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Article

Research progress on thermal comfort evaluation in vehicle cab

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Abstract: In order to improve thermal comfort of vehicle cab, reduce driver fatigue and further improve work efficiency, researches on thermal comfort of vehicle cab are summarized. Research background of thermal comfort for vehicle cab is analyzed. And then related research progress on thermal environment in vehicle cab is studied from aspect of time and space, and thermal environment inside and outside vehicle are compared. Affecting factors of thermal comfort in vehicle cab are discussed in depth, which conclude thermophysical parameters, human physiological factors, clothing thermal resistance and other secondary factors. And thermal comfort evaluation indexes are analyzed in depth. Evaluation methods of thermal comfort in uniform environment are analyzed, related experimental research and theoretical analysis are summarized, and it also points out some problems in thermal comfort of vehicle at this stage, and also gives corresponding solutions. The future trend of thermal comfort of vehicle cab is predicted. Analysis results can provide theoretical guidance for optimization design of air conditioning supply parameters and structural parameters, and has significant meaning of improving thermal comfort of vehicle cab.

Keywords: thermal environment; thermal comfort; thermal model

1. Research background

With the development of the economy, the number of cars has increased rapidly, according to relevant data, as of the end of 2022, the China's car ownership was about 131 million units. By the end of 2023, China's car ownership had reached 280 million. But in addition to the convenience that people enjoy the car brings, it also causes a lot of problems. For example, (1) due to excessive heating in summer or too cold in winter, excessive use of air conditioning consumes huge energy, so the method of district heating in the car and personalized heating method can be used to solve the problem of huge energy consumption; (2) at the same time, because traditional cars use gasoline as the power raw material, the increase in car ownership is bound to lead to an increase in demand for oil resources, and at the same time, car travel will emit a large number of pollutants, and will also bring huge pollution to the environment. Therefore, research on thermal environment and comfort in the automobile cabin is also an important key topic for energy conservation and emission reduction. Therefore, the emergence of new energy vehicles can effectively solve this problem [1].

Development prospects of new energy vehicles are also very impressive. According to the 2019 Electric Vehicle Outlook Report released by Bloomberg New Energy Finance, it is estimated that by 2040, there will be 548 million electric vehicles worldwide, accounting for about 32% of the global passenger car number by then; (3) there is also no meeting thermal comfort of the driver in the car, for example, due to the cold temperature in the car in winter, the human hands and feet are cold, which affects the speed of hitting the steering wheel and the speed of pressing the brake, thereby increasing the traffic accident rate. In the car interior, people are in an environment with light, sound and heat, so the comfort of heat, light and sound will affect the comprehensive comfort of the human body. Among them, in the single factor of human comfort research, the earliest and most concerned is thermal environment, thermal environment to provide people with thermal comfort, but also to the greatest extent to affect the energy consumption of the entire system, so this article focuses on the impact of thermal comfort on the human body, but does not mean that sound, light, and pressure have no effect on the human body in the car [2,3]. A good thermal comfort environment can also relieve driver fatigue, improve their irritability, and thus better concentrate and ensure driving safety [4,5]; (4) finally, because the car body material is thin-walled steel, the specific heat capacity of the material is very small, so that the heat insulation and heat storage capacity of the car is poor, so thermal environment inside the car is greatly affected by the external environment, in real life due to the owner's negligence, the pet left in the car resulting in summer high temperature death is common. At the same time, the high temperature in the car after receiving sun exposure in the static state will not only bring strong thermal shock to the occupants, but also the excessive temperature in the car is easy to bring about the aging of internal items, spontaneous combustion of the interior items, explosion and other hazards [6]. This further demonstrates the importance of studying interior temperature regulation controllers, which are currently poorly studied. (5) thermal environment inside the car will also affect the defrosting and defogging effect of the window surface, which greatly affects the driver's driving vision, resulting in unnecessary traffic accidents. Therefore, research on thermal comfort of automobiles based on the above five points is necessary and extremely important, which has also attracted the attention of international scholars.

Main contribution is to study research progress on analysis and evaluation of thermal environment of vehicle cabins. By analyzing existing research results, the main research directions for thermal comfort of vehicle cabins are proposed to improve the reliability of research on thermal comfort of vehicle cabins. This is conducive to proposing more effective measures for thermal comfort of vehicle cabins, thereby improving thermal comfort of drivers.

2. Progress on thermal environment analysis in vehicle cab

From the first chapter, it can be seen that based on the popularity of vehicles in people's lives, research on thermal environment of cockpit has received more and more attention. During the driving of the car, especially in summer, cockpit is often uncomfortable for people to ride for a long time in a complex thermal environment [7]. Therefore, research on thermal environment of the car cabin has also attracted the attention of international scholars. Since the 70s of the last century, developed countries in Europe and America have begun to concern problem of thermal smoothness and thermal comfort of passenger compartment [8]. A good thermal environment in the car is of great significance to the driver's driving experience and driving safety, the cockpit is overheated, and the driver is easy to feel sleepy; Over cooling of cockpit can also reduce the agility of driver. thermal environment in cabin is not only important for the driver's driving safety, but also for the driving experience of the passengers. Poor thermal environment in the car can also cause nausea, vomiting and other adverse physical health conditions of passengers. Airflow organization in the cockpit of a passenger car is one of the factors that affect thermal environment in the cabin, which in turn affects thermal comfort level in the cabin [9]. Therefore, improving the airflow organization in the car has also effectively improved human comfort, which is beneficial to human health and can also achieve energy-saving effects. Many well-known car companies are also studying ways to enhance thermal comfort of human body by adjusting airflow organization in the cabin (adjusting parameters air outlet temperature, outlet speed and relative humidity, changing airflow distribution in the space) [10]. Airflow organization is used in field of thermal comfort, and poor airflow organization in cabin causing problems such as uneven temperature distribution, which reduces thermal comfort level of passenger car cockpits [11]. Relevant literature knows that there are relevant requirements for thermal comfort of the cockpit: during cooling process of the cockpit of a passenger car in summer, the airflow velocity around the occupants is not easy to exceed 0.5 m/s, and the airflow velocity in this range can make the occupants have a slight feeling of blowing wind, and will not make the occupants feel uