



Comparative study on differences of human thermal characteristics in cabin between driving and idle state

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Abstract

An experimental study on the dynamic thermal environment and the occupant's overall thermal sensation of the vehicle cabin in automatic air conditioning mode under different driving states respectively in summer and winter is conducted. Experimental results show: The temperature and humidity's change with time of the passenger compartment will be affected by the driving state under the same set temperature as well as occupant's skin temperature and overall thermal sensation. Convective and radiative heat transfer in both seasons and evaporative heat transfer in summer change dramatically over time and are affected by the driving state while other forms of heat transfer keep basically stable. The total heat storage rate is mainly affected by the difference in metabolic rate under different driving conditions of body rather than the difference in total heat transfer. Overall thermal sensation and mean skin temperature have a good linear correlation but different linear coefficients in different conditions, which are less affected by driving states in winter. PMV can accurately reflect real OTS under idle condition in both seasons and under driving condition in summer. But PMV has a large deviation under driving condition in winter.

Keywords Vehicle cabin · Driving state · Heat transfer characteristic · Overall thermal sensation

Nomenclature

Parameters	Meaning	Dimension
t_a	Mean air temperature	°C
t_r	mean radiant temperature	°C
M	rate of metabolic heat production	W·m ⁻²
W	rate of mechanical work accomplished	W·m ⁻²
S	rate of heat storage in body	W·m ⁻²
C_v	rate of convective heat	W·m ⁻²
C_d	rate of conductive heat	W·m ⁻²
R	rate of radiant heat	W·m ⁻²
E_{sk}	total evaporative heat loss from skin	W·m ⁻²
E_{res}	evaporative heat loss from respiration	W·m ⁻²
C_{res}	convective heat loss from respiration	W·m ⁻²
R_e	total heat loss from respiration	W·m ⁻²
f_{cl}	clothing area factor	/

I_{cl}	clothing insulation	clo
t_{cl}	clothing surface temperature	°C
h_c	convective heat transfer coefficient	W·m ⁻² ·K ⁻¹
h_r	linear radiative heat transfer coefficient	W·m ⁻² ·K ⁻¹
ε	body emissivity	/
k_{cl}	clothing thermal conductivity	W·m ⁻¹ ·K ⁻¹
x_{cl}	clothing thickness	m
E_{sw}	evaporative heat loss by sweat	W·m ⁻²
E_{dif}	evaporative heat loss of moisture diffused through skin	W·m ⁻²
r_{ev}	evaporation efficient of sweat	/
m_{sw}	sweat rate	g·m ⁻² ·h ⁻¹
h_{fg}	latent heat of water vaporization	kJ·kg ⁻¹
w	skin wettedness of whole body	/
w_{sw}	skin wettedness caused by sweat	/
E_{max}	maximum evaporation rate from skin	W·m ⁻²
h'	overall sensible heat transfer coefficient	W·m ⁻² ·K ⁻¹
i_m	total vapor permeation efficiency	/
LR	Lewis Ratio	K·kPa ⁻¹
$P_{sk,s}$	saturated water vapor pressure on the skin surface	kPa
P_a	water vapor pressure in ambient air	kPa

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Q	total heat transfer W
Sa	total heat storage rate W
MST	Mean skin temperature °C
OTS	Overall thermal sensation /

1 Introduction

As the city develops and lifestyle changes, vehicle gradually changes from luxury to mass consumer product. Allnut 's research [1] shows that thermal discomfort can reduce driver's efficiency and may cause misoperation. Uncomfortable thermal environment can easily lead to nausea, chest tightness and other symptoms that affect driving safety [2]. Therefore, it is increasingly important to guarantee the thermal comfort of vehicle driver.

However, due to the particularity of the structure and operation of vehicle, the thermal environment inside the vehicle cabin is very different from that of the building. Firstly, its internal thermal environment is susceptible to the external. Secondly, vehicles are more affected by solar radiation than buildings. Thirdly, the inner space is small and the layout is complex, which is greatly affected by the air conditioning. Therefore, the thermal environment of vehicle cabin has a feature of high non-uniformity and transient state.

Due to the above reasons, many studies on thermal comfort in buildings cannot be directly applied to vehicle cabin. Many scholars have studied the thermal sensation or thermal comfort of vehicle cabin's passengers based on the characteristics of vehicle environment. Mezrhab and Bouzidi [3] developed a numerical model that studies thermal comfort of cars in terms of changes in solar radiation, type of glass, color of car, and the radiation characteristics of the materials in the car. Han [4] et al. used a three-dimensional model in the RadTherm which is an advanced thermal management design and analysis tool developed by ThermoAnalytics and Ford Motor Company to evaluate the effects of different environmental thermal loads on thermal comfort. Kaynakli [5] used the empirical equations to calculate the human sweat rate and the average skin temperature based on the body heat balance equation, and analyzed the effect of heating and cooling process on body heat exchange. A numerical model for the exchange of heat and mass between the human body and thermal environment inside the vehicle under steady-state conditions was established [6], which could calculate total sensible and latent heat loss, skin temperature, skin moisture rate, PMV and PPD value. Guan et al. [7] used environmental chambers to simulate 16 typical winter and summer conditions for human comfort experiments and examined data from vehicle cabins under high transient conditions. Their following study established a thermal sensation model [8] that combines both physical and psychological factors and uses environmental and personal parameters to determine physiological responses. Taniguchi [9]

developed a multiple linear regression model based on tests. The overall thermal sensation in this model is only related to the thermal sensation of the facial part while ignores the effect of other body parts. Zhang [10–12] et al. established a local and overall thermal sensation and thermal comfort model by thermal reaction experiments through a sleeve of conditioned air that enclosed the segment. Zhang Wencan [13] conducted a cooling experiment on the idle vehicle in South China and used the human thermal regulation model coupling with the cabin environment to make simulations.

Nevertheless, the existing studies on thermal sensation in vehicle cabin are mostly tested under idle condition or laboratories. Few of them have been conducted under driving condition [14–16]. Therefore, we conducted experiments in vehicle cabin respectively in driving and idle state in summer and winter to study the difference of thermal environment, human objective and subjective response. This paper reports our findings.

2 Methodologies

The experiment was carried out in a vehicle cabin whose model is BYD E6. The vehicle was placed under an outdoor carport to avoid direct solar radiation under idle condition. The direction which faced the direct solar radiation was avoided as far as possible and the car visor was always kept open. Therefore, the subsequent analysis only considers the temperature variation inside the car caused by diffuse solar radiation without considering direct solar radiation.

2.1 Participants

A total of 15 male and 15 female college students (mean values \pm standard deviation of age, 25.5 ± 2.25 years; height, 169.4 ± 7.22 cm; weight, 59.7 ± 9.62 kg) were recruited for the experiments. All subjects were healthy, non-smokers who were not taking any prescription medication and were all approved by the local research ethics committee. Subjects were asked to avoid alcohol, smoking, and intense physical activity at least 24 h prior to each experimental session. In order to avoid the impact of clothing differences on test results, all subjects were required to wear uniform clothes of short sleeves, shorts and sandals in summer while long sleeves, trousers and sneakers in winter.

2.2 Design of Experiment

2.2.1 Arrangement and time schedule

Before the start of the experiment, each sensor was arranged in the vehicle cabin. The subjects involved in the experiment rested in the office where the temperature was close to the

thermal comfort zone, and they could only sit still or walk around. After the arrangement of the measuring points was completed, the passenger compartment doors were kept open for one hour, so that the environment of the vehicle cabin could be consistent with the external. After an hour, close all the doors and let the cabin lay for an hour. During this time, the skin temperature probes were placed on the test positions of the driver. After the phase was over, the driver entered the car, turned on the air conditioning and set the temperature of the automatic mode. The direction of the air vents were kept horizontal. All instruments were turned on and kept for an hour. It should be noted that since the driver needs to drive the car under driving condition, the rear row also enters a recorder at the same time. Multiple experiments were performed per person per condition.

2.2.2 Experimental conditions

The experimental conditions are shown in Table 1. The set status of air conditioning is automatic and inner loop.

2.2.3 Parameter measurement

The location of the collection points is shown in Figs. 1 and 2. The 1st–3rd point measure the temperature and wind speed around foot, abdomen and head. The 4th–5th point measure the temperature of base and back of seat. The 6th point measures the relative humidity around the driver and the 7th point measures globe temperature (refers to the comprehensive temperature expressed by temperature index when a person or an object is subjected to the combined effects of radiant heat and convective heat in a radiant heat environment). The temperature data was collected every 5 s, the relative humidity data was collected every 5 min and the globe temperature was collected every 1 min.

2.2.4 Driver's parameter measurement

The objective parameters of body are the skin temperature. The position of each measuring point of body is shown in Fig. 3. The 1st–4th point is the skin temperature of the head, chest, back, and abdomen respectively. The 5th–7th is that of left upper arm, left lower arm, and left hand skin, respectively. The 8th–10th is that of the corresponding right arm. The 11th–

13th is that of left thigh, left calf, and left foot respectively. The 14th–16th is that of the corresponding right leg. Skin temperatures were collected every 5 s.

The overall thermal sensation is the overall cold or hot feeling of people in an environment. As shown in Fig. 4, the subjective thermal sensation evaluation was evaluated by the thermal comfort questionnaire proposed by the ASHRAE standard [17]. This article only surveyed the overall thermal sensation and recorded it every 5 min. The driver's voting value was recorded by the rear recorder under driving condition.

2.2.5 Experimental equipment

The main device configuration of the test system is shown in Table 2:

3 Data manipulation

Before the data processing, normality test was carried out for multiple experiments of single-person and single-condition. The experiments with large deviation were excluded and the mean value of the remaining experiments was taken as the experimental result of single-person and single-condition. Finally, the average of experimental data of 30 people in single-condition was taken as the experimental result of the condition.

3.1 Mean skin temperature

Due to non-uniform environment inside the car, using area weighted values is a safe measure to consider the local skin temperature difference. Thus, mean skin temperature is an area-weighted value as shown in formula (1-1):

$$\overline{t_{sk}} = \int t_{sk} dA_{sk} / A \quad (1-1)$$

where t_{sk} is the local skin temperature, dA_{sk} is the corresponding local surface area, and A is the total area. The specific values refer to Butera's research results [18].

3.2 Mean air temperature, wind speed and mean radiant temperature

The temperature-weighted PMV model of Matsunaga [19] used weighted air temperature to calculate the PMV in a non-uniform thermal environment. This article refers to its method and calculation is shown in formula (2-1):

$$t_a = 0.1 \times t_{head,air} + 0.7 \times t_{abdomen,air} + 0.2 \times t_{foot,air} \quad (2-1)$$

where $t_{head,air}$, $t_{abdomen,air}$ and $t_{foot,air}$ are the temperature of air around head, abdomen and foot. The mean wind speed is

Table 1 Experimental conditions.

Working condition	Mode	Set temperature
Refrigeration	Idle	26 °C
	Driving	
Heating	Idle	28 °C
	Driving	

Table 2 Main equipment configuration.

