Experimental study on dynamic thermal environment of passenger compartment based on thermal evaluation indexes

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Abstract
In this article, the thermal environment and the human thermal comfort of car cabin under different driving states in summer were studied experimentally. The weighted predictive mean vote model and the weighted equivalent temperature model were used for calculation and compared with the experimental values. The experimental results show that the air temperature and relative humidity distribution in cabin are affected by the space position and driving state. The temperature of the cabin seat, which is affected by solar radiation and crew, in the heating stage is slightly higher than the air temperature, while the cooling rate in the cooling stage is much lower than the air temperature. The predictive mean vote model and the equivalent temperature model are basically consistent with the actual thermal comfort of human body under the idle and driving conditions with the change of time. The prediction accuracy of the two models under the idle condition is higher than that under the driving condition, and the overall prediction accuracy of the equivalent temperature model is higher than that of the predictive mean vote model.

Keywords
Vehicle cabin, thermal environment, thermal comfort, predictive mean vote model, equivalent temperature model

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Introduction

Thermal comfort of vehicle cabin has always been one of the main concerns of car owners, researchers, and the automotive industry, which has a significant influence of passengers' comfort and driver's driving. In addition, a large amount of energy is required for automotive heating ventilation and air-conditioning (HVAC) systems to maintain thermal comfort in the cabin. However, the vehicle is characterized by poor thermal insulation and complex space and are susceptible to solar radiation. The convention heat transfer between the vehicle and the environment is greatly increased because of high-speed driving. So the air heat transfer in vehicle cabin is highly non-uniform and transient, which is significantly different from the thermal environment in the building. Therefore, how to scientifically and effectively control the thermal comfort of the cabin and reduce energy waste is an important task of the automotive HVAC system.

Many scholars have studied the thermal environment or thermal comfort in vehicle cabin by numerical simulation or experiment. Chakroun and Al-Fahed\textsuperscript{1} studied thermal comfort in cars parked in the sun during the Kuwaiti summer. In addition, the differences of air temperature inside the car between covering the front windshield and the four side windows were studied comparatively. Shojaee et al.\textsuperscript{2} analyzed the influence of air supply parameters on the distribution of flow field and temperature field in passenger compartment by computational fluid dynamics (CFD). Zhang et al.\textsuperscript{3,4} proposed the computing model of the three-dimensional (3D) temperature distribution and flow field in the cabin by the commercial software FLUENT, which was verified with experimental data. The influence of different factors such as the number of passengers, cooling load, and ambient temperature on thermal comfort and energy consumption was also studied. Guan et al.\textsuperscript{5,6} studied human comfort experimentally by simulating 16 typical climatic conditions in the environment chamber, which was also compared with the highly transient conditions in the cabin. The thermal sensation model, which took into account both physical and psychological factors, was established in the paper. Zhang et al.\textsuperscript{7} conducted a study on thermal comfort during the heating period under idling state in the climate of South China, which showed that the mean skin temperature of human body could be used to reflect the human thermal comfort. Chien et al.\textsuperscript{8} conducted a study to evaluate the thermal comfort of passengers during cooling. In this research, the temperature field and flow field in the compartment were analyzed by transient numerical analysis and verified by experiments, and the local thermal comfort of passengers was evaluated by the predictive mean vote (PMV) method proposed by Fanger.\textsuperscript{9} The results showed that the average temperature decreased rapidly and the flow field became very complicated during the initial cooling period, and began to stabilize after 10 min. The local PMV value indicated that only the feet remained uncomfortable after 20 min. Han and Huang\textsuperscript{10} proposed a numerical simulation on an MPV vehicle and analyzed the effects of different solar incident angles, solar radiation intensity, air supply temperature, speed, and the breathing condition of the passenger on thermal comfort.
The equivalent temperature was used to evaluate the thermal comfort of human body.

