Numerical simulation and experimental research on the thermal comfort of a passenger compartment considering the influence of solar radiation

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Abstract: Computational fluid dynamics (CFD) method is used to study the effect of solar radiation model on the thermal environment of passenger compartment. The thermal comfort of passenger compartment is evaluated by equivalent temperature and mean radiation temperature and the correctness of the simulation results is verified through passenger compartment cooling performance experiment. The results show that the solar radiation parameters have different effects on the thermal comfort of passenger compartment. Among them, the solar azimuth has no obvious effect on the thermal comfort of passenger compartment. The change of the solar altitude will cause different solar radiation and radiation intensity changes in various parts. Changes in radiation intensity have a great impact on thermal comfort.

1. Introduction

With the development of the automobile industry, consumers have more higher requirements for passenger compartment. The thermal comfort of passenger compartment is a very important index for evaluating the quality of automobiles. It is a factor that must be paid attention to by the modern automobile manufacturing industry. A good driving environment will make driving safer, and the fatigue of passengers after travel will be greatly reduced.

In recent years, many scholars in academia have used computational fluid dynamics methods to study the thermal comfort of passenger compartment. Compared with traditional tests, this method not only achieves the advantages of visualized results, but also reduces the project development cycle. Zhang H[1] conducted 109 experiments under transient conditions, and proposed a local and overall thermal sensation model that can predict transient non-uniform environments. Zhang H[2-4] used the local thermal sensation and local comfort model to study the thermal comfort of passenger compartment. Singh O[5] studied the effect of dynamic vents on the thermal comfort of passenger compartment and the results showed that the passenger compartment could be cooled faster and maintained a uniform temperature distribution at a specific exhaust angle. Simion M[6] analyzed the effects of the air temperature, relative humidity, average radiation temperature, wind speed, human activity level and clothing on the thermal comfort of passenger compartment.

Based on the human comfort model, this paper used numerical simulation methods to simulate seven typical working conditions to explore the effects of the three parameters of the sun’s azimuth, altitude and radiation intensity on the thermal environment of passenger compartment in the solar radiation
model. The equivalent temperature and the mean radiation temperature were used to evaluate the influence of solar radiation on the thermal comfort of passenger compartment.

2. Establishment of numerical simulation model

2.1. Numerical Model

The airflow velocity inside the passenger compartment is relatively small, and the air density remains basically unchanged, so the airflow inside passenger compartment is regarded as a three-dimensional incompressible gas. The continuity, momentum and energy equations are as follows:

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \]  
\[ \frac{\partial}{\partial t}(\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \cdot (\mathbf{τ}) + \rho \mathbf{g} + \mathbf{F} \]  
\[ \frac{\partial}{\partial t}(\rho \mathbf{E}) + \nabla \cdot ((\rho \mathbf{E} + p) \mathbf{u}) = \nabla \cdot \left( k_{\text{eff}} \nabla T - \sum_j h_j J_j + \left( \tau_{\text{eff}} \cdot \mathbf{v} \right) \right) + S_h \]  
\[ \tau = \mu \left[ \nabla \mathbf{u} + \nabla \mathbf{u}^T - \frac{2}{3} \nabla \mathbf{I} \right] \]

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

2.2. Simulation model

Built a three-dimensional simulation model of passenger compartment, which mainly includes: body, dummy, interior and seat, as shown in Figure 1. In this article, there was only one dummy model, which was designated as the driver. It was divided into fourteen parts. In STAR-CCM+, passenger compartment model was meshed, and the air duct, grille, dummy and other areas were locally encrypted.

![Figure 1 The geometric model of the passenger compartment](image)

2.3. Thermal comfort model

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[7]. The equivalent temperature is determined by formula (5).

\[ T_{eq} = \begin{cases} 
0.5 \times (T_a + T_r) & \text{if } v_a < 0.1 \text{ m/s} \\
0.55T_a + 0.45T_r + \frac{0.24 - 0.75 \sqrt{v_a}}{1 + I_{cl}} (36.5 - T_a) & \text{if } v_a > 0.1 \text{ m/s}
\end{cases} \]
where, $T_a$ is the air temperature around the human body; $T_r$ is the mean radiant temperature; $I_{cl}$ is the clothing thermal resistance; $v_a$ is the air velocity.

2.4. The experiment of cooling performance

Indoor and outdoor test conditions have a great influence on the thermal comfort of passenger compartment[8]. There are many uncontrollable factors in outdoor test, so indoor constant temperature environment simulation cabin is used to reduce the influence of external factors on the cooling performance test.

In the experiment, the air conditioner selected the maximum cooling mode and the blowing mode and the air volume adjustment was placed at the maximum position. There were sixteen sensors in passenger compartment to monitor the temperature. The experimental data and simulation results were shown in Figure 2. The maximum error between the experimental data and the simulation results was less than 15%, within the error range, which verified the correctness of the simulation model.

![Figure 2 Comparison of experimental data and simulation results](image)

3. Results and discussion

3.1. Analysis of the velocity field and temperature field

As shown in Figure 3, the airflow entered passenger compartment from inlets, and a small part of the airflow was blocked by the front seats, forming circulating flows in the front space. Most of the air entered the rear row through the gap between the seat and the vehicle body, and formed partial circulation flows in the rear row area. These circulation flows were very effective in reducing the temperature of passenger compartment. The air flows backed to the front row area of passenger compartment along the roof and under the seat.

![Figure 3 Streamline inside passenger compartment during the cooling process](image)
Air temperature is an important factor which affects the thermal comfort of passenger compartment. A comfortable temperature range is 21 to 25.5 °C[9]. Figure 4 shows temperature cloud diagram at the section Y= -0.38m. As shown in Figure 4, the temperature was mostly in the comfort zone. However, the high temperature of the air around the driver's feet and legs may cause the driver to be uncomfortable in this area.

Combined with the analysis of the speed field, the reasons for the local high temperature were: 1. The exit position was not properly arranged, which caused the temperature of the driver’s legs and feet to be too high; 2. Most of the front exhaust flow flowed into the rear row, which was not able to cool the legs and feet of the driver.

3.2. Analysis of the thermal comfort

Figure 5 shows the equivalent temperature of each part of the driver. The equivalent temperature of the whole body of the driver was 27.9 °C, and the whole body was in a relatively hot state. The chest, abdomen and right upper arm were in the comfort zone. The equivalent temperature of the legs and feet was between 34 and 36 °C, and they were in the overheated area. The surrounding airflow speed was low, and the heat emitted by the legs and feet cannot be taken away in time. The equivalent temperature of the left arm was obviously cold. The left arm blocked part of the airflow blowing to the driver’s face, making the left arm in a cold state.

3.3. The influence of solar radiation parameters on human thermal comfort

In the numerical simulation, solar radiation has a great influence on the internal environment of passenger compartment. In summer, part of the solar radiation enters passenger compartment in the form of heat radiation, which increases the internal temperature of passenger compartment and affects the comfort of passengers. The solar load depends on the performance of the glass, the sun's incident angle and the incident solar spectrum. Table 1 shows the parameters under various cases.
Table 1  Solar radiation parameters under various cases

| Case   | Azimuth (°) | Altitude angle (°) | Radiation intensity(W/m²) |
|-------|-------------|--------------------|--------------------------|
| case 1 | 120         | 90                 | 1000                     |
| case 2 | 160         | 90                 | 1000                     |
| case 3 | 200         | 90                 | 1000                     |
| case 4 | 160         | 50                 | 1000                     |
| case 5 | 160         | 70                 | 800                      |
| case 6 | 160         | 70                 | 1000                     |
| case 7 | 160         | 70                 | 1200                     |

Figure 6 shows the air velocity around each part of the driver's body under different cases. The intake air volume remained unchanged, so the velocity field in passenger compartment was not changed significantly under different solar radiation parameters. The air velocity around the left arm was high, the velocity was between 1.5 and 2.0 m/s, and the convection heat exchange was strong. The air velocity around the driver's legs and feet was less than 0.2 m/s, and the cooling effect was slightly poor. The air velocity around other parts was 0.3-0.5 m/s.

Figure 7 shows the mean radiant temperature and equivalent temperature of each part of the driver's body at different azimuths. It can be seen that with the change of the azimuth angle, the mean radiation temperature and equivalent temperature of the driver's body was not change, indicating that the azimuth angle of solar radiation had little effect on the thermal comfort of passenger compartment.
Figure 8 shows the mean radiant temperature and equivalent temperature of the driver's body surface at different altitude angles. When the altitude angle was 50°, the incident angle of solar radiation was small, the solar radiation received by the driver's chest, abdomen and arms was stronger than other altitude angles. When the altitude angle was 70°, the solar radiation received by the driver's left and right hands was stronger than other altitude angles. When the altitude angle was 90°, the solar radiation received by the driver's legs is stronger than other altitude angles. Therefore, we can obtain the following law from the average radiation temperature map. As the solar altitude angle changes, the driver’s body receives different solar radiation. When the altitude angle was small, the upper part of the driver’s body receives stronger solar radiation. As the altitude angle became larger, the lower part of the driver's body receives higher solar radiation. Due to the obstruction of the instrument panel, sunlight cannot directly shine through the glass to the driver's legs and feet, so the mean radiation temperature of the driver’s feet was low.

As shown in Figure 8, it can be seen that the driver’s body equivalent temperature was 28.4, 30.1 and 29.8 °C under the three cases, and the driver was in a relatively hot state as a whole. Under the three cases, the equivalent temperature of the left arm was low. This was because the left arm blocked part of the airflow blowing to the chest and abdomen. The solar radiation received by the right arm was higher, so the equivalent temperature becomes higher. The equivalent temperature of the feet and legs was higher. This was due to the low airflow velocity in this area, which cannot take away heat in time.

Figure 9 shows the average radiation temperature and equivalent temperature of the driver's body surface under different radiation intensities. For every increase of 200 W/m² of radiation intensity, the radiation temperature of each part of the driver's body will increase by 1-3 °C.
In case 5-7, the driver's body equivalent temperature was 28.2, 29.8 and 31.7 °C, and the driver was in a relatively hot state. Due to the high air velocity in the left arm, the left arm had a cold feeling, and the air velocity in the feet and legs was small, and the heat exchange was not timely, so the driver’s feet and legs had a strong feeling of heat.

4. Conclusions

This paper takes a hybrid vehicle as the research object. Aiming at the problem of solar radiation on thermal comfort, the CFD simulation method is used to analyze the influence of solar altitude angle, azimuth angle and radiation intensity on the comfort of passenger compartment. The accuracy of the simulation results is verified through the cooling performance experiment. The main research content and conclusions of the paper are as follows:

- The numerical simulation of passenger compartment was carried out, and the difference between the simulation results and the experimental data was within 15%, which verified the correctness of the simulation results.
- The equivalent temperature model was used to evaluate the thermal comfort of passenger compartment. The comfort of the driver's head, chest and abdomen was better, and the comfort of other parts was poor.
- The azimuth angle of solar radiation had no obvious influence on the thermal comfort, and the change of the altitude angle made the solar radiation received by various parts of the driver different. The solar radiation intensity had a greater impact on thermal comfort. When the radiation intensity increased by 200 W/m², the equivalent temperature of each part of the driver's body increased by 1-3 °C.

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