Thermal Comfort Analysis of Passenger Compartment of a Hybrid Vehicle

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Abstract. The internal environment of the passenger compartment directly affects the mental state of the driver and passengers. The research on the thermal comfort of the passenger compartment has become an important topic in the automotive industry. This paper used computational fluid dynamics method to study the thermal environment of the passenger compartment and the thermal comfort of the human body under different air outlets. Predictive mean vote model and equivalent temperature model were used for calculation. The influence of solar radiation on the velocity and temperature field in the passenger compartment was considered in the simulation process, and the correctness of the simulation results was verified by the cooling performance experiment of air conditioning. The results showed that the position of the air outlet had a great influence on the driver's thermal comfort. When the air outlet was on the driver's side, the driver's thermal comfort was the best.

1. Introduction
As a convenient means of transportation, vehicles have become an important part of people's daily life. While enjoying the convenience and speed brought by vehicles, people have put forward higher requirements on the thermal comfort of the passenger compartment. A comfortable thermal environment can relieve fatigue, improve work efficiency and driving safety [1].

With the development of computational fluid dynamics, many scholars have studied the thermal comfort of the passenger compartment through numerical simulations and experiments. Among them, numerical analysis methods not only visual simulation results but also shorten the product development cycle and save R&D costs. Alahmer A [2] used the Berkeley and the Fanger models to study human comfort and discussed the influence of relative humidity and dry bulb humidity on the thermal comfort of cabin environment and human thermal sensation. The research showed that controlling relative humidity and dry bulb humidity at the same time can make the cabin reach the comfort zone faster than controlling dry bulb humidity alone in both the cooling and the heating processes. Oh M S [3] studied the influence of local air conditioning system on cabin, and analyzed the performance of air conditioning
system under different air flow rate and air temperature. Compared with the conventional situation, the energy consumption of air conditioning system was reduced by 20.8% and 30.2%. Moon J H [4] studied the effect of solar radiation on the comfort of the passenger compartment by comparing the Fanger model and the equivalent temperature model and found that the effect of solar radiation should be considered when evaluating thermal comfort. Zhou X [5] studied the thermal comfort of vehicles in summer through driving conditions, indoor and outdoor parking condition. It was found that the air temperature and the surface temperature of human body in the car changes transiently and unevenly. Zhang L [6] used the weighted predictive mean vote model and the weighted equivalent temperature model to study the thermal environment of the passenger compartment and thermal comfort of human body under different driving conditions in summer. It was found that the prediction accuracy of these two models under idle condition was higher than that under driving condition, and the overall prediction accuracy of the equivalent temperature model was higher than that of the predictive mean vote model.

In this paper, the thermal flow field in the cabin was numerically analyzed. The influences of solar radiation, convective heat transfer, human heat dissipation and relative humidity on the thermal environment and human thermal comfort of the passenger compartment were considered in the calculation. The distribution mechanism of velocity field and temperature field in the passenger compartment was studied under different air outlet positions. The thermal comfort of passengers was evaluated by using the predicted mean vote and the equivalent temperature models.

2. Establishment of Numerical Simulation Model

2.1. Numerical Model

The airflow velocity inside the passenger compartment was relatively small and mach number is less than 0.3. The airflow inside the passenger compartment is regarded as a three-dimensional incompressible fluid. The mass conservation, momentum equation, and energy equation are solved using the finite volume method.

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0
\]

(1)

\[
\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \cdot \tau + \rho g + \mathbf{F}
\]

(2)

\[
\frac{\partial (\rho E)}{\partial t} + \nabla \cdot (\rho \mathbf{u} E + \mathbf{u} \rho E + \mathbf{u} \mathbf{u} \rho E) = \nabla \cdot \left( k_{\text{eff}} \nabla T - \sum_{j} h_{j} J_{j} + \left( \tau_{\text{eff}} \cdot \mathbf{v} \right) \right) + S_{h}
\]

(3)

\[
\tau = \mu \left[ (\nabla \mathbf{u} + \nabla \mathbf{u}^T) - \frac{2}{3} \nabla \mathbf{I} \right]
\]

(4)

where, \( \rho \) is the density of fluid, \( \mathbf{u} \) is the velocity of fluid, \( p \) is the static pressure, \( g \) is the gravitational forces, \( \mathbf{F} \) is the external body force, \( \mu \) is the dynamic viscosity, \( I \) is the unit tensor, \( k_{\text{eff}} \) is the effective conductivity and \( \tau \) is the stress tensor.

