Investigation on Numerical Simulation of Radiation Heating Thermal Environment in Car Cabin

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Abstract. Based on the automobile energy saving and requirements for thermal comfort of heating environment in a car, a capillary radiation heating system for automobile is presented, and the 3D flow field and temperature field of air in the passenger compartment are simulated by using SC/Tetra software. To consider the effect of human thermoregulation, human thermal regulatory model is incorporated with numerical simulation. The thermal comfort of passenger compartment is evaluated by PMV-PPD comfort index basing on the simulation results. It concludes that the distributions of flow field and temperature field of radiation heating environment are relatively homogeneous. Human thermoregulation has a big influence on the temperature distribution in the near region around the human body. Analyzing the PMV values of body surfaces, it concludes that the radiation penal surface temperature should be set to 30°C under the most comfortable environment for human. The research results provide basis for the using of radiation heating technology in a car.

1. Introduction

With the development of automobile waste heat utilization and the pursuit of high quality interior environment, people pay more and more attention to research and improve the thermal comfort in a car. Today it relies mainly on hot air from automobile air conditioning to increase the temperature inside the car. Compared with radiation heating, the hot air convection heating often causes the unhomogeneous of temperature distribution, turbid air, draught sensation and strong sense of hot-dry feeling. The radiation heating has been widely used in buildings heating systems because of its energy conservation, high efficiency and more comfortable environment. Many scholars have studied the thermal comfort of radiation heating environment. Ho et al.[1] built the numerical models of floor heating system by the finite difference method and the finite element method, respectively. It shows the finite difference method gave slightly higher temperature values and required more execution time, but steady state results from their simulation compared well with the experimental results. Holopainen et al.[2] built the simulation model of floor heating system using an uneven nodal network theory. The results showed that the uneven gridding method was more profitable with the homogenous floor case, and the calculation time was shorter.

Chunying Yang et al.[3] studied the flow field and temperature field distribution in low temperature hot water radiation heating room. Bingyang Wu[4] studied the thermal comfort interior and operational control strategy of the capillary radiation air conditioning system, it concluded the optimum layout conforms of capillary. Due to no using of radiation heating technology in the car, there were few research on the thermal comfort of radiation heating environment. This paper proposes a capillary radiation heating system for the car, using SC/Tetra software simulate the car’s cabin...
radiation heating environment with human thermal regulatory model, and it also discusses how to evaluate the thermal comfort of passenger compartment.

Table 1. Nomenclature of main symbols

| Nomenclature | Greek symbols |
|--------------|---------------|
| $t_{cl}$ surface temperature of clothes ($^\circ$C) | $\alpha_{cl}$ convective heat transfer coefficient (W/(m$^2$·$^\circ$C)) |
| $t_a$ air temperature ($^\circ$C) | $\theta$ circumferential coordinate (rad) |
| $f_{cl}$ dressing area coefficient | $\theta_{mrt}$ mean radiation temperature ($^\circ$C) |
| $W$ mechanical work (W/m$^3$) | $\lambda$ tissue heat conductivity coefficient (W/(m·$^\circ$C)) |
| $M$ metabolic rate (W/m$^2$) | $\tau$ time variable (s) |
| $p_a$ steam partial pressure (Pa) | $\beta$ coefficient of volume expansion (1/$^\circ$C) |

2. Capillary Radiation Heating System in the Car

The capillary radiation heating system uses automobile exhaust heat to warm water, the hot water has a reciprocating circular flow in the capillary tubes which are covered with covering material, and there is thermal insulation under the capillary tubes. At the same time the surface of covering material exchanges heat with in-car air by radiation and natural convection. The system setup is shown in figure 1. The pressure in the closed heating water tank increases due to water vaporizing a little, and forms differential pressure with the atmospheric pressure, then hot water is pushed into the capillary tubes by the pressure. The pressure in the closed heating water tank without passing hot exhaust reduces due to water cooling and forms some vacuum in it, the differential pressure between it and auxiliary water tank with open hole pushes the cooled water in the capillary tubes back to the closed heating water tank. This water flow can circulate in the pipeline between the closed heating water tank and auxiliary water tank[5]. The closed heating water tank with heat transfer install around the car’s exhaust pipe, the auxiliary water tank is placed in the car trunk, the capillary radiant panels (i.e. the capillary tubes covered with a blanket) lay on the floor and behind the front seats’ back. The both ends of capillary tubes are connected with water collector and separator, and then two pipes are connected with them to the two water tanks. According to the temperature inside the car and water level in the closed heating water tank, the controller controls circular flowing frequency of water in the heat system to realize the automatic control in car heating. The thermal insulation, capillary tubes and covering material make up to the capillary radiant panels. Figure 1 shows the radiant panel setup.