Test items	Instrument	Model	Test Range	Accuracy
Temperature	T-thermocouple	Omega	0~50 °C	±0.1 °C
Wind speed	Thermosensitive anemometer	testo425	0–20 m·s-1	±0.01 m·s-1
Humidity	Humidity Sensor	testo625	0~100%RH	±2.5 %RH
Globe temperature	Globe thermometer	SZ-JTR04	-20 °C-125 °C	±0.5 °C
Vehicle	BYD	E6	/	/
Data collection	Data acquisition instrument	Agilent 34970A	/	/

calculated by referring to the influence factors in (2–1). Its calculation is shown in formula (2-2):

$$v_a = 0.1 \times v_{head,air} + 0.7 \times v_{abdomen,air} + 0.2 \times v_{foot,air} \tag{2-2}$$

where $v_{head,air}$, $v_{abdomen,air}$ and $v_{foot,air}$ are the speed of the air around head, abdomen and foot. v_a is the mean wind speed.

According to the ISO7726 [20] standard, the mean radiant temperature calculation for forced convection is as shown in eq. (2-3):

$$t_r = \left[(t_g + 273)^4 + \frac{1.1 \times 10^8 \times v_a^{0.6}}{\varepsilon_g \times D^{0.4}} \times (t_g - t_a) \right]^{1/4} - 273 \tag{2-3}$$

where t_r is the mean radiant temperature, ε_g is the black ball emissivity which is about 0.95, D is the diameter of black ball which is 0.04 m in our experiment and t_g is the globe temperature.

3.3 Human body heat exchange

Heat dissipates from the body to immediate surroundings by several modes of heat exchange: sensible heat flow (including convection and radiation), latent heat flow from sweat evaporation and from evaporation of moisture diffused through the skin, sensible heat flow and latent heat flow from evaporation of moisture during respiration.

The following expression is the thermal balance equation:

$$(M-W-S) \cdot A = C_v \cdot A_v + C_d \cdot A_d + R \cdot A_r + E_{sk} \cdot A + (E_{res} + C_{res}) \cdot A \tag{2-4}$$

The M of driver is about 1met when the car is idle and 1.2–1.7met when the car is driving [21]. An average-1.45met under driving condition was taken (1met = 58.15 W·m-2). The W is generally 0 [22]. A , A_v , A_d , A_r are respectively the area of total area of the human, that of convective heat, that of conduction and that of radiant heat.

Fanger [23, 24], Gagge [25], Hardy [26] and Rapp [27] give quantitative information on calculating heat exchange, which has been adopted in ASHRAE [28] and related standard. The calculation formulas used in this paper are mainly based on the ASHRAE standard [28] assisted with other studies.

Convective heat loss:

$$C_v = f_{cl} h_c (t_{cl} - t_a) \tag{2-5}$$

Radiant heat loss:

$$R = f_{cl} h_r (t_{cl} - t_r) \tag{2-6}$$

In addition:

$$h_r = 4\varepsilon\sigma \frac{A_r}{A} \left(273 + \frac{t_{cl} + t_r}{2} \right)^3 \tag{2-7}$$

$$C_v + R = \frac{\overline{t_{sk}} - t_{cl}}{0.155 I_{cl}} \tag{2-8}$$

The C_v and R can be solved by combing above four formulas.

Fig. 1 Front view of the measuring points

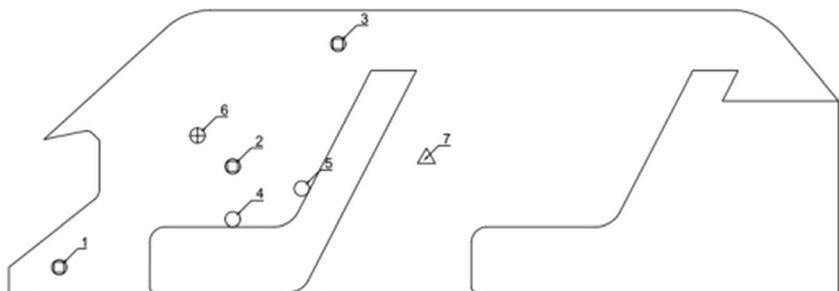
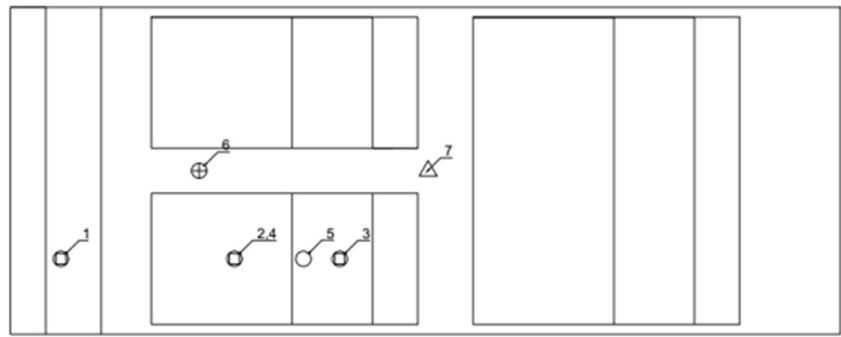


Fig. 2 Top view of the measuring points



Heat loss from respiration:

$$E_{res} = 0.0173M(5.87 - p_a) \quad (2 - 9)$$

$$C_{res} = 0.0014M(34 - t_a) \quad (2 - 10)$$

$$R_e = E_{res} + C_{res} \quad (2 - 11)$$

Heat loss from conduction:

$$C_d = k_{cl} \cdot \frac{t_{sk} - t_i}{x_{cl}} \quad (2 - 12)$$

where t_{sk} is temperature of the skin which occurs conduction and t_i is temperature of seat.