Most of studies on thermal comfort of cabin were conducted under laboratory or outdoor parking conditions, and only a few were conducted under driving conditions.\textsuperscript{11,12} It is necessary to objectively evaluate the thermal environment and thermal comfort of the passenger compartment under real driving conditions. Moreover, the usage of PMV model of uniform environment and equivalent temperature $t_{eq}$ model of non-uniform environment in passenger compartment is still controversial. Therefore, in this article, the cooling characteristics of vehicle cabin were studied under the driving and idle condition. The dynamic changes of thermal environment and human thermal comfort in the cabin were analyzed, and the differences of various parameters in time, cabin position, and cabin driving state were compared. Meantime, the weighted PMV model and the weighted equivalent temperature $t_{eq}$ model were used for calculation and compared with the experimental values.

\textbf{Introduction of experiment}

\textit{Experiment of thermal environment}

Due to the uneven and unsteady thermal environment in the cabin, temperature, humidity, wind speed, and mean radiation temperature were measured at multiple positions of the cabin, as shown in Figures 1 and 2. The air temperature and wind speed of the feet, abdomen, and head of the driver were measured at 1st–3rd. The seat temperature of the driver’s hip, waist, and back were measured at 4th–6th. The air temperature and wind speed of the rear passenger’s feet, abdomen, and head were measured at 7th–9th. The seat temperature of the rear passengers’ hip, waist, and back were measured at 10th–12th. Relative humidity in front and back rows were measured at 13th–14th. The mean radiation temperature in the cabin was measured at 15th. The wind speed of outlets of the air conditioner was measured at 16th–19th. There were sensors outside the car, measuring the temperature and humidity of outside air.

\textbf{Figure 1.} Vertical view of measuring point in cabin.
Experiment of thermal comfort

Twenty graduate students (10 male students and 10 female students) volunteered to participate in this study as subjects. They all understood the purpose, methods, and procedures of this study. They were asked to stay away from alcohol and strenuous exercise for at least 18 h before the experiment and to wear uniform to avoid clothing differences that might affect test results.

In order to calculate the weighted PMV value and the weighted $t_{eq}$ value, it is necessary to measure the skin temperature of each part of the human body. Each measuring positions of human skin temperature are shown in Figure 3.

The comfortable questionnaire which is put forward by ASHRAE standard\textsuperscript{13} is used to evaluate the human thermal comfort. The seven values are “ + 3,” “ + 2,” “ + 1,” “0,” “−1,” “−2” and “−3,” respectively, reflect the subjective thermal sensation of “hot,” “warm,” “slightly warm,” “neutral,” “slightly cool,” “cool,” and “cold.” This article only conducts a questionnaire on the overall thermal sensation.

\begin{figure}[h]
  \centering
  \includegraphics[width=0.5\textwidth]{figure2.png}
  \caption{Front view of measuring point in cabin.}
  \label{fig:figure2}
\end{figure}

\begin{figure}[h]
  \centering
  \includegraphics[width=0.5\textwidth]{figure3.png}
  \caption{Human skin temperature measuring points.}
  \label{fig:figure3}
\end{figure}
**Experimental instrument**

The main experimental instruments are shown in Table 1.

**Table 1. Main experimental instruments.**

| Test items          | Instrument       | Model  | TekEst Range      | Uncertainty |
|---------------------|------------------|--------|-------------------|-------------|
| Air temperature     | PT100            | Omega  | −50°C to 100°C    | ±0.1°C      |
| Seat temperature    | PT100            | Omega  | −50°C to 100°C    | ±0.1°C      |
| Human skin temperature | H & H thermocouple | Omega  | −50°C to 100°C    | ±0.3°C      |
| Relative humidity   | Humidity Sensor  | Vaisala| 0–100 %RH         | ±1.5 %RH    |
| Velocity            | Thermo-sensitive anemometer | E+E   | 0–10 m/s          | ±0.15 m/s   |
| Globe temperature   | Globe thermometer | SZ-JTR04 | −20°C to 125°C   | ±0.2°C      |
| Heat flux           |                 | HFM-215 | 12–3500 W/m²      | ±2%         |
| Vehicle             | SUV              | BYD    | /                 | /           |
| Data collection     | Data acquisition instrument | Agilent 34970A | /                 | /           |

**Experimental procedure**

Before the experiment, each sensor was arranged inside and outside of the vehicle. The temperature sensors need to be shielded by the belt with low solar radiation absorption rate, so as to avoid solar radiation to affect the test accuracy. Volunteers who took part in the experiment rested, sited, read, or walked quietly in office with temperature close to the human thermal comfort zone.