![Figure 1. Capillary radiation heating system](image-url)

3. Numerical Simulation

Under the environment of radiation heating system, the radiation penal and human bodies produce...
heat, and there is no other heat source. The corresponding models are as follows.

3.1 Passenger Compartment Geometrical Model

The important points of this paper are to study the thermal comfort and analyze the flow field and temperature field of passenger compartment environment. In accordance with the importance of influencing factors, the engine cabin, trunk and wheels may be ignored, which have tiny influence to the simulation. In addition, the passenger compartment structure is complicated and numerical simulation mainly reflects the car overall environmental features, so on the basis of simplifying the cabin structure correspondingly, the passenger compartment geometrical model is established according to Santana 2000 car compartment dimension in figure 2.

Figure 2. Simplified geometric model of car

The specific simplifies are as follows:
(1) Simplify the instrument panel and ignore the steering wheel;
(2) The front and rear seats are simplified to simple geometries and simplify the microscopic structure of roof, doors, interior decoration;
(3) There are a driver and a passenger in the car, the passenger sits on the right rear seat;
(4) The radiant panels lay on the floor and behind the front seats’ back.

3.2 Numerical Model

In order to simplify the question and guarantee the calculation accuracy, the following assumptions are made:
(1) The in-car air is incompressible and its density meets Boussinesq hypothesis;
(2) The cabin is sealed well and there is no air leakage;
(3) Besides the capillary radiation penal and human body, there is no other source of heat;
(4) The air flow is steady laminar flow containing natural convection;
(5) Ignore the influence of solar radiation because the solar radiation is weak in winter.

The air flow and heat transfer process are in accordance with the three laws of mass, momentum and energy conservation, in computational fluid dynamics, the expressions of these conservation laws are governing equations, and can be expressed by the following equations.

Mass conservation equation:
\[
\frac{\partial u_i}{\partial x_i} = 0
\]  (1)

Momentum conservation equation:
\[
\frac{\partial p u_i}{\partial t} + \frac{\partial p u_j u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \mu \left(\frac{\partial^2 u_i}{\partial x_j^2} + \frac{\partial^2 u_j}{\partial x_i^2}\right) - \rho g_i (T - T_0)
\]  (2)

Energy conservation equation:
\[
\frac{\partial \rho c_p T}{\partial t} + \sum_{j} \frac{\partial \rho c_p u_j T}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \lambda \frac{\partial T}{\partial x_j} \right) + q
\]  

(3)

Where \( \rho \) is density of fluid, \( T \) is temperature of fluid.

Under the radiation heating, air flow in the car belongs to natural convection phenomenon, which is caused by gravity difference when air is heated leading to its density changes, this can be dealt with Boussinesq model. Computational fluid dynamics (CFD) software contains a variety of radiation models, and radiation models of different CFD software are not the same. SC/Tetra uses Flux method and VF (View Factor) method to solve the radiation heat transfer [6], and the VF method is used in this paper. A view factor is defined between two surfaces, and determined by their shape and relative positions. Here, consider the surfaces A and B whose VF(viewed from A) is defined as \( F_{AB} \). Suppose the surface A emits the energy \( Q_A \), and the energy that reaches the surface B from A is \( Q_{A-B} \), then \( F_{AB} \) is \( \frac{Q_{A-B}}{Q_A} \).

3.3 Human Thermoregulation-model

It needs to consider the human thermoregulation and the heat exchanging between body and environment when studying thermal comfort, and many scholars combine these factors with indoor environment for simulation study through the establishment of the human thermoregulation-model. SC/Tetra uses the thermoregulation-model Jos, developed by the research group of Prof. Shin-ichi Tanabe et al. at Waseda University in Japan [6]. Thermoregulation-model uses the human body bio-heat equation to get skin temperature, this equation is as follow:

\[
\rho C \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 T}{\partial \theta^2} + \sum \left( q_m + BC_b \left( T_b - T \right) \right)
\]

(4)

Where \( \rho \) is tissue density, \( T \) is tissue temperature, \( \lambda \) is tissue heat conductivity coefficient.

Through the above equation, the human body thermoregulation system provides the human body temperature for the flow field simulation, and the flow field simulation provides air velocity and temperature distribution ambient each stage of body for human body thermoregulation system, the calculation repeats iteration until the convergence[7].

3.4 Grid Generation and Boundary Conditions

The quality of the grid greatly affects the computation time and simulation precision. For the complex structure of car cabin, it’s hard to generate the structured grid. The unstructured tetrahedral grid strongly adapts, but will increase the number of grid and computation time. Considering the above factors, using SC/Tetra pre-processing software generates unstructured tetrahedral grid. It refines the grids in different levels for the surfaces of body, seats and cabin structure, and inserts boundary layer. Finally, the nodes number of grids is 199955, the total number of elements is 742674. Figure 3 shows the grid model.