Evaporative heat loss from skin:

$$E_{sk} = E_{sw} + E_{dif} \quad (2 - 13)$$

$$E_{sw} = w_{sw} E_{max} = w_{sw} \cdot h' \cdot i_m \cdot LR \cdot (P_{sk,s} - P_a) \quad (2 - 14)$$

$$E_{dif} = 0.06(1 - w_{sw}) E_{max} \quad (2 - 15)$$

To solve E_{sk} , we need to know w_{sw} . Therefore, we import another method to calculate E_{sw} as shown formula (2-16):

$$E_{sw} = r_{ev} m_{sw} h_{fg} / 3600 = \left(1 - \frac{w^2}{2}\right) m_{sw} h_{fg} / 3600 \quad (2 - 16)$$

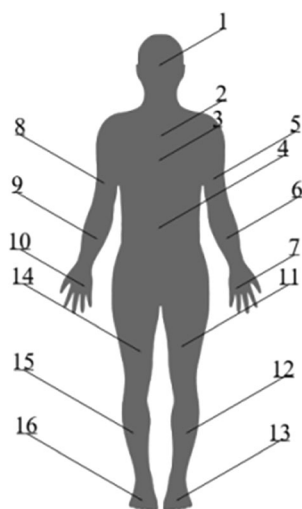


Fig. 3 Human skin temperature measurement points map

The study of Kubota’s study [29, 30] proposed an assumption that the regulatory thermal sweating rate is a linear function of the deviation of mean skin temperature from that of thermal neutrality and it has been verified based on Stolwijk’s data for none-heat acclimated people:

$$m_{sw} = 0.63(M - W - 58) + 50 \left(\frac{t_{sk} - t_{sk,0}}{t_{sk,0}} \right) \quad (2 - 17)$$

In addition:

$$w = 0.06 + 0.94w_{sw} \quad (2 - 18)$$

The w_{sw} can be solved by combing the formula (2-14), (2-16), (2-17), (2-18) and then the E_{sk} can be solved. The other values are determined according to ASHRAE Handbook [25] too.

In the subsequent analysis, when body absorbs heat from the environment, the heat is negative, and when body releases heat to the environment, the heat is positive.

The PMV model proposed by Fanger [23] meaning the Predicted Mean Vote of subjects is also calculated to compare

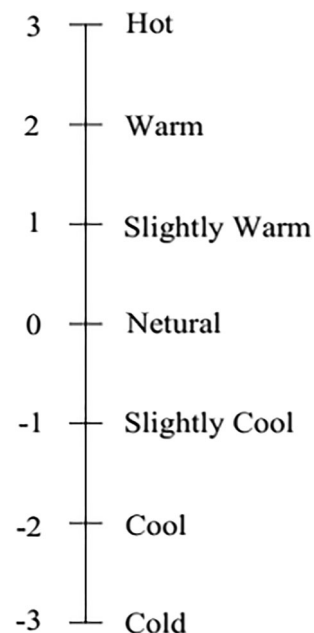


Fig. 4 Thermal sensation scale used in the experiment

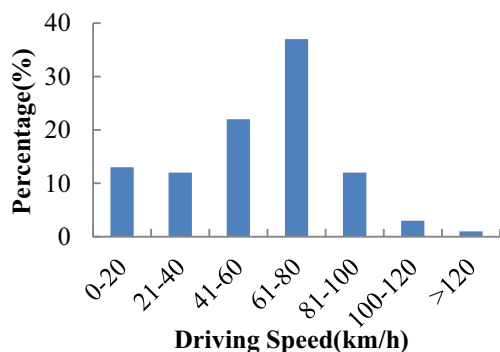


Fig. 5 Driving speed map under driving condition

with the actual overall thermal sensation. The formula is as follows:

$$PMV = (0.303e^{-0.036M} + 0.028) TL \tag{2 - 19}$$

TL means human thermal load reflecting the degree of deviation from the body’s thermal balance. Its specific calculation can be seen ASHRAE Handbook [25].

4 Results

4.1 Summer condition

4.1.1 Vehicle speed, air temperature and relative humidity

As Fig. 5 shows, the driving speed distribution basically conforms to the normal distribution, which 35% of driving time keeps driving speed in 61–80 km/h and the percentage on both sides is lower. The percentage in 0–20 km/h doesn’t match normal distribution, which is because the vehicle needs to deal with various traffic conditions during driving.

Figures 6 and 7 show the variation of air temperature and relative humidity in refrigeration condition. It can be seen that as the cooling progresses, the temperature continues to drop and the relative humidity rises and eventually stabilizes. On the other hand, air temperature under driving condition is always higher than that under the idle condition and as a result the relative humidity is exactly the opposite. This may be due

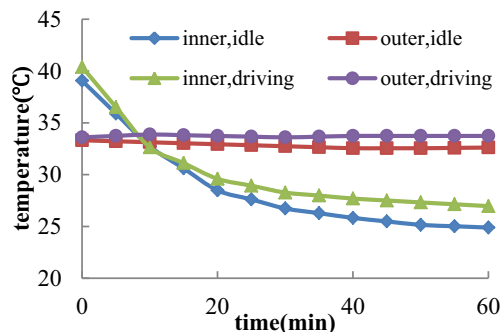


Fig. 6 Variation of air temperature in refrigeration condition

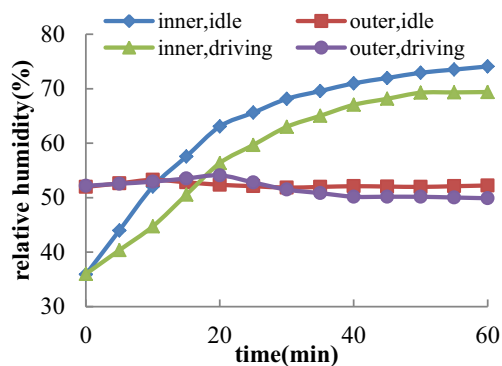


Fig. 7 Variation of relative humidity in refrigeration condition

to the movement of vehicle enhances heat transfer between the vehicle surface and the external environment [31].