2.2. Simulation Model

Built a three-dimensional simulation model of the cabin, which mainly included the car body, interior trim, seat, air duct and dummy, etc. After the doors, windows and roof were hidden, the internal structure of the passenger compartment was shown in Fig. 1. There were six air conditioning inlets and one outlet in the passenger compartment. Four inlets were located on the dashboard: one on the driver's left side, one on the passenger's right side, and two in the center. The other two air inlets were located at the top of the left and right seats in the middle row, and the air outlet was located at the top of the passenger's
feet. In this paper, there was only one dummy, which was designated as the driver and divided into fourteen body parts. The model was meshed with polyhedral mesh and prism mesh. The number of meshes in the passenger compartment was thirteen million.

![Figure 1](image_url)  
**Figure 1** Computational model of the passenger compartment with the driver.

When analyzing the thermal comfort of the passenger compartment. The area of the passenger compartment exposed to solar radiation will produce a large amount of radiant heat flow, especially the solar radiation through the window, which will have a great impact on the thermal environment and thermal comfort of the passenger compartment. The surface to surface (S2S) model was used in this paper.

2.3. Thermal Comfort Models

American Society of Heating Refrigerating and Air Conditioning Engineers has a clear definition of thermal comfort. Thermal comfort is the state of consciousness that the human body is satisfied with the thermal environment. In 1970, Fanger proposed the predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD) [7].

The model takes into account six factors, including the degree of human activity, clothing thermal resistance, air temperature, average radiation temperature, air flow rate and relative humidity. The model is divided into seven values to predict the cold and hot sensation of the human body. 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”. The thermal comfort equation is as follows:

\[
PMV = \left[0.303 \exp(-0.036M) + 0.028 \right] \\
\left\{ \left( M - W \right) - 3.05 \times 10^5 \times \left[ 5733 - 0.99 \left( M - W \right) - P_e \right] \right\} \\
\times \left\{ -0.42 \left[ \left( M - W \right) - 58.15 \right] - 1.7 \times 10^{-5} \times M \times (5867 - P_e) \right\} \\
\times \left\{ -0.0014M \times (34 - T_s) - f_d \times h_x \times (T_o - T_s) \right\} \\
-3.96 \times 10^{-5} \times f_d \times \left[ (T_o + 273)^3 - (T_s + 273)^3 \right] \\
T_o = 35.7 - 0.028(M - W) \\
-I_o \times \left\{ 3.96 \times 10^{-5} \times f_d \times \left[ (T_o + 273)^3 - (T_s + 273)^3 \right] + f_d \times h_x \times (T_o - T_s) \right\} \\
h = \begin{cases} 
2.38 |T_o - T_s|^{0.25} & |T_o - T_s|^{0.25} > 12.1 \sqrt{v_o} \\
12.1 \sqrt{v_o} & 2.38 |T_o - T_s|^{0.25} < 12.1 \sqrt{v_o}
\end{cases} (7)
\]

\[
f_d = \begin{cases} 
1.00 + 1.290 \times I_o & I_o \leq 0.078 m^2 K / W \\
1.05 + 0.645 \times I_o & I_o > 0.078 m^2 K / W
\end{cases} (8)
\]
where, $M$ is human metabolic rate; $W$ is human external work rate; $P_e$ is partial vapor pressure; $T_a$ is the air temperature around the human body; $f_{s/d}$ is the ratio of the naked surface and the dressed body surface; $T_d$ is the clothing surface temperature; $T_r$ is the mean radiant temperature; $h_e$ is the coefficient of convective heat transfer; $I_{cl}$ is the clothing thermal resistance.