![Figure 3. Grid model](image-url)
The boundary conditions for radiation heat mean thermal boundary condition. The capillary radiant panel installation position sets as constant temperature boundary, and the temperature is the surface temperature of radiation penal. The car body sets as the third kind boundary condition, giving the corresponding heat transfer coefficient and the external environment temperature of each part, and the heat transfer coefficients of each part are calculated by steady-state heat transfer method. It considers convective heat exchange between the outside surface of car body and external air, heat conduction of car body, and convective heat exchange between the inside surface of car body and air in passenger compartment) [8]. The heat transfer coefficient of each part is shown in table 2 (Here the velocity of car is 40km/h.). Under the standard condition, the surface temperature of radiation penal is 30°C and the external environment temperature is 0°C. The seats’ surfaces set as stationary wall considering heat transfer. Both of the driver and passenger are male, 20 years old, and wear suits, their body fat rate is 15%, cardiac index is 2.58L/(min·m²) and metabolic rate is 100W/m². The emissivity of radiation penal and human body is 0.9, the glass emissivity is 0.5, and others’ is 0.8. The initial conditions are that the temperature of air inside the car is 8°C, and the relative humidity is 50%.

### Table 2. Heat transfer coefficient of car body part (W/(m²·K))

| Body part      | Roof | Bottom | Doors | Pillars | Windows | Dash penal | Rear penal | Instrument penal |
|----------------|------|--------|-------|---------|---------|------------|------------|------------------|
| Heat transfer coefficient | 3.51 | 5.37   | 2.03  | 3.24    | 6.58    | 6.66       | 5.93       | 5.70             |

#### 3.5 Thermal Comfort Evaluation Index

P.O. Fanger [9] established the mathematical expression of PMV (predicted mean vote) according to the human body heat balance principle, and established the mathematical relationship between PPD (predicted percent dissatisfied) and PMV using the method of probability analysis, these expressions are as follows:

\[
PMV = [0.303 \exp(-0.036M) + 0.028] \times \left\{ M - W - 0.0014M(34 - t_a) \right\} \\
- 0.0173M[5.867 - p_a] - 3.05 \times [5.733 - 0.007(M - W) - p_a] - 0.42 \times (M - W - 58.15) \\
- 3.96 \times 10^{-8} f_{cl} \left[ (t_{cl} + 273)^4 - (\theta_{met} + 273)^4 \right] - \alpha_{cl} f_{cl} (t_{cl} - t_a) \right\}
\]

(5)

\[
PPD = 100 - 95 \exp \left[ -0.2179 \text{PMV}^2 + 0.03353 \text{PMV} \right] \right\}
\]

(6)

Where \( f_{cl} \) is dressing area coefficient, determined by the clothing thermal resistance.

PMV-PPD index considers human activity intensity, air temperature, air humidity, mean radiant temperature, air velocity and clothing thermal resistance, and it determined most people’s feeling levels of warm and cold through subjective feeling survey. The evaluation standard of the indoor thermal environment (ISO 7730) which made by international standard organization put forward the recommended value of PMV-PPD: the value of PMV is between -0.5~+0.5, allowing 10% of people feel not satisfied. This paper uses PMV-PPD to evaluate the thermal comfort of passenger department.

### 4. Simulation Results and Discussion

#### 4.1 Distributions of Velocity and Temperature Field

In order to analyze the velocity field and temperature field more clearly, it selects the vertical section of driver and passenger (YZ plane of the car), and human body surface to study the velocity and temperature distributions. When the external environment temperature is 0°C, the surface temperature of radiation penal is 30°C, the velocity and temperature distributions in the car are shown in figure 4. From figure 4 (a), (b), it can be seen that the density of air nearby radiation penal becomes small, the hot air rises up and cold air drops in the car because of density difference effect, so the air forms moving air flow around human body and seats. The air nearby the seat back radiation penal rises to the
top of the cabin with relatively high speed. The highest velocity is 0.38 m/s when reaching steady state, and it appears at the front seat back. The distribution of velocity is homogeneous, and the average value is 0.1 m/s. From figure 4 (c), (d), it can be seen that the temperature of air in upper side of the cabin is higher, the middle air temperature is lower when reaching steady state, this is because the hot air rises up in the relatively small car cabin.

![Velocity and Temperature Distributions](image)

**Figure 4.** Distributions of velocity field and temperature field in the car.

The result of simulation indicates that vertical temperature difference is about 3°C. Due to the heat action of radiation penal and the obstruction of the seats, the temperature field distribution is some unhomogeneous on the cross-section (XY plane of the car) of human foot, but it is more homogeneous on the XY plane above chair face in different height.