After the arrangement of measuring sensors, all doors of the cabin should be kept open, and shade curtains should be arranged in front of the windshield to avoid interference from solar radiation, so as to keep the thermal environment of the cabin consistent with the external thermal environment. After 1 h, the shade was removed, all doors were closed, and the cabin was exposed in the sun for 1 h. After the exposure test, two testers including a driver and a passenger sitting in the back row got into the car at the same time. And then they immediately turned on the air conditioner under automatic mode. The air outlet direction was adjusted to the level. The temperature, humidity, and air speed data were collected every 5 s, the globe temperature data were collected every 1 min, and the subjective surveys of human comfort were conducted every 5 min.

During the experiment, the air-conditioning was set to run automatically, internal circulation, cooling, and 26°C, no matter the car was under idle or driving state.
Data processing

Mean skin temperature

The mean skin temperature of the upper body and the lower body need to be calculated, respectively, because of the calculation of the thermal evaluation index. The research of Butera\textsuperscript{14} on human skin temperature is referred for the calculation of average skin temperature, as shown in formulas (1) and (2)

\begin{equation}
t_{up,bo} = 0.218t_{ch} + 0.096t_{ab} + 0.158t_{ba} + 0.082t_{wa} + 0.091(t_{le,up,arm} + t_{ri,up,arm}) + 0.072(t_{le,lo,arm} + t_{r,lo,arm}) + 0.060(t_{le,ha} + 0.060t_{ri,ha})
\end{equation}

\begin{equation}
t_{lo,bo} = 0.221t_{le,th} + 0.0221t_{ri,th} + 0.194(t_{le,ca} + t_{ri,ca}) + 0.085(t_{le,fo} + t_{ri,fo})
\end{equation}

Weighted PMV model

According to the PMV–PPD model proposed by Fanger,\textsuperscript{9} the calculation method of PMV is as follows

\begin{equation}
PMV = (0.303e^{-0.036M} + 0.028)(M - W - 3.05 \times 10^{-3} \times [5733 - 6.99(M - W) - P_a]) - 0.42[(M - W) - 58.15] - 1.7 \times 10^{-5}M(5876 - P_a) - 0.0014M(34 - t_a) - 3.96 \times 10^{-8}f_{cl}[t_{cl} + 273.15]^4 - (t_r + 273.15)^4 - f_{cl}h_c(t_{cl} - t_a)
\end{equation}

\begin{equation}
P_a = \phi_a P_s
\end{equation}

\begin{equation}
P_s = 610.6 \exp\left(\frac{17.26t_a}{273.3 + t_a}\right)
\end{equation}

\begin{equation}
f_{cl} = \begin{cases} 
1.00 + 1.29I_{cl} & I_{cl} \leq 0.078 \\
1.05 + 0.645I_{cl} & I_{cl} > 0.078
\end{cases}
\end{equation}

\begin{equation}
t_{cl} = \frac{35.7 - 0.0275(M - W) + I_{cl}f_{cl}[4.13(1 + 0.01dT) + h_c t_a]}{1 + I_{cl}f_{cl}[4.13(1 + 0.01dT)] + h_c}
\end{equation}

\begin{equation}
dT = t_r - 20
\end{equation}

\begin{equation}
h_c = \begin{cases} 
2.7 + 8.7v^{0.67} & 0.15 < v < 1.5 \\
5.1 & 0 < v < 0.15
\end{cases}
\end{equation}

where $M$ is human metabolic rate, which is 1 met = 58.15 W/m\textsuperscript{2} under idle state and is 1.5 met under driving state; $W$ is human external work rate, which is 0 under sitting state; $P_a$ is partial vapor pressure; $\phi_a$ is the ambient relative humidity; $t_a$ is
the ambient temperature; $I_{cl}$ is thermal resistance of clothing. $f_{cl}$ is the ratio of surface area of clothed body to that of nude body; $v$ is the air velocity around the man; $h_c$ is heat transfer coefficient of clothing surface.

