



Thermal Comfort Assessment of Occupants in Special Vehicle Cabin

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Abstract. Due to the specific function and ventilation limitation, the cabin of special vehicles is generally narrow and enclosed, in which occupants are faced with uncomfortable conditions such as high heat load, less cold source, and lack of fresh air. The thermal comfort assessment method is a crucial research premise of thermal environment and thermal comfort. Therefore, it is necessary to study the thermal comfort assessment method of occupants in the special vehicle cabin. Firstly, this paper analyzed the distribution characteristics of a variety of typical environmental parameters and the subjective assessment results of the occupants on the surrounding air environment in order to obtain the thermal boundary conditions necessary for Computational Fluid Dynamics (CFD) steady-state flow field simulation of the special vehicle cabin. Then according to the research of occupants' thermal comfort in the special vehicle cabin, the changes in thermal comfort temperature due to thermal adaptation of the occupants are investigated to obtain the thermal comfort assessment model that meets the needs of different seasons and different mission phases.

Keywords: Thermal comfort · Assessment methods

1 Introduction

Human thermal comfort is a reflection of satisfaction with the surrounding air environment and an integrated determination of psychological and physiological factors. The principal factors that affect human thermal comfort depend on the air temperature, humidity, air velocity, and other environmental parameters to which a person is exposed. The thermal comfort of occupants cannot be measured directly with instruments but can only be collected in the form of questionnaires [1]. In addition, the human body is not completely passive to the ambient air environment but actively adapts and interacts with the environment, which explains why the human thermal adaptation is the reason for the discrepancy between the results of many artificial climate laboratory studies and those of actual research studies. In China, seasonal changes can cause wide variations in outdoor air temperature. Differences in individual dress and environmental adaptations make a single temperature control standard unable to satisfy the demands of the thermal environment in the special vehicle cabin during different seasons [2–4]. Particularly in the

northern regions, the atmospheric environment temperature varies considerably from season to season throughout the year, which may lead to adaptive changes of human thermal comfort under different outdoor atmospheric temperatures.

2 Cabin Environment Test

In order to obtain the seasonal influence, experiments were carried out once a month in 12 months, and a total of 158 questionnaires were carried out. Gender and age are also important factors affecting human thermal comfort, and many studies have pointed out that women and the elderly have higher requirements for temperature and thermal comfort than other groups. However, considering the particularity of the vehicle, this paper only selects adult men as the test object.

2.1 Subjective Questionnaire Data

The thermal comfort of occupants cannot be measured directly with instruments but can only be collected in the form of questionnaires. Therefore, the analysis of subjective questionnaire data is very important, which is an important basis for evaluating the thermal environment comfort of vehicle cabin. As shown in Tables 1 and 2, the subjective questionnaire mainly studies and analyzes the thermal sensation in the cabin and the satisfaction of three environmental parameters, namely wind speed, temperature and humidity [5, 6].

Table 1. Method of thermal voting results

Thermal sensitivity						
Cold	Cool	A little cold	Moderate	A little warm	Warm	Hot
-3	-2	-1	0	1	2	3

Table 2. Environmental parameter satisfaction voting method

Environmental parameters satisfaction (wind speed, temperature, humidity)		
Hope to be lower	Moderate	Hope to be higher
-1	0	1

Through the analysis of the subjective questionnaire of heat feeling, it is considered that the current thermal environment in the vehicle cabin still does not fully meet the requirements of passengers for thermal comfort, and about half of passengers are not satisfied with the heat feeling in the cabin. On the other hand, the thermal environment in the cabin often makes the passengers in a hot state. In most cases, the cabin temperature control is generally high.