4.1.2 Mean skin temperature and overall thermal sensation

Figure 8 shows the variation of mean skin temperature and overall thermal sensation in refrigeration condition. It can be seen that due to the excessive initial temperature in the car, the mean skin temperature has experienced a brief rapid increase, then slowly declines and eventually stabilizes. The trend of overall thermal sensation is similar. It is worth noting that the rising phase under driving condition lasts longer and the maximum skin temperature is higher. The skin temperature difference is small when stable, but the overall thermal sensation is lower under idle condition.

4.1.3 Heat transfer

Figure 9 shows the variation of heat transfer in refrigeration condition. The amount of heat loss from respiration is small and does not change much. The heat conduction gradually becomes 0 as the temperature difference between back and seat decreases. Convective and radiative heat transfer gradually shifts from absorption to release. Evaporative heat transfer undergoes a process of slowly increasing and then slowly decreasing because of change in body sweat. Respiration

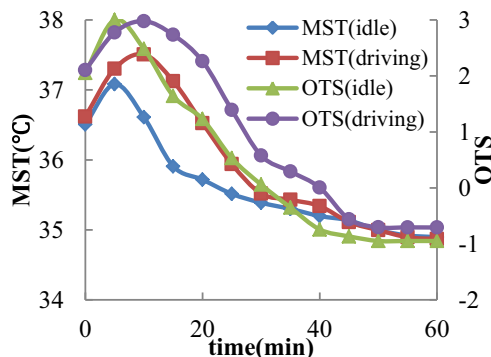


Fig. 8 Variation of mean skin temperature (MST) and overall thermal sensation (OTS) in refrigeration condition

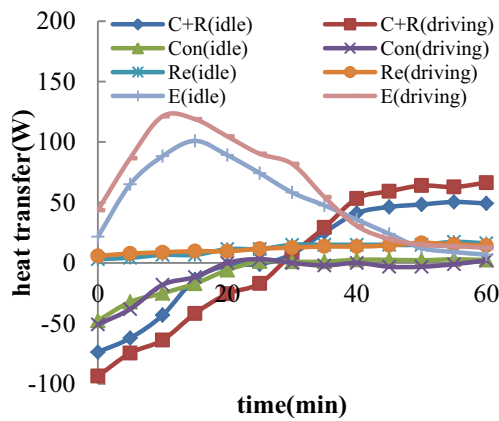


Fig. 9 Variation of heat transfer in refrigeration condition (C + R: convective and radiant heat loss, Con: conductive heat loss, Re: respiratory heat loss, E: evaporative heat loss)

and conduction heat are not much different in different driving states. The amount of convective and radiative heat and evaporative heat under driving condition are always more than that under idle. This may prove that the increase in speed can promote the heat transfer coefficient between body and surrounding system. In addition, this shows that in summer the car air-conditioning system can further reduce the blowing temperature and relative humidity within the first 20–30 min to improve the sensible and latent heat exchange of body, thereby reaching thermal comfort faster.

4.2 Winter condition

4.2.1 Vehicle speed, air temperature and relative humidity

As Fig. 10 shows, the driving speed distribution is similar to that in summer. Figures 11 and 12 show the variation of air temperature and relative humidity in heating condition. The trend of change is basically the same as the summer condition, but the direction is opposite. Air temperature under driving condition is always lower than the idle, which leads the diversity in relative humidity.

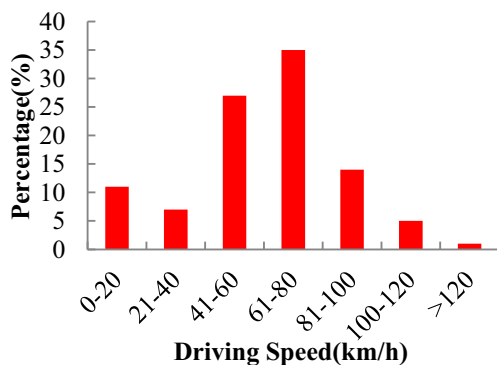


Fig. 10 Driving speed map under driving condition

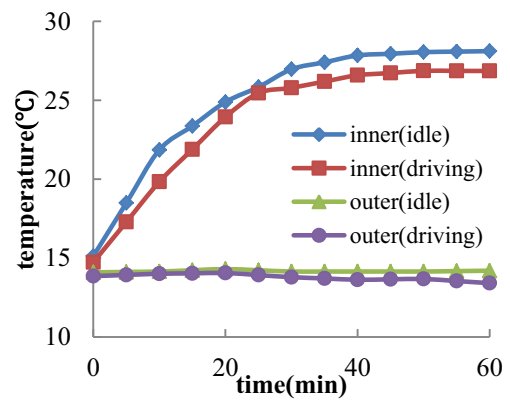


Fig. 11 Variation of air temperature in heating condition

4.2.2 Mean skin temperature and overall thermal sensation

Figure 13 shows the variation of mean skin temperature and overall thermal sensation in heating condition. It can be seen that the mean skin temperature experiences a slow rise and eventually stabilizes, which is similar as overall thermal sensation because of increase of temperature inside the car. There is no turning point that exists in the summer condition. Mean skin temperature is always higher under driving condition than that under idle. The overall thermal sensation at initial stage is almost the same, but it is higher under driving condition in late stage of the experiment.