According to the area-weighted PMV model proposed by Ingersoll et al., PMV of each part of the human body is calculated separately, and then weighted based on the formula (11)

$$PMV = 0.21PMV_{he} + 0.56PMV_{up,bo} + 0.23PMV_{lo,bo}$$

Weighted equivalent temperature $t_{eq}$ model

According to SAE J2234-2012, if there is an imaginary closed space with zero wind speed, where the convective and radiant heat transfer between human body and the space are consistent with the real environment, the temperature of the imaginary space is the equivalent temperature of the real environment. The calculation method is as follows

$$t_{eq} = t_{sk} - \frac{C + R}{h_{cal}}$$

$$C = h_c(t_{cl} - t_a)$$

$$R = \varepsilon \sigma f_{cl} f_{eff} \left[ (t_{cl} + 273.15)^4 - (t_r + 273.15)^4 \right]$$

$$t_{cl} = t_{sk} - 0.155I_{cl}(C + R)$$

where $t_{sk}$ is mean human skin temperature; $C$ is the convective heat transfer between human body and environment; $R$ is the radiative heat exchange between the body and environment; $h_{cal}$ is the heat transfer coefficient between human body and environment under the imaginary environment, which is 6.3 W/m²; $v$ is the air velocity around the man; $h_c$ is heat transfer coefficient of clothing surface; $t_{cl}$ is the mean temperature of the outer surface of the clothed body; $t_a$ is the ambient temperature; $\varepsilon$ is the human emissivity, which is 0.97; $\delta$ is boltzmann’s constant, which is $5.67 \times 10^{-8}$W/(m² K⁴); $I_{cl}$ is thermal resistance of clothing. $f_{cl}$ is the ratio of surface area of clothed body to nude body; $t_r$ is the mean radiant temperature; $f_{eff}$ is the effective radiant area coefficient of body, which is 0.8 under sitting state.

According to the calculation of weighted equivalent temperature in SAE J2234-2012, $t_{eq}$ of each part of human body was calculated separately, and then weighted based on the following formula (16)

$$t_{eq} = 0.1\times t_{eq,head} + 0.7\times t_{eq,upper, body} + 0.2\times t_{eq,upper, body}$$

Since $t_{eq}$ cannot be directly compared with the subjective thermal sensation votes (TSV) of human body, the relationship between $t_{eq}$ and TSV in the cabin environment is converted, as shown as Figure 4.
Analysis and discussion

Analysis of thermal environment

Influence of position on air temperature. The experiment lasts for 120 min. The first 60 min are the preheating stage, and the last 60 min are the cooling and cooling stage. It can be seen from Figures 5 and 6 that the air temperature in the cabin under idle condition is significantly stratified in the vertical direction.

During the preheating stage, the air temperature of the driver and rear passenger from top to bottom are distributed from high to low. The maximum temperature difference between the head and the feet occurs on 20 min, which of the driver and rear passenger are 8.6°C and 7.6°C, respectively.

The main reason of the significantly stratified temperature in the vertical direction is that the upper air is strongly influenced by solar radiation. In addition, the
air speed of the top is higher than that of the bottom, as is the coefficient of heat transfer with the environment, so the heat flux density of the top is greater than that of the bottom. At the same time, the mean rise rate of the upper air temperature is much higher than that of the lower air temperature due to the heat storage of interior decorations such as car seats and carpets. The passenger position in the back row is slightly less affected by solar radiation than that in the front row because of vehicle structure. Therefore, the heating rate and maximum temperature difference in the back row are slightly less than that in the driver’s position.

During the preheating phase, the vertical temperature difference reaches the peak value first and drops slightly later until the downward trend flattens out, while the lower air temperature rises after 20 min of preheating, the upward trend weakened and finally flattened out. It is the reason that after 20 min, the influence of the difference of temperature rising rate between the upper and lower layers is gradually smaller than that of heat exchange between the upper and lower layers. The heat of the upper air transferred to the lower air is more than that gained from outside. As the temperature difference between the upper and lower air decreases, the heat gradually becomes balanced, and finally, the temperature difference maintains constant.

