from respondents, Men are accounted for 59% and women for 41%. The age distribution of the majority of respondents is between 20 and 50 years old, accounting for 75%, while those less than 20 years old and more than 50 years old are accounted for 15% and 10%, respectively. All the respondents come from three interior spaces: the residential cabins, the dining room and the cockpit. Basic information about the respondents is presented in Table 1. The $I_d$ represents the thermal resistance of the clothing. The type of clothing of the respondents is also recorded in detail during the survey and the overall insulation is estimated as the sum of the individual values listed in ASHRAE standard 55.[30]

Furthermore, in the survey on human thermal comfort, it is necessary to exclude differences resulting from individual factors of the respondents. Statistical $t$-tests are adopted to analyze the differences between the respondents in the residential cabins, the dining room and the cockpit. The results reveal that it does not exist significant differences ($p > 0.5$) between respondents from the three different spaces. It indicates that the error caused by the individual differences of respondents is negligible.

2.4 Experimental measurements and field questionnaires
Throughout whole 2019 year, a field questionnaire was conducted on the thermal comfort of crew and passengers on the ship. The field questionnaire is divided into three groups: winter, summer and transitional seasons, with the corresponding time periods being July 10-September 1 (summer), November 20-January 5 (winter) and March 10-May 10 (transition seasons), respectively. To further investigate human thermal comfort on the ship, the questionnaire mainly includes the subjective thermal responses of the respondents, such as thermal sensation, thermal acceptance and thermal preference. For the adequately describe the subjective thermal responses, a standard 7-point scale is adopted for expressing the thermal sensation.[18]

<table>
<thead>
<tr>
<th>Location</th>
<th>Season</th>
<th>Sample size</th>
<th>Age (years)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>$I_d$ (clo)</th>
<th>Metabolic rate (met)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential cabin</td>
<td>Winter</td>
<td>156</td>
<td>15-65</td>
<td>169.1 ± 4.5</td>
<td>67.3 ± 6.7</td>
<td>1.4 ± 0.1</td>
<td>1.1 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>117</td>
<td>13-61</td>
<td>168.3 ± 4.8</td>
<td>68.5 ± 4.9</td>
<td>0.4 ± 0.1</td>
<td>1.2 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>Transition seasons</td>
<td>121</td>
<td>12-70</td>
<td>165.1 ± 5.1</td>
<td>68.4 ± 6.4</td>
<td>0.7 ± 0.1</td>
<td>1.0 ± 0.1</td>
</tr>
<tr>
<td>Dining room</td>
<td>Winter</td>
<td>230</td>
<td>9-63</td>
<td>168.5 ± 3.9</td>
<td>69.1 ± 5.0</td>
<td>1.5 ± 0.1</td>
<td>1.2 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>267</td>
<td>10-65</td>
<td>167.2 ± 4.0</td>
<td>69.2 ± 5.2</td>
<td>0.3 ± 0.1</td>
<td>1.3 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>Transition seasons</td>
<td>263</td>
<td>15-71</td>
<td>168.1 ± 4.1</td>
<td>68.5 ± 5.5</td>
<td>0.5 ± 0.1</td>
<td>1.2±0.1</td>
</tr>
<tr>
<td>Cockpit</td>
<td>Winter</td>
<td>13</td>
<td>25-50</td>
<td>172.8 ± 1.9</td>
<td>67.5 ± 1.2</td>
<td>1.0 ± 0.1</td>
<td>1.2 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>15</td>
<td>21-50</td>
<td>173.5 ± 2.1</td>
<td>67.2 ± 1.1</td>
<td>1.0 ± 0.1</td>
<td>1.2 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>Transition seasons</td>
<td>15</td>
<td>25-50</td>
<td>173.4 ± 1.8</td>
<td>67.3 ± 1.5</td>
<td>1.0 ± 0.1</td>
<td>1.2 ± 0.1</td>
</tr>
</tbody>
</table>
Similarly, a 5-point scale for thermal acceptance and a 2-point scale for thermal preference is used to present the thermal responses of the respondents, respectively, as shown in Table 2. In addition, the thermal resistance of clothing and the metabolic rate (activity intensity) play critical roles in the thermal comfort of the respondents. They are also recorded in the questionnaire. The evaluation on the thermal resistance of clothing and the magnitude of the metabolic rate are dependent on American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standard 55.\(^\text{[30]}\)

In the field questionnaire on subjective thermal responses, the thermal environment is measured in the three interior spaces. The measured thermal environmental parameters include air temperature, relative humidity and air speed. According to the ASHRAE standard 55, the measuring device MI6401 is placed near the respondent during the field questionnaire. It is a height of 0.6m above the ground when the respondent is sitting, or 1.1m when the respondent is standing. Information on the adopted MI6401 tester (Fig. 2) is shown in Table 3.