4.2.3 Heat transfer

Figure 14 shows the variation of heat transfer in heating condition. Except the convection and radiation heat transfer, the other forms of heat exchange are small and change little. Convection and radiation heat transfer rapidly decrease in the first ten minutes and they are higher under driving condition, which further demonstrates that the increase in speed can promote the heat transfer coefficient between body and the surrounding system. But when this stage is over, they only slowly decrease and are almost identical under different driving conditions. In addition, from the view of control, in the

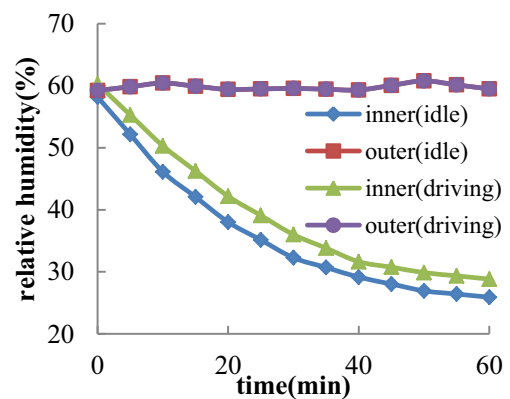


Fig. 12 Variation of relative humidity in heating condition

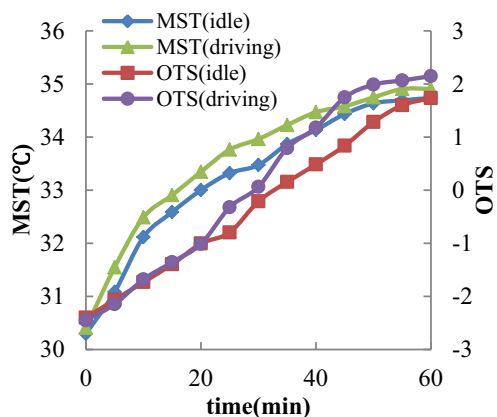


Fig. 13 Variation of mean skin temperature (MST) and overall thermal sensation (OTS) in heating condition

winter the car air conditioner can further increase the blowing temperature in the first 20–30 min without considering the relative humidity (relative humidity needs to be considered in summer), thereby making the subject reach thermal comfort faster.

5 Discussions

5.1 Total heat exchange and heat storage rate

Figures 15 and 16 show the variation of total heat exchange and heat storage rate in refrigeration and heating condition. Q is the total heat exchange of the human body. S_a is the total heat storage rate. Under the refrigeration condition, the total heat has undergone a change of direction and reaches the maximum and stabilizes at 20 min. To the opposite, heat storage rate reduces quickly first and then gradually flattens. Total heat exchange under driving condition is always higher than that under idle. The change of total heat under heating condition is similar as convection and radiation heat transfer under

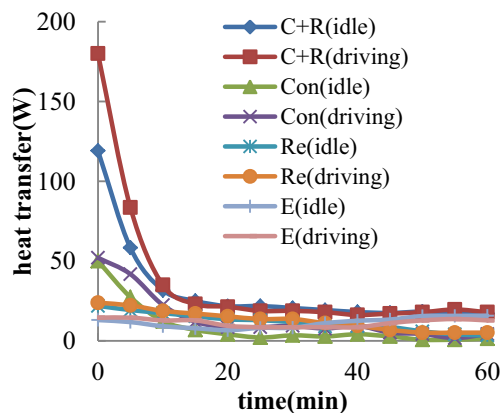


Fig. 14 Variation of heat transfer in heating condition (C + R: convective and radiant heat loss, Con: conductive heat loss, Re: respiratory heat loss, E: evaporative heat loss)

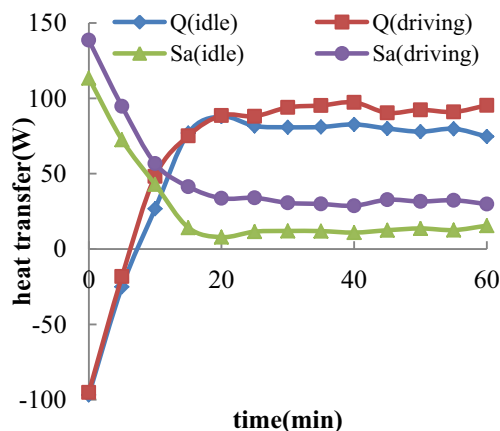


Fig. 15 Variation of total heat exchange and heat storage rate in refrigeration condition

heating condition. On the other hand, no matter which season, heat storage rate under driving condition is always higher than that under idle. Therefore, it can be concluded that divergence of heat storage rate is mainly caused by differences in metabolic rate in different driving states instead of discrepancy in heat exchange.

At the same time, it can be seen that, heat storage rate is almost stable after 20 min. But the overall thermal sensation is stable until the last 10 min of the experiment. Therefore, the overall thermal sensation of body in the dynamic thermal environment of the car is not suitable to be characterized by the heat storage rate.