In the cooling stage, the air temperature of the cabin is obviously stratified, which is different from the preheating stage and is also different between the front and rear. The stratification of air temperature at the driver’s position is the same as that at the preheating stage, but the temperature difference is smaller because of the cooling effect of the air-conditioning. Due to the horizontal setting of the air outlet, the cold air diffuses up and down after blowing to the driver’s body surface, so the upper and the lower air at the driver’s position are effectively cooled, and the cooling rate is relatively close. The cold air can only blow to the upper level of the rear passenger, which is blocked by the front seat. As a result, the air
temperature of the rear passenger’s feet and abdomen can hardly drop down, which are higher than the air temperature of his head.

**Influence of driving state on air temperature.** Figures 7 and 8, respectively, show the air temperature distribution of different parts of the driver and the rear passenger under driving conditions. It can be seen that the air temperature stratification law in the cabin is basically consistent with that under idle speed. However, through comparative analysis with idle speed condition, when the temperature change in cabin tends to be flat, the maximum air temperature difference between layers under driving condition is smaller than that under idle condition. As shown in Table 2, the air temperature is more uniform than that under idle condition. It is
the reason that in the process of driving, the convective heat transfer between air and cabin is enhanced. The heat transfer from inside to outside under driving condition is more, when the inside temperature is higher than the outside one, so the cooling rate of cabin is higher than that under idle condition. The heat transfer from outside to inside under driving condition is more, when the outside temperature is lower than the inside one, so the cooling rate of cabin is less than that under idle condition. Combined with the effects of the two processes, the maximum air temperature difference under driving condition is smaller than that under idle condition.

Relative humidity distribution. Figures 9 and 10, respectively, show relative humidity changes of different positions in the cabin under idle and driving condition. In the preheating stage, the relative humidity in the cabin decreases gradually and tends to be stable in the later stage, which decreases from about 50% at the beginning to about 35% at the end. The relative humidity in the front of compartment is lower than that in the rear compartment. The main reason for the great change of humidity in the cabin is that the air temperature rises greatly, while the moisture content stays the same, which causes the relative humidity to decrease greatly.

In the cooling stage, the relative humidity in the cabin increases gradually and tends to be stable in the later stage, which increases from about 50% at the

| Location | Idle | Driving |
|----------|------|---------|
| Driver   | 3.5°C | 1.5°C   |
| Rear     | 2.6°C | 2.0°C   |

**Figure 9. Relative humidity change of different positions (idle).**
beginning to about 35% at the end. It is the reason for the rapid rise of relative humidity in the cabin that not only the air temperature in the cabin drops sharply but also when just enter the cabin, the volunteers sweat a lot due to the high temperature, making the air moisture content greatly increase.

Seat temperature distribution. The change diagram of seat temperature with time, which is mean value of idle and driving conditions, is shown in Figure 11. As can be seen from the figure, the temperature of the back, hips, and waist of the seat is basically the same. In the heating stage, the temperature of the seat is higher than that of the inside air. In the cooling stage, the air temperature drops rapidly, while the seat temperature drops slowly, falling to a temperature close to that of human

Figure 10. Relative humidity change of different positions (driving).

Figure 11. Seat temperature changes over time.
skin after 80 min. In the heating stage, the seat temperature keeps rising because of the heat storage. When it reaches about 30 min, due to the heat convection transfer between the seat and the lower air, the heat dissipation loss of seat gradually equates with heat storage, and the temperature basically remains unchanged. In the cooling stage, since the seat back, waist, and hip are in contact with the clothing, the heat is dissipated slowly through conduction, resulting in a very slow cooling rate.

**Analysis of thermal comfort**

**Analysis on TSV change.** Figure 12 show that the change of subjective TSV of drivers and rear passengers with time under idle and driving conditions. When the participants entered the cabin from a comfortable office environment, although the air conditioner was turned on, the skin temperature rose rapidly in a short time because the air and seat temperature in the cabin was higher after the cabin was exposed to the sun. Therefore, the participants got hotter and hotter, and the TSV kept rising. The temperature in the cabin decreased continuously and then tends to stabilize, so did the TSV.