### Table 2. Subjective thermal response evaluation scale.

<table>
<thead>
<tr>
<th>Thermal response</th>
<th>-3</th>
<th>-2</th>
<th>-1</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal sensation</td>
<td>Cold</td>
<td>Cool</td>
<td>Slightly cool</td>
<td>Neutral</td>
<td>Slightly warm</td>
<td>Warm</td>
<td>Hot</td>
</tr>
<tr>
<td>Thermal acceptance</td>
<td>Clearly unacceptable</td>
<td>Just unacceptable</td>
<td>acceptable</td>
<td>Just acceptable</td>
<td>Clearly acceptable</td>
<td>Warmer</td>
<td></td>
</tr>
<tr>
<td>Thermal preference</td>
<td>Cooler</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(t_0\) is the operative temperature, \(t_a\) is the air temperature and \(t_r\) is the radiation temperature. \(A\) is a parameter that depends on the air speed. According to ASHRAE standard 55, \(A\) takes the value 0.5 when the air speed is less than 0.2m/s, assigning 0.6 when the air speed is between 0.2 m/s and 0.6 m/s, assigning 0.7 when the air speed is greater than 0.6 m/s.\(^\text{[34]}\) The radiation temperature \(t_r\) can be obtained by Eq. (2).

\[
t_r = \left[(t_g + 273)^4 + 2.5 \times 10^8 \times v^{0.6} \times (t_g - t_a)\right]^{\frac{1}{4}} - 273
\]

\(t_g\) is global temperature, \(v\) is air speed.

### 2.5 Thermal comfort evaluation index

Thermal environmental parameters that affect the human thermal comfort on the ship include air temperature, relative humidity, radiation temperature and air speed.\(^\text{[31]}\) As one of the most commonly used thermal comfort evaluation indexes, the operative temperature \(t_o\) is a comprehensive temperature that takes into the account the air temperature, air speed and radiation temperature effects on human thermal comfort. Operative temperature is widely adopted for the estimation human thermal comfort in interior spaces and semi-open spaces on land.\(^\text{[32]}\) The equation for the operative temperature is shown below:\(^\text{[33]}\)

\[
t_o = A \times t_a + (1 - A) \times t_r
\]

### 2.6. Statistical analysis of data

Considering the large amount of discrete data collected from field questionnaires, regression analysis is a more intuitive method for presenting data trends. Therefore, a linear fitting is taken to demonstrate the relationship between operative temperature and thermal sensation voting. Besides, a polynomial fitting is taken to demonstrate the relationship between operative temperature and thermal acceptance frequency and thermal preference frequency. All data statistics and regression analyses are operated based on Excel (Microsoft Corporation) and Origin 18.0 (OriginLab Inc.).

### 3. Results

#### 3.1. Thermal environmental parameters on the ship

The air temperature, the air speed, the relative humidity and the radiant temperature are the dominant environmental parameters affecting the human thermal comfort on the ship. The environmental parameters are obtained by the MI6401...
Table 3. Specifications of the MI6401 thermal environmental parameters tester.