PPD is used to estimate the percentage of people who feel too cold or too warm in the same thermal environment. When PMV is determined, PPD can be determined according to formula (10).

$$PPD = 100 - 95 \times \exp \left( -0.03353 \times PMV^4 - 0.2179 \times PMV^2 \right)$$

Equivalent temperature is a temperature of a homogenous space, with mean radiant temperature equal to air temperature and zero air velocity, in which a person exchanges the same heat loss by convection and radiation as in the actual conditions under assessment [8]. The model can evaluate the thermal comfort of various parts of the human body, and has good applicability to the passenger compartment, which is a non-uniform environment with dense space and obvious changes in temperature field and velocity field. The equivalent temperature is determined by formula (11).

$$T_{eq} = \left\{ \begin{array}{ll}
0.5 \times (T_a + T_r) & \text{if } v_a < 0.1 \text{ m/s} \\
0.55T_a + 0.45T_r + \frac{0.24 - 0.75 \sqrt{v_a}}{1 + I_{cl}} \times (36.5 - T_a) & \text{if } v_a > 0.1 \text{ m/s}
\end{array} \right.$$  

3. Results & Discussion

3.1. Analysis of the Velocity Field

The air velocity and direction have a great impact on the comfort of human body. ASHRAE recommends that the air velocity in the comfort zone should be 1 m/s [9]. Higher velocity will lead to unnecessary cooling of the sensitive parts of the body and affect the comfort of passengers.

Fig. 2 shows the streamline and velocity vector of the passenger compartment during the cooling process. The airflow formed a local recirculation flow in the front row which can take away more heat. The air velocity on both sides of the driver's arm was significantly higher than other positions, which was related to the distribution of air conditioning inlets. Part of the airflow flowed into the middle and rear rows through the gap between the seats and the body of passenger compartment. It can be seen from the streamline that there was less airflow around the driver's legs, which caused the driver's leg temperature to be too high and affects comfort. It can be seen from the velocity vector diagram that the airflow formed a large number of recirculation flows on the driver's face, abdomen and feet. The recirculation flow effectively mixed the cold air with the hot air to achieve rapid cooling of the passenger compartment.

The air velocity of the driver's foot was less than 0.1 m/s, and the cooling effect was slightly poor which will cause the driver's foot discomfort. The air velocity of the abdomen was 0.5-1.0 m/s and that of the head was 0.26 m/s. The air came from inlets blew directly to the abdomen which resulted low air velocity of the face. The airflow velocity of the hand was 1.5-2 m/s. The higher air velocity may be caused by the hand blocking the airflow from inlets to the abdomen.
3.2. Analysis of the Temperature Field
The air temperature in the passenger compartment is an important factor affecting comfort. A comfortable passenger compartment temperature ranges from 21-25.5 ℃ [9]. The ways of heat-exchange in the passenger compartment are mainly based on convection heat transfer and heat conduction. If the speed dead zone exists in the passenger compartment, the temperature will be higher. It will affect the comfort of passengers. If the air is not well circulated, it will affect passenger mental state.

3.3. Analysis of the Thermal Comfort
According to the PMV-PPD value recommended in the standard ISO7730, when -0.5 < PMV < 0.5 and PPD < 10%, the human body is in a comfortable state; when PMV=0, PPD=10%, the human body is in the best comfortable state.
Fig. 4 shows the PMV value of each part of the driver's body. The driver's body PMV value was 0.86 and the PPD value was 20.61%. The body was in a state of partial heat. The PMV value of the driver's right upper arm was 0.41 which is in a relatively comfortable state. In some areas, thermal comfort was in poor condition. Especially in the foot and leg area, the PMV value was between 1.6 and 1.9 which indicates that the driver had strong discomfort in this area.

![Figure 4](image)

**Figure 4**  PMV-PPD values of each parts of the driver's body

Fig. 5 shows the equivalent temperature of various parts of the driver's body. Different color lines represent different thermal sensation: too cold (black), cold but comfortable (red), neutral (blue), warm but comfortable (green), too hot (purple). This range indicates thermally acceptable levels for different body parts. The equivalent temperature of the whole body was 27.2℃ which was between warm but comfortable and too hot. The equivalent temperature of the legs and feet was between 33 and 35℃ which is in the too hot zone. The other parts of the driver's body were in the comfort zone. A lot of cold air blew to the abdomen of the human body, so the comfort of the upper part of the driver's body was better.

![Figure 5](image)

**Figure 5** Equivalent temperature of various parts of the driver's body

3.4. The Influence of Air Outlet Position on Thermal Comfort

With the change of the air outlet position, the air distribution in the passenger compartment will also change accordingly. To examine the influence of the position of the air outlet effect on the thermal comfort of the passenger compartment, three cases were compared. The boundary conditions of the three cases were the same but the air outlet position was different. The Out-P was the basic case where the air outlet was located near the copilot's foot. The Out-D was a case where the air outlet is located near the driver's foot. The Out-R was a case where the air outlet was located at the rear of the passenger compartment.
Fig. 6 shows the air velocity and temperature around the driver under different cases. Different outlet positions had a great influence on the airflow organization inside the passenger compartment. In the Out-D case, the air outlet was near the driver's feet, so the airflow speed of the air around the driver's legs and feet was significantly higher than that of the other two cases. Correspondingly, more heat can be taken away and the driver can be in a more comfortable environment, which can also be seen from the air temperature. In the three case, the air temperature around the driver's upper body was not much different. However, the temperature difference between the feet and the legs was large. The temperatures of the feet in the Out-P were approximately 10°C higher than those in the Out-D. These data showed that the position of the air outlet had a great influence on the speed field and temperature field inside the passenger compartment. In addition, thermal comfort was directly affected by this difference.
Fig. 7 shows the PMV values of various parts of the driver's body under different cases. In the Out-D and Out-R cases, the PMV values of the driver's whole body were 0.97 and 0.72. The PMV of the driver was smaller than that of the other two cases. In the Out-R case, the driver's PMV value was between 0.5 and 1.4. The high PMV of the legs indicates that the driver had a strong sense of discomfort in this area. In the Out-D case, the PMV value of each part of the driver's body was between -0.5 and 1.0. The PMV value was smaller than the other two case.

Fig. 8 shows the equivalent temperature of each part of the driver's body. In the Out-D and Out-R cases, the equivalent temperature of the driver's whole body was 26.1℃ and 28.4℃. According to ISO14505-2. 2006, the driver was in the comfort zone under the case of Out-D, except for the head. From the distribution of equivalent temperature, the comfort of the passenger compartment in the Out-D case was better than that in the Out-P and Out-R cases

4. Conclusions

In this paper, a numerical simulation of the passenger compartment under different air outlet positions was carried out, and evaluated thermal comfort in the passenger compartment. The following conclusions were followed:

4.1.1. The solar radiation was considered in the thermal environment simulation, and obtained the distribution of velocity field and temperature field in the passenger compartment. Two models of predicted mean vote and equivalent temperature were used to analyze the driver's thermal comfort.

4.1.2. The distribution of velocity field and temperature field in the passenger compartment was uneven. The air velocity near the driver's feet and legs was small, which cannot take away heat and make the temperature rise. Changing the position of the air outlet can effectively change this situation.

4.1.3. The position of the air outlet has a great influence on the airflow organization in the passenger compartment. If the layout is unreasonable, the driver will be in an uncomfortable zone. In this study, the air outlet was located near the foot of the copilot. As a result, the air speed around the driver's legs and feet was low and the heat dissipation was not timely, which made the driver feel uncomfortable. By improving the position of the air outlet, the thermal comfort of the driver can be effectively improved.

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