Through comparative analysis, the TSV of the driver and the rear passenger are basically the same in the TSV rising stage. It is because, the air temperature in the cabin is much higher at this stage and the human thermal sensation is less affected by the cold air of air-conditioning. In the TSV descending stage, the TSV of the driver and the rear passenger decrease at different rates and the TSV of the rear passenger are always higher than that of the driver. It is because, the cold air directly blows to the driver, while the rear passenger is less affected by the cold air due to the obstruction of the seat. Therefore, the cooling effect of the front of the cabin is better than that of the rear.

![Figure 12. TSV changes with time.](image-url)
The duration of TSV rising under driving condition is longer than that under idle condition. It is the reason that the occupants, especially the driver, are more nervous and concentrated in driving, and the metabolic rates of both are higher than that in idle. In the descending stage of TSV, the driver’s TSV are always lower than the rear passenger’s, which was similar to the idling condition. The difference is that the TSV of the driver and rear passenger under driving conditions are always higher than that under the idle condition. The reason is that the metabolic rates of both are higher than that under idle condition and the difference of metabolic rates in the descending stage has more significant influence on TSV than that in the rising stage.

Analysis on absolute deviation of $T_{eq}$ model. As shown in Figures 13 and 14, human thermal sensation of experiment value is compared with that of $T_{eq}$ model under idle and driving conditions. The time trend of the $T_{eq}$ model is basically the same as that of experiment value, but there are deviations between the data of both. Under idle condition, the maximum deviation in TSV rising stage can reach 1, while 90.9% of deviations in TSV falling stage are within the range of $-0.2$ to $+0.2$. It indicates that the $T_{eq}$ model has a larger prediction deviation in TSV rising stage under idle speed condition, which can predict accurately in TSV falling stage. Under driving condition, the TSV deviations are basically around 0.5 at the initial stage, while 90.9% of the deviations in the TSV falling stage are within the range of $-0.2$ to $+0.5$. It indicates that the prediction deviation of the $T_{eq}$ model under driving condition is larger while the prediction accuracy is lower, compared with that under idle condition.

Analysis on absolute deviation of PMV model. As shown in Figures 15 and 16, human thermal sensation of experiment value is compared with that of PMV model under idle and driving conditions. The time trend of the PMV model is basically the same as that of experiment value, but there are deviations between the data of both.
Under idle condition, the maximum deviation can reach 0.6, while 92.3% of deviations are within the range of −0.5 to + 0.2. It indicates that the prediction deviation of the PMV model under driving condition is larger while the prediction accuracy is lower, compared with that under idle condition.

It can be seen from the analysis above that the prediction accuracies of the two models under idle condition are higher than that under driving condition. In the TSV rising stage, the prediction accuracy of PMV is higher than that of the $T_{eq}$ model, while in the TSV descending stage, the prediction accuracy of the $T_{eq}$ model under idle condition is higher than that of the PMV model. In general, the prediction accuracy of the $T_{eq}$ model is higher than that of the PMV model. The deviation distributions of the two models are concentrated under idle condition, which
are dispersed under driving condition. The prediction deviation of the $T_{eq}$ model is inclined to be positive, while that of PMV model is inclined to be negative.

**Analysis on relative deviation of models.** In order to facilitate the analysis of relative deviation, the thermal sensation index range of $-3$ to $+3$ is adjusted to $0$ to $+7$. Figure 17 shows the relationship on TSV between experimental value and the predicted value of the $T_{eq}$ model. Almost 92.3% of data under idle condition are within the range of $-10\%$ to $+10\%$, and 100% of data under driving condition are within the range of $-20\%$ to $+10\%$. The relative accuracy of the $T_{eq}$ model under idle condition is higher than that under driving condition. Figure 18 shows...
the relationship on TSV between experimental value and the predicted value of the PMV model. Around 92.3% of data under idle condition and 92.3% of data under driving condition are both within the range of −10% to +20%. The relative accuracy of the PMV model under idle condition is similar to that under driving condition. Therefore, the comparative analysis of the two figures shows that the relative accuracy of the $T_{eq}$ model is higher than that of the PMV model.