Figure 5 shows the temperature distribution of human body surface, it can be seen that the human thermoregulation makes the temperature around the human body be higher than temperature of air in other parts of car cabin. Except near heads and hands, the feet and legs’ area temperature is higher than pelvis and body trunks’ area. This is because the heat action of radiation penal makes the feet and legs’ area temperature increasing. The heads and hands’ area temperature is high because that the human thermoregulation plays a full role in adjusting temperature around human body, and these positions are not shielded by clothes, its temperature is close to skin temperature.

### 4.2 Thermal Comfort Analysis

![Temperature Distribution](image)

**Figure 5.** Temperature distribution of human body surface
In order to fully analyze the thermal comfort of radiation heating environment based on the velocity and temperature field got by simulation, this paper mainly exports the average air temperature, velocity and average PMV values of different parts of human body to elevate the thermal comfort of passenger compartment. Besides, it also simulates the thermal environment in the car when the radiation penal surface temperature is 26°C, 28°C, 32°C and 35°C respectively, and calculates PMV values to analyze the thermal comfort of every operation condition. When calculating PMV values, the clothes thermal resistance sets to 1clo (0.155(m²·K)/W), and body metabolic rate of seating posture activities sets to 1.2met (69.8W/m²) [10]. Table 3 shows the average air temperature and velocity under different radiant panel surface temperature.

Table 3. Air parameters under different radiant panel surface temperature.

| Radiant panel surface temperature(°C) | 26  | 28  | 30  | 32  | 35  |
|--------------------------------------|-----|-----|-----|-----|-----|
| Average temperature(°C)             | 16.1| 17.1| 18.0| 18.8| 19.8|
| Average velocity(m/s)               | 0.068| 0.071| 0.073| 0.075| 0.077|

It can be seen from table 3 that the average air velocity increases when the radiant panel surface temperature increases, and the growth is so small that it can be ignored. The average air velocity is under 0.1m/s. It indicates that the air velocity of radiant heating environment is more in line with the requirements of the human body thermal comfort, it won’t cause draught sensation. When the temperature of radiation penal surface increases 2°C, the average air temperature increases 1°C, and when the radiation penal surface temperature is 26-28°C, the average air temperature is 16.1-18.8°C. The reference recommends that the average air temperature in car is 16-18°C, and the average air velocity in car is less than 0.2m/s in Winter [11], it can be conducted that the air velocity of the radiation heating environment meets the requirement, and the radiation penal surface temperature shouldn’t be below 26°C. Figure 6 shows the PMV distribution in driver and passenger vertical section when the radiation penal surface temperature is 30°C. Figure 7 show the average PMV values of different parts of human body under different radiation penal surface temperature.
(a) Average PMV values of passenger  (b) Average PMV values of driver

**Figure 7.** Average PMV values of different parts of human body under different radiation penal surface temperature

It can be seen from figure 6 that PMV values around human body are higher than other parts’ PMV values in the car, the PMV values of front and back instrument corners are the lowest. Because the velocity distribution is homogeneous and its value is small, the change of PMV values is mainly caused by the change of air temperature. It can be seen from figure 7 that the PMV values of heads and hands are higher, and the PMV values of breast and pelvis are lower. When the radiation penal surface temperature is 30°C, the PMV values of breast and pelvis are between -0.7 and -0.5, the PMV values of feet are bigger than 0.5, other parts’ PMV values are between +0.5 and -0.5. That’s to say that most parts’ PMV values are in line with the requirement of thermal comfort. More than 10% of people feel not satisfied about the feet, breast and pelvis, but won’t feel uncomfortable. When the radiation penal surface temperature is higher than 32°C, the PMV values of feet are higher than 1, people feel the feet hot; When the radiation penal surface temperature is lower than 28°C, the PMV values of breast and pelvis are low, these parts of body feel cold.

5. Conclusions
Through the numerical simulation of the radiation heating environment in the car and thermal comfort analyzing, it concludes that:

1. The distributions of flow field and temperature field of radiation heating environment are relatively homogeneous. The average air velocity is under 0.1m/s, and there is no strong convection flow, so it won’t cause draught sensation. Heat radiation makes the temperature of car body increase, which reduces the heat loss of human body radiation heat. The vertical temperature difference is small, and temperature field meets the lower part of body warm and the upper part of body cool, this environment is more comfortable to people.

2. Human thermoregulation has a big influence on temperature distribution in the near region around the human body, so it is necessary to incorporate the human thermoregulation model with the numerical simulation.

3. When the radiation penal surface temperature is 30°C, the PMV values of most parts of body are between +0.5 and -0.5, people feel most comfortable. When the radiation penal surface temperature is lower than 28°C, the breast and pelvis feel cool; when it’s above 32°C, feet feel hot. So the radiation penal surface temperature should be 28~31°C.

4. Put forward a new way of radiation heating in the car, and present the operating conditions that meet the requirement of thermal comfort. The results provide basis for the using of radiation heating technology in a car, and promote the study of thermal comfort of passenger compartment.

6. References
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