6 Linear relationship between mean skin temperature and overall thermal sensation

Figure 17 shows the relationship between mean skin temperature and overall thermal sensation. It can be seen that they have such a good linear correlation under different conditions that skin temperature can be used to characterize overall

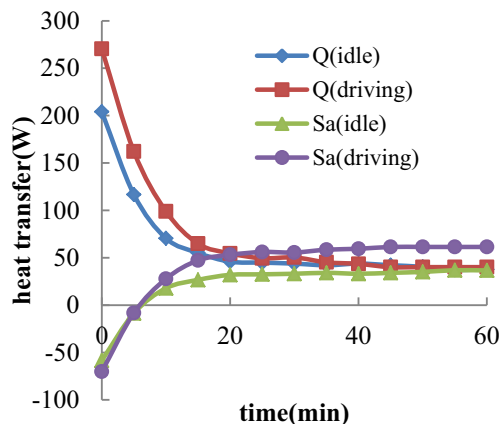


Fig. 16 Variation of total heat exchange and heat storage rate in heating condition

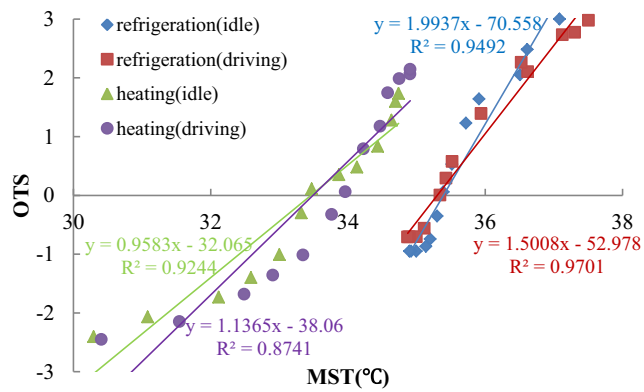


Fig. 17 Relationship between mean skin temperature (MST) and overall thermal sensation (OTS)

thermal sensation, which is consistent with Zhou's [32] view. However, there are differences in linear coefficients under different conditions. The linear coefficient in summer under driving condition is lower than that under idle. Although there are also differences of linear coefficients in winter, the difference is small. Therefore, for winter condition, skin temperature under idle condition can be used to characterize overall thermal sensation under driving. Accuracy will be lower if this method is adopted in summer.

6.1 Applicability of PMV model

Figures 18 and 19 show the relationship between actual thermal sensation and PMV value. They show that in idle state data points are almost in the range of -0.5 to $+0.5$, which demonstrate that PMV can reflect the true overall thermal sensation accurately. However, in driving state accuracy will be reduced to some extent. The degree of reduction under summer condition is very low. Therefore PMV can still reflect the true thermal sensation. Nevertheless, in winter condition the deviation is mainly concentrated in $+0.5$ to $+1$, which demonstrates that PMV can't reflect the true overall thermal sensation. Thus, except the driving condition in winter, PMV can be used to represent true overall thermal sensation.

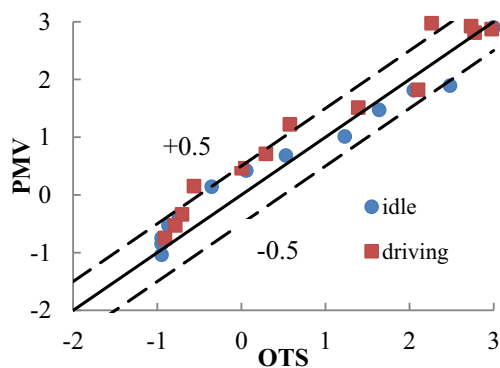


Fig. 18 Relationship between actual thermal sensation (OTS) and PMV value in summer condition

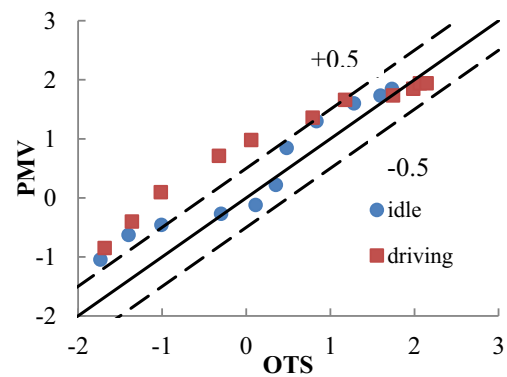


Fig. 19 Relationship between actual thermal sensation (OTS) and PMV value in winter condition

7 Conclusions

We conducted experiments in the automatic mode of air conditioning in a vehicle respectively in summer and winter in different driving states, measuring the cabin's environmental parameters and human objective and subjective parameters. The heat transfers of body were calculated and analyzed. The study led to the following conclusions:

- 1) The temperature and humidity's change with time of the passenger compartment will be affected by the driving state under the same set temperature as well as occupant's skin temperature and overall thermal sensation.
- 2) Convective and radiative heat transfer in both seasons and evaporative heat transfer in summer change dramatically over time and are affected by the driving state while other forms of heat transfer keep basically stable.
- 3) The total heat storage rate is mainly affected by the difference in metabolic rate under different driving conditions of body rather than the difference in total heat transfer.
- 4) OTS and MTS have a good linear correlation but different linear coefficients under different conditions, which are less affected by driving states in winter.
- 5) PMV can accurately reflect real OTS under idle condition in both seasons and under driving condition in summer. But PMV has a large deviation under driving condition in winter.

There are still some limitations in this article. For example, this article ignores the effects of direct solar radiation which has an important influence in the actual driving process. In addition, when there are a large number of people in the car, environment inside the car will change due to human heat dissipation, which means thermal sensation is different when the same vehicle is populated with full-capacity and under-capacity. On the other hand, this article only analyzes the overall thermal sensation, without examining the local thermal

sensation. Future research will be carried out from above perspectives and then more reliable and practical control strategies can be put forward.