Through the analysis of the subjective questionnaire on the satisfaction of environmental parameters, it can be seen that the percentage of questionnaires that are dissatisfied with the temperature in the cabin and wanting the air temperature in the cabin to increase or decrease is lower than the percentage of questionnaires that the thermal feeling vote is not 0, which are 41.7% and 58.8% respectively. This shows that not all passengers who feel uncomfortable with heat have the expectation of adjusting the air temperature in the cabin. In order to analyze the causes of this phenomenon, the temperature expectation voting of passengers and thermal voting are combined to further analyze the temperature expectation of passengers in the cabin in different thermal voting value ranges [7]. Through the analysis of the subjective questionnaire on the satisfaction of environmental parameters, it can be seen that the percentage of those who are not satisfied with the cabin temperature and want the air temperature change in the cabin is lower than the percentage of those who do not have a thermal vote of 0, and the former is 41.7%, while the latter is 58.8%. This shows that not all passengers who feel uncomfortable with heat have the expectation of adjusting the air temperature in the cabin. In order to analyze the causes of this phenomenon, the temperature expectation voting of passengers and thermal voting are combined to further analyze the temperature expectation of passengers in the cabin in different thermal voting value ranges, as shown in the figure below (Fig. 1).

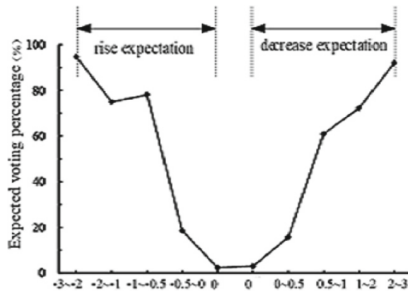


Fig. 1. Expected voting percentage of temperature in each thermal voting interval

Therefore, the tolerance of passengers to the indoor thermal environment is an important reason for the formation of “not all passengers who are uncomfortable with thermal voting have the expectation of adjusting the indoor air temperature”. The tolerance of passengers have a great impact on their temperature expectation voting, especially in the range of $-0.5\sim 0$ and $0\sim +0.5$. On the other hand, when the cabin thermal environment is in the partial heat state, the percentage decreases significantly from $+1\sim +2$ interval to $+0.5\sim +1$ interval, while when the cabin thermal environment is in the partial cold state, the percentage does not decrease from $-2\sim -1$ interval to $-1\sim -0.5$ interval. The passengers still have high temperature rise expectations in the $-1\sim -0.5$ thermal sense interval. This may be due to the fact that the body itself is more sensitive to cold than the heat. Cold sensation makes it easier for passengers to feel unbearable, which is similar to the results of other body heat sensation studies.

2.2 Objective Environmental Measurement Data

In addition to the subjective questionnaire, the objective environment in the cabin was monitored and recorded, mainly including the temperature change rule of each wall of the cabin, which is the necessary thermal boundary condition for obtaining the CFD steady-state flow field simulation of the cabin in a stable state.

Each wall in the cabin is an important boundary for radiative heat exchange with the passenger’s body in the cabin. The measurement of the temperature of each wall in the cabin can help to understand the radiative heat transfer environment of the passenger. Therefore, the temperature of each wall in the cabin is monitored and recorded, and the thermal boundary conditions necessary for the steady-state CFD flow field simulation of the cabin in a stable state are obtained from its variation rules. In this paper, the steady-state calculation is only carried out for the cabin environment in the numerical simulation, so only the measurement results in the stable stage are selected. Take the average number of test states such as ceiling, floor and sidewall temperature for calculation. According to the test results, the average temperature values of ceiling, floor and side wall in the stable stage are 24.1 °C, 22.3 °C and 23.1 °C, respectively.

2.3 PMV Index of Human Thermal Comfort

PMV value is an important index of human thermal comfort, representing the average cold and hot sensation of most people in the same environment. In a limited space, the thermal comfort of personnel is determined by six main factors, among which air temperature, average radiation temperature, partial pressure of water vapor in the air (or relative humidity), and air flow are determined by the environment, while the other two factors including the metabolic rate of the human body and clothing thermal resistance depend on human themselves.

Danish Professor Fanger established the famous PMV thermal comfort prediction and evaluation model based on the theory of human thermal balance and a large number of artificial climate experiments, which has been recognized internationally. PMV model can predict and calculate human PMV under the influence of human metabolic volume, clothing thermal resistance, ambient air temperature, flow rate, humidity and other factors. The PMV equation can be written as:

$$\begin{aligned}
 PMV = & 0.303e - 0.036M + 0.0275 \times M - W - 3.05 \times 10^{-3} \\
 & \times 5733 - 6.99M - W - Pa - 0.42 \times M - W - 58.15 \\
 & - 1.7 \times 10^{-5} \times M \times 5867 - Pa - 0.0014M34 - ta - 3.96 \times 10^{-8}fcl \\
 & \times tcl + 2734 - tr + 2734 - fclhctcl - ta
 \end{aligned} \tag{1}$$