<table>
<thead>
<tr>
<th>Environmental parameters</th>
<th>Range</th>
<th>Resolution</th>
<th>Accuracy</th>
<th>Source</th>
<th>International standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature (°C)</td>
<td>-20~60</td>
<td>0.1</td>
<td>± 0.2</td>
<td>Metrel, Germany</td>
<td>ISO7730/ASHRAE55-2013</td>
</tr>
<tr>
<td>Relative humidity (%)</td>
<td>0~10</td>
<td>0.1</td>
<td>± 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10~90</td>
<td>0.1</td>
<td>± 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>90~100</td>
<td>0.1</td>
<td>± 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Globe temperature (°C)</td>
<td>10.0~49.9</td>
<td>0.1</td>
<td>± 0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>50.0~84.9</td>
<td>0.1</td>
<td>± 1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>85.0~120</td>
<td>0.1</td>
<td>± 1.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air velocity (m/s)</td>
<td>0.1~9.99</td>
<td>0.01</td>
<td>± 0.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10.0~20.0</td>
<td>0.1</td>
<td>± 0.05</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The thermal environment measuring device on the ship. Air temperature (Fig. 3), air speed and relative humidity (Fig. 4) are presented on the ship in three different seasons, winter, summer and transition seasons. From the results we have obtained, one can be founded that the temperatures are primarily distributed between 15 °C and 17 °C during the winter and transitional seasons, but the temperature is significantly higher in the transitional season than in the winter. The temperature distribution is primarily between 19 °C and 23 °C during the summer on the ship. The air speed distribution is mainly concentrated around 0.0-0.1 m/s on the ship during the winter, summer and transition seasons, with the three seasons accounting for 80%, 75%, 84%, respectively. Furthermore, the mean air speed is higher in the summer than in the winter and transition seasons. The relative humidity exists some differences among the three different seasons on the ship, with the lowest relative humidity in winter, mainly distributed between 50%-70%. The highest relative humidity in summer, it is mainly distributed between 60%-80%, followed by the transition seasons. Besides, the respondents to this questionnaire are all from the residential cabins, the dining room and the cockpit. The thermal environment also has certain difference in three different interior spaces. Each season is divided into three groups according to the residential cabin, the dining room and the cockpit. Table 4 and Table 5 are presented the mean and maximum values of the thermal environmental parameters for the residential cabin, the dining room and the cockpit, respectively. They are included air temperature, air speed and relative humidity, and radiation temperature.

From the data we have collected in winter, the recorded highest mean air temperature is 18.1 °C in the dining room. The mean air temperatures are 17.5 °C and 16.5 °C in the residential cabins and the cockpit respectively, which are 0.6 °C and 1.6 °C lower than in the dining room. However, during the summer and transition seasons, the recorded highest mean air temperatures are 27.3 °C and 21.7 °C in the cockpit, followed by 27.1 °C and 21.3 °C in the residential cabins, and the lowest presented 27.0 °C and 21.1 °C in the dining room, respectively.

3.2 Thermal sensation voting

The human thermal sensation voting is the most realistic expression on personal subjective thermal responses. It is also the primary component of the filed questionnaire. The thermal sensation voting is performed on a standard seven-point scale, divided into three groups based on three different seasons: winter, summer and transition seasons. Fig. 5, (winter) and
The thermal sensation voting distribution +1 (slightly warm) is slightly higher than thermal neutrality 0 (neutral) in the dining room. However, the highest percentage distribution remains at 0 in winter and summer, which is consistent with the residential cabins and the cockpit. A possible explanation is that the restaurant is more crowded and warmer in the summer. Furthermore, in summer, the proportion of thermal sensation voting distribution +1 (slightly warm) is slightly higher than thermal neutrality 0 (neutral) in the dining room. However, the highest percentage distribution remains at 0 in winter and summer, which is consistent with the residential cabins and the cockpit. A possible explanation is that the restaurant is more crowded and warmer in the summer.

### 3.2.1 Thermal neutral temperature

The thermal neutral temperature is the temperature corresponding to the human thermal sensation voting at 0. It is also the most satisfactory expression on the human subjective thermal responses. Considering the three different seasons on the ship, a linear fitting method is performed to obtain the thermal neutral temperature in different spaces. The operative temperatures are divided into three groups for winter season (Fig. 7), summer season and transition seasons (Fig. 8). Each group is linearly fitted for the residential cabins, the dining room and the cockpit, with ($R^2 > 0.5$). From the results we have obtained in winter, one can be concluded the lowest thermal neutral temperature is occurred in the cockpit, followed by the residential cabins and the highest in the dining room at 18.7 °C, 18.8 °C and 20.0 °C, respectively. On the contrary in summer contrast, the dining room occurs the lowest thermal neutral temperature, followed by the residential cabins, and the smallest thermal neutral proportion occurs in the dining room.