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References

- Alahmer A, Mayyas A, Mayyas AA et al (2011) Vehicular thermal comfort models; a comprehensive review. *Appl Therm Eng* 31(6–7):995–1002
- F Norin, D Wyon (1992) Driver vigilance—the effects of compartment temperature. SAE Technical Paper No. 920168. Society of Automotive Engineers, Inc, Warrendale, PA, USA
- Mezrhab A, Bouzidi M (2006) Computation of thermal comfort inside a passenger car compartment. *Appl Therm Eng* 26(14–15): 1697–1704
- T. Han, Kuo-Huey Chen, B. Khalighi (2010) Assessment of various environmental thermal loads on passenger thermal comfort. SAE
- Kaynakli O, Pulat E, Kilic M (2005) Thermal comfort during heating and cooling periods in an automobile. *Heat Mass Transf* 41(5):449–458
- Kaynakli O, Kilic M (2005) An investigation of thermal comfort inside an automobile during the heating period. *Appl Ergon* 36: 301–312
- Guan Y, Hosni MH, Jones BW, Giolda TP (2003) Investigation of human thermal comfort under highly transient conditions for automotive applications—part 1. *ASHRAE Transact* 10:885–897
- Guan Y, Hosni MH, Jones BW, Giolda TP (2003) Investigation of human thermal comfort under highly transient conditions for automotive applications—part 2. *ASHRAE Transact* 109:898–907
- Taniguchi Y, Hiroshi A, Kenji F (1992) Study on car air conditioning system controlled by car occupants' skin temperatures—part 1: research on a method of quantitative evaluation of car occupants' thermal sensations by skin temperature. SAE Technical Paper Series
- Arens E, Hui Z et al (2010) Thermal sensation and comfort models for non-uniform and transient environments: part I: local sensation of individual body parts. *Build Environ* 45(2):380–388
- Zhang H, Arens E et al (2010) Thermal sensation and comfort models for non-uniform and transient environments, part II: Local comfort of individual body parts. *Build Environ* 45:389–398
- Zhang Hui E (2010) Arens, et al. thermal sensation and comfort models for non-uniform and transient environments: part III: whole-body sensation and comfort. *Build Environ* 45(2):399–410
- Zhang Wencan (2013) Study on the key Technology of Thermal Environment and Occupant's thermal comfort analysis in vehicle cabins, South China University of Technology
- Alahmer A, Mayyas A et al (2011) Vehicular thermal comfort models: a comprehensive review. *Appl Therm Eng* 31:995–1002
- Croitoru C, Nastase I et al (2015) Thermal comfort models for indoor spaces and vehicles—current capabilities and future perspectives. *Renew Sust Energ Rev* 44:304–318
- A. Chothave, Y. Mohite, V. Poal, P. Pamarthi (2017) A Method to Evaluate Passenger Thermal Comfort in Automobile Air Conditioning Systems, SAE Technical Paper. 2017-26-0150
- American Society of Heating, Refrigerating, and Air-conditioning Engineers, Inc. (ASHRAE) (2004) Thermal environmental conditions for human occupancy. ANSI/ASHRAE 55–2004. Atlanta (GA): ASHRAE
- Butera FM (1998) Chapter 3-Principles of thermal comfort. *Renew Sust Energ Rev* 2:39–66
- Matsunaga (1993) Evaluation and measurement of thermal comfort in the vehicles with a new thermal manikin. SAE papers. No.931958
- E. International Standard Organization (2002) ISO 7726: Ergonomics of the Thermal Environment-Instruments for Measuring Physical Quantities, International Standard Organization, Geneva, Switzerland
- ISO (2004) EN ISO 8996, Ergonomics of the Thermal Environment—Determination of Metabolic Rate, International organization for Standardization, Geneva
- Zhang B, Yan B, Gao X et al (2006) Experimental research on interrelation between gaseous metabolism or energy metabolism and kinetic efficiency within different motions on heaviest load. *J Xi'an Inst Phys Educ* 23(1):56–61
- Fanger PO (1967) Calculation of thermal comfort: introduction of a basic comfort equation. *Build Eng* 73(2):III.4.1
- Fanger PO (1970) Thermal comfort analysis and applications in environmental engineering. McGraw-Hill, New York
- Gagge AP, Hardy JD (1967) Thermal radiation exchange of the human by partitioned calorimetry. *J Appl Physiol* 23(2):248–258
- Hardy JD (1949) Heat transfer. In: Newburgh LH (ed) Physiology of heat regulation and science of clothing. W.B. Saunders, London
- Rapp G, Gagge AP (1967) Configuration factors and comfort design in radiant beam heating of man by high temperature infrared sources, *Build. Eng.* 73(2):III.1.1
- ASHRAE (2005) Handbook—Fundamentals (SI). Chapter 8 Thermal Comfort
- H. Kubota, T. Yamakoshi, N. Kamata (1996) Prediction of mean skin temperature as an index of human response to thermal environment, *Proceeding of Indoor Air Quality and Climate*, Nagoya, Japan
- Kubota H, Yamakoshi T, Kamata N et al (2004) Prediction of mean skin temperature for people in hot environment considering evaporation efficiency of sweating. *J Environ Eng* 575:83–89
- Mao Y, Wang J, Li J (2018) Experimental and numerical study of airflow and temperature variations in an electric vehicle cabin during cooling and heating. *Appl Therm Eng* 137:356–367
- Xiaojie Z, Dayi L, Qingyan C (2019) Experimental investigation of thermal comfort in a passenger car under driving conditions. *Build Environ* 149:109–119

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