Outer surface temperature of clothing can be written as:

$$tcl = 35.7 - 0.028M - W - Icl \times \{3.96 \times 10^{-8} \times fcltcl + 2734 - ta + 2734 + fclhctcl - ta\} \tag{2}$$

Convective heat transfer coefficient can be written as:

$$hc = hc1 = 2.38tcl - ta0.25, hc1 > hc2hc2 = 12.1va, hc1 < hc2 \tag{3}$$

where M is Human metabolic rate, W/m²;

W is the work done by the human body, W/m^2 ;
 I_{cl} is Clothing thermal resistance, $m^2 \cdot K/W$;
 P_a is water vapor partial pressure in the surrounding environment, Pa;
 t_a is the temperature of the air around the body, $^{\circ}C$;
 t_{cl} is outer surface temperature of clothing, $^{\circ}C$;
 t_r is the average radiation temperature of the surrounding environment, $^{\circ}C$;
 f_{cl} is area coefficient of human clothing,
 h_c is convective heat transfer coefficient, $W/m^2 \cdot K$.

3 Thermal Comfort Assessment

In this paper, data from 10 adult male occupants under operating conditions at three different vent layout locations were measured, and the thermal comfort assessment function values at each measuring point were analyzed. The comparison of PMV value under different operating conditions is shown in the following table, from which it can be seen that the average thermal comfort of operating condition one is the best (Table 3).

Table 3. Comparison of PMV values under different condition

	Condition 1	Condition 2	Condition 3
Occupant 1	-0.541880	-0.622669	-0.551913
Occupant 2	-0.403320	-0.619861	-0.713797
Occupant 3	-0.538620	-0.603890	-0.504080
Occupant 4	-0.289780	-0.198996	-0.252513
Occupant 5	-0.521500	-0.626236	-0.626244
Occupant 6	-0.189910	-0.226786	-0.134982
Occupant 7	-0.164970	-0.338291	-0.261541
Occupant 8	-0.166170	-0.225226	-0.114887
Occupant 9	-0.207000	-0.148893	-0.287032
Occupant 10	-0.323740	-0.572772	-0.213723
Average PMV value	-0.334690	-0.418362	-0.366071

According to the measured results and test data of special vehicle cabins, covering different seasonal climate conditions throughout the year, the iterative calculation formula of PMV under different seasonal conditions is obtained through regression analysis. The thermal comfort assessment PMV values of the corresponding locations of coordinates were calculated by bringing the corresponding air temperature, mean radiation temperature, air relative humidity, air flow rate, human metabolic rate, and clothing thermal resistance from the simulation into the established PMV functional relationship. The closer this PMV value is to 0, the better the thermal comfort of the cabin.

4 Conclusion

In this paper, a subjective questionnaire survey on the thermal sensation and environmental satisfaction of the special vehicle cabin was carried out on 158 adult males in 12 months, which demonstrated the temperature expectation of the occupants in different thermal sensation voting ranges. Besides, the thermal boundary conditions essential for the simulation of the cabin CFD steady-state flow field were obtained by monitoring and recording the cabin environment, especially the temperature variation patterns of the cabin surfaces. The results showed average temperature values of 24.1 °C, 22.3 °C, and 23.1 °C for the ceiling, floor, and sidewalls of the cabin during the steady-state phase respectively. The thermal comfort analysis of the cabin occupants and the change in thermal comfort temperature caused by occupants' thermal adaptation was investigated to obtain the thermal comfort assessment model for the needs of different seasons and different mission phases. Finally, the PMV assessment method was applied with the input of results and data from actual vehicle measurements, which were used to guide the optimal design of the vehicle's air supply temperature and air supply air volume in different seasons and task phases, ultimately realizing a thermal adaptation control strategy for the special vehicle's thermal environment.

Compliance with Ethical Standards. The study was approved by the Logistics Department for Civilian Ethics Committee of North Vehicle Research Institute.

All subjects who participated in the experiment were provided with and signed an informed consent form.

All relevant ethical safeguards have been met with regard to subject protection.

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