#### Table 4. Statistics on the thermal environmental parameters of the residential cabin and dining room.

<table>
<thead>
<tr>
<th>Season</th>
<th>Parameter</th>
<th>Residential cabin</th>
<th>Dining room</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$t_a$ (°C)</td>
<td>$t_r$ (°C)</td>
<td>$v$ (m/s)</td>
</tr>
<tr>
<td>Winter</td>
<td>Mean</td>
<td>17.5</td>
<td>17.2</td>
</tr>
<tr>
<td></td>
<td>Max</td>
<td>26.3</td>
<td>26.1</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>5.0</td>
<td>4.8</td>
</tr>
<tr>
<td>Summer</td>
<td>Mean</td>
<td>27.1</td>
<td>27.3</td>
</tr>
<tr>
<td></td>
<td>Max</td>
<td>32.0</td>
<td>32.1</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>16.0</td>
<td>16.3</td>
</tr>
<tr>
<td>Transition</td>
<td>Mean</td>
<td>21.3</td>
<td>21.4</td>
</tr>
<tr>
<td>seasons</td>
<td>Max</td>
<td>29.1</td>
<td>29.2</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>10.0</td>
<td>10.5</td>
</tr>
</tbody>
</table>

#### Table 5. Statistics on the thermal environmental parameters of the cockpit.

<table>
<thead>
<tr>
<th>Season</th>
<th>Parameter</th>
<th>Cockpit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$t_a$ (°C)</td>
<td>$t_r$ (°C)</td>
</tr>
<tr>
<td>Winter</td>
<td>Mean</td>
<td>16.5</td>
</tr>
<tr>
<td></td>
<td>Max</td>
<td>25.2</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>5.2</td>
</tr>
<tr>
<td>Summer</td>
<td>Mean</td>
<td>27.3</td>
</tr>
<tr>
<td></td>
<td>Max</td>
<td>32.3</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>16.7</td>
</tr>
<tr>
<td>Transition</td>
<td>Mean</td>
<td>21.7</td>
</tr>
<tr>
<td>seasons</td>
<td>Max</td>
<td>29.7</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>11.5</td>
</tr>
</tbody>
</table>

Fig. 5 The thermal sensation voting of respondents in three interior spaces in winter.

Fig. 6 (summer and transition seasons) demonstrate the frequency distribution of thermal sensation voting among the three groups of respondents who participated in the questionnaire. On the basis of those results we found that the cockpits present the highest percentage of thermal neutrality (voting 0) in the three different seasons. It is accounted for 70%, 78% and 68% in the winter, summer and transition seasons, respectively, followed by the residential cabins. The
highest is the cockpit with 23.9 °C, 24.5 °C and 25.1 °C respectively. Similarly, during the transition season, the dining room had the lowest thermal neutral temperature, followed by the residential cabins, and the highest is the cockpit with 21.7 °C, 21.8 °C and 22.5 °C. This finding is consistent with the summer.

3.3 Thermal acceptance
To further demonstrate the subjective thermal response of the respondents, Thermal acceptance is a frequency that reflects the number of respondents being able to accept it. As passenger ships are expected to be able to provide a comfortable environment. Therefore, we take acceptable level over 90% of respondents as an evaluation indicator. A 5-point scale is adopted to express the thermal acceptance of the respondents. Similarly, the thermal sensation voting is divided into three groups: winter season, summer season and transition seasons. Each group is fitted with a polynomial in three different spaces for different operative temperatures. Fig. 9 presents the thermal acceptance frequency for three spaces in winter. The thermal acceptance frequency for the residential cabins, the dining room and the cockpit are fitted with polynomials respectively. The fitting...
equations are listed below for three spaces in Eq. (3), Eq. (4) and Eq. (5), all with \( R^2 > 0.88 \). On the basis of those results in winter, it can be found that the highest operative temperature occurred in the dining room for over 90% the thermal acceptance frequency, followed by the residential cabins, and the lowest operative temperature in the cockpit with 21.5 °C, 20.1 °C and 18.6 °C, respectively. Fig. 10(A) illustrates the thermal acceptance frequency in summer on the ship, with the fitted equations for three different spaces: Eq (6), Eq (7), Eq (8) with \( R^2 > 0.9 \). We can easily find that the highest operative temperature is in the cockpit for more than 90% thermal acceptance frequency, followed by the residential cabin and the lowest in the dining room with 25.1 °C, 24.8 °C and 24.0 °C, respectively. Fig. 10 (B) presented the thermal acceptance frequency during the transition season with the fitted equations for the three spaces Eq. (9), Eq. (10), Eq. (11) with \( R^2 > 0.9 \). Similarly, the highest operative temperature was in the cockpit for more than 90% thermal acceptance frequency, followed by the residential cabin and the lowest occurring in the dining room with 22.4 °C, 22.2 °C and 20.5 °C, respectively. This result is consistent with the summer.