Previous studies have mostly used PMV model or $T_{eq}$ model for engineering prediction. For example, the study of Chakroun and Al-Fahed\(^1\) considered the effect of using different combinations of internal covering on the PMV. Mahmoud et al.\(^18\) developed a 3D simulation of two different manikins to study the influence of the different shapes on the flow patterns, the equivalent temperature ($T_{eq}$) and the comfort assessment using PMV thermal indices. Oh et al.\(^19\) numerically calculated thermal comfort indices (including PMV and $T_{eq}$) by varying the air distribution ratios in the front and the ceiling vents of the localized air-conditioning system. But few studies compared model with real thermal sensation. Zhang\(^20\) investigated the environmental parameters inside a vehicle parked outside for almost 1 year with four subjects and found that PMV cannot accurately predict thermal sensation in a car. Alahmer et al.\(^21\) used Berkeley model to predict the human thermal comfort and compared with PMV. It was found that before the 4-min mark, the relative humidity has an opposite effect on the human comfort on the PMV scale. The results of this article make up for the lack of comparison between the model and the real thermal sensation.

**Conclusion**

In this article, the thermal environment and the human thermal comfort under idling and driving conditions were experimentally studied. The cooling characteristics of the thermal environment of the driver’s and the rear passenger’s positions in
the cabin under the cooling condition were analyzed, and then the driver’s thermal comfort was analyzed, based on the PMV model and $T_{eq}$ model. The main research conclusions are as follows:

1. The air temperature in the cabin is mainly affected by the space position and driving state. Under idle condition, in the preheating stage, the air temperature of the driver and rear passenger from top to bottom are distributed from high to low, and the heating rate and maximum temperature difference of the rear passenger are slightly lower than that of the drive. Under idle condition, in the cooling stage, the air temperature distribution rule at the driver’s position is the same as in the preheating stage, but the temperature difference is smaller, while the air temperature at the feet and abdomen of the rear passenger are higher than that at the head. Under driving condition, the air temperature distribution rule in the cabin is basically the same as that under idle condition, but the temperature drops faster than that under idle condition and the temperature uniformity is higher than that under idle condition.

2. The humidity distribution of the cabin is also affected by the space position and driving state. Under idle condition, the relative humidity in the front compartment is lower than that in the rear compartment. In the cooling stage, the relative humidity increases with the progress of cooling and tends to be stable in the later stage. Under driving condition, the relative humidity difference between the front and rear is smaller than that under idle condition.

3. The temperature of the car seat is affected by solar radiation, which is slightly higher than that of the air in the cabin during the heating stage. During the cooling stage, the temperature of the seats drops slowly, falling to a temperature closed to that of human skin after 80 min.

4. The time variation trend of TSV of PMV model and $T_{eq}$ model are basically consistent with that of experiment under idle and driving conditions, but there are deviations in both models. According to the comprehensive analysis of absolute deviation and relative deviation, the prediction accuracies of both models under idle condition are higher than that under driving condition, but the overall prediction accuracy of the $T_{eq}$ model is higher than that of the PMV model.

**Declaration of conflicting interests**

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### Appendix 1

**Nomenclature**

**Letter symbols**

- \( C \) convective heat (W)
- \( f \) area coefficient
- \( h \) heat transfer coefficient (W/(m\(^2\) K))
- \( I \) thermal resistance (K/W)
- \( M \) metabolic rate (W/m\(^2\))
- \( P_a \) partial vapor pressure (Pa)
- \( R \) radiant heat (W)
- \( t \) temperature (\( ^\circ \text{C} \))
- \( v \) air velocity(m/s)
- \( W \) external work (W/m\(^2\))
- \( \delta \) Boltzmann’s constant
- \( \varepsilon \) emissivity
- \( \phi \) relative humidity

**Subscripts**

- \( a \) Ambient
- \( ab \) Abdomen
- \( arm \) Arm
- \( ba \) Back
- \( bo \) Body
- \( ca \) Calf
- \( ch \) Chest
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