In winter, the fitted equations for the residential cabin, the dining room and the cockpit are presented as follows:

- **Residential cabin**:
  \[
  y = -0.028 \times t_o^2 + 1.197 \times t_o - 11.731 \quad (R^2 = 0.898) \tag{3}
  \]

- **Dining room**:
  \[
  y = -0.025 \times t_o^2 + 1.150 \times t_o - 11.827 \quad (R^2 = 0.888) \tag{4}
  \]

- **Cockpit**:
  \[
  y = -0.023 \times t_o^2 + 0.937 \times t_o - 11.731 \quad (R^2 = 0.904) \tag{5}
  \]

In summer, the fitted equations for the residential cabin, the dining room and the cockpit are presented as follows:

- **Residential cabin**:
  \[
  y = -0.032 \times t_o^2 + 1.731 \times t_o - 22.119 \quad (R^2 = 0.984) \tag{6}
  \]

- **Dining room**:
  \[
  y = -0.023 \times t_o^2 + 1.199 \times t_o - 14.344 \quad (R^2 = 0.966) \tag{7}
  \]

- **Cockpit**:
  \[
  y = -0.031 \times t_o^2 + 1.655 \times t_o - 21.183 \quad (R^2 = 0.978) \tag{8}
  \]

In transition seasons, the fitted equations for the residential cabin, the dining room and the cockpit are presented as follows:

- **Residential cabin**:
  \[
  y = -0.032 \times t_o^2 + 1.731 \times t_o - 22.119 \quad (R^2 = 0.984) \tag{9}
  \]

- **Dining room**:
  \[
  y = -0.023 \times t_o^2 + 1.199 \times t_o - 14.344 \quad (R^2 = 0.966) \tag{10}
  \]

- **Cockpit**:
  \[
  y = -0.031 \times t_o^2 + 1.655 \times t_o - 21.183 \quad (R^2 = 0.978) \tag{11}
  \]

### 3.4 Thermal preference

In order to further comprehensively express on the subjective thermal response to the respondents, it is facilitated to achieve the more comfortable and satisfactory thermal environment on the ship. Thermal preference represents an expression that the human prefer temperature. Similarly, we adopt a 2-point scale to express the respondents’ thermal preference, including warmer (+1) and colder (-1). Considering the three different
Fig. 11 Thermal preference frequency in winter.

In winter, the fitted equations for the residential cabin, the dining room and the cockpit are presented as follows:

Residential cabin (cooler) Eq. (12):  
\[ y = 0.006 \times t_o^2 - 0.185 \times t_o + 1.498 (R^2 = 0.954) \]  
\[ y = -0.002 \times t_o^2 - 0.021 \times t_o + 1.681 (R^2 = 0.988) \]  

Dining room (cooler) Eq. (14); dining room (warmer) Eq. (16):  
\[ y = -0.004 \times t_o^2 - 0.121 \times t_o + 0.947 (R^2 = 0.973) \]  
\[ y = -0.002 \times t_o^2 - 0.189 \times t_o + 3.493 (R^2 = 0.981) \]  

Cockpit (cooler) Eq. (17); cockpit (warmer) Eq. (19):  
\[ y = 0.005 \times t_o^2 - 0.149 \times t_o + 1.097 (R^2 = 0.952) \]  
\[ y = -0.003 \times t_o^2 - 0.015 \times t_o + 1.006 (R^2 = 0.978) \]  

In summer, the fitted equations for the residential cabin, the dining room and the cockpit are presented as follows:

Residential cabin (cooler) Eq. (18); residential cabin (warmer) Eq. (19):  
\[ y = 0.005 \times t_o^2 - 0.213 \times t_o + 2.171 (R^2 = 0.987) \]  
\[ y = 3.07 \times 10^{-4} \times t_o^2 - 0.836 \times t_o + 2.321 (R^2 = 0.987) \]  

Dining room (cooler) Eq. (20); dining room (warmer) Eq. (21):  
\[ y = -1.625 \times 10^{-4} \times t_o^2 + 0.084 \times t_o - 1.576 (R^2 = 0.974) \]  

In addition, Fig. 11(B) indicates the frequency of the thermal preference temperature during the transition seasons, with fitted Eq. (4), Eq (5), Eq (6), all with $(R^2>0.9)$. Similarly, the highest operative temperature for thermal preference occurs in the cockpit with 22.5°C, 22.3°C and 20.6°C, respectively. The finding for thermal preference temperature is consistent with that of the thermal acceptance temperature.

In winter, the fitted equations for the residential cabin, the dining room and the cockpit are presented as follows:

- Residential cabin (cooler) Eq. (12):  
  \[ y = 0.006 \times t_o^2 - 0.185 \times t_o + 1.498 (R^2 = 0.954) \]  

- Residential cabin (warmer) Eq. (13):  
  \[ y = -0.002 \times t_o^2 - 0.021 \times t_o + 1.681 (R^2 = 0.988) \]  

- Dining room (cooler) Eq. (14); dining room (warmer) Eq. (15):  
  \[ y = -0.004 \times t_o^2 - 0.121 \times t_o + 0.947 (R^2 = 0.973) \]  
  \[ y = -0.002 \times t_o^2 - 0.189 \times t_o + 3.493 (R^2 = 0.981) \]  

- Cockpit (cooler) Eq. (16); cockpit (warmer) Eq. (17):  
  \[ y = 0.005 \times t_o^2 - 0.149 \times t_o + 1.097 (R^2 = 0.952) \]  
  \[ y = -0.003 \times t_o^2 - 0.015 \times t_o + 1.006 (R^2 = 0.978) \]  

Fig. 12 Thermal preference frequency. (A) summer; (B) transitional seasons.

Fig. 12(A) indicates the frequency of the thermal preference temperature at three different spaces in summer, with the fitted Eq. (4), Eq. (5), Eq. (6), all with $(R^2>0.9)$. However, the highest operative temperature occurs in the cockpit for thermal preferences, followed by the residential cabin and the lowest in the dining room with 25.6°C, 25.5°C and 24.3°C, respectively. In addition, Fig. 11(B) indicates the frequency of the thermal preference temperature during the transition seasons, with fitted Eq. (4), Eq (5), Eq (6), all with $(R^2>0.9)$. Similarly, the highest operative temperature for thermal preference occurs in the cockpit with 22.5°C, 22.3°C and 20.6°C, respectively. The finding for thermal preference temperature is consistent with that of the thermal acceptance temperature.
4. Discussion

4.1 Spaces for human thermal comfort on the ship

Personal subjective thermal responses have different performance in different spaces. Published literatures have shown that thermal sensation voting, more than 80% thermal acceptance and thermal preference exhibit a clear difference between indoor spaces and semi-open spaces. Although the locations are considered interior spaces on the ship, the different interior spaces also exhibit some variation in subjective thermal responses. By summarizing the results, Table 6, Table 7 and Table 8 provides the thermal neutral temperature, the more than 90% of the respondent thermal acceptance temperature and the thermal preference temperature for the residential cabins, the dining room and the cockpit, respectively. In winter, the thermal neutral temperatures are 20.2 °C for the dining room, 18.8 °C for the residential cabin and 18.7 °C for the cockpit, the latter being 1.9 °C, 0.2 °C and 1.9 °C, 0.2 °C higher than the previous two.

From these results we have obtained, one can concluded that the thermal acceptance and thermal preference temperatures are higher than the thermal neutral temperature in the residential cabin and dining rooms. This indicated that the respondents prefer a warmer environment in interior spaces on the ship, regardless of winter, summer and the transitional season. This finding is contrary to previous studies which have suggested that interior spaces presented lower thermal acceptance and thermal preference temperature than thermal neutral temperature buildings on land in summer. In addition to environmental parameters, thermal behaviors also provide an important contribution. A possible explanation for these results is that the we normally adopt air-conditioning for cooling in the summer on the ship, which can result in the lower temperature affecting the subjective thermal response. Besides, Comparing the thermal acceptance and thermal preference temperature and the thermal neutral temperature in the cockpit, we can find that there are slight differences between them with respect to the dining room and residential cabins. This may be explained by that the cockpit crew have been for a long time on the ship and more adaptable to the fluctuations of environment.

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<tr>
<th>Table 6. Thermal neutral temperature.</th>
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<td>Transition seasons</td>
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<th>Table 7. Thermal acceptance temperature for over 90% of respondent.</th>
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<th>Table 8. Thermal preference temperature.</th>
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<td>Transition seasons</td>
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4.2 Seasons and human thermal comfort on the ship

Environmental parameters are the dominant factors influencing the subjective thermal response of the respondents. It may be safely said that there are differences in environmental parameters for different seasons. In the residential cabin, the thermal neutral temperature, thermal acceptance and thermal preference temperature are 18.8 °C, 20.1 °C and 22.3 °C in winter, respectively, the former being 1.3°C and 3.5°C lower than the latter two. The thermal neutral temperature, thermal acceptance and thermal preference temperature are 24.5 °C, 24.8 °C and 25.5 °C in summer, respectively, the former being 0.3 °C and 1.0 °C lower than the latter two. The values are 21.8 °C, 22.2 °C and 22.3 °C in transition seasons, the former being 0.4 °C and 0.5 °C lower than the latter two. In the dining room, the thermal neutral temperature, thermal acceptance and thermal preference temperature are 20.2 °C, 21.5 °C and 23.2 °C in winter, respectively, the former being 1.3 °C and 3.0 °C lower than the latter two. The thermal neutral, thermal acceptance and thermal preference temperatures are 23.9 °C, 24.0 °C and 24.3 °C in summer, respectively. The values are 20.5 °C, 20.5 °C and 20.6 °C in the transition seasons, respectively. In the cockpit, the thermal neutral temperature, thermal acceptance and thermal preference temperature are provided 18.7 °C, 18.6 °C, 18.9 °C (winter); 25.1 °C, 25.1 °C, 25.6 °C (summer); and 22.5 °C, 22.4 °C, 22.5 °C (transition seasons), respectively.

On the basis of the results, we can find that the thermal preference temperature is greater than the thermal acceptance temperature and the thermal neutral temperature in winter, the smallest being the thermal neutral temperature. This finding is consistent with summer and the transitional seasons. From the results we have obtained, one can concluded that the crew and passengers prefer warmer temperature in interior spaces, regardless of winter, summer or transitional seasons. Similarly, a possible explanation is that air conditioning and other thermal behavior are adopted for the interior spaces on the ship.

5. Conclusion

A one-year field survey is conducted for human thermal comfort on the ship in hot summer and cold winter areas of China. We obtain realistic subjective thermal responses of the respondents by the field questionnaires. The influence of different interior spaces, seasonal variations and the thermal environment on the human thermal comfort are investigated on the ship. The thermally neutral temperature, the above 90% respondent thermal acceptance temperature, and the thermal preference temperature were derived and synthetically compared by linearly fitting the thermal sensation voting. The following conclusions are derived:

1. The air speed is higher in the summer than in the winter and transition seasons on the ship. Relative humidity occurs lowest in winter, primarily distributed 50%-70%, and highest in summer, primarily distributed 60%-80%, and subsequently in the transition seasons.

2. In winter, summer and transition seasons, the 90% thermal acceptance temperature and thermal preference temperature present higher than the thermal neutral temperature in the residential cabin and dining room. In winter, the thermal preference temperature (22.3 °C) and the thermal acceptance temperature (20.1 °C) are 3.5 °C and 1.3 °C higher than the thermal neutral temperature (18.8 °C) in the residential cabin, respectively. The dining room is correspondingly higher 3.0 °C and 1.3 °C. In winter, the crew and passengers prefer warmer environments in the interior spaces, especially in the residential cabins. In summer, the thermal preference temperature (25.5 °C) and the thermal acceptance temperature (24.8 °C) are 1.0°C and 0.3 °C higher than the thermal neutral temperature (24.5 °C) in the residential cabin, respectively, with the dining room correspondingly higher 0.4 °C and 0.1 °C, respectively. During the transition seasons, the thermal preference temperature (22.3 °C) and thermal acceptance temperature (22.2 °C) are 0.5 °C and 0.4 °C higher than the thermal neutral temperature (21.8 °C) in the residential cabin, respectively, with the dining room correspondingly higher 1.2 °C and 0 °C, respectively. Similarly, during the transitional season and summer months, crew and passengers want a slightly warmer environment. People prefer to be in a warmer environment in the interior spaces on the ship, regardless of winter, summer or transitional seasons.

3. The difference between the thermal neutral temperature and the 90% thermal acceptance temperature in the cockpit present small, both less than the thermal preference temperature. In winter, the thermal neutral and thermal acceptance and the thermal preference temperature are obtained 18.7 °C, 18.6 °C and 18.9 °C respectively, in summer correspondingly 25.1 °C, 25.1 °C and 25.6 °C respectively and in the transition season correspondingly 22.5 °C, 22.4 °C and 22.5 °C respectively. Cockpit crew are more adapted to temperature fluctuations resulting from seasonal changes, compared to the other two spaces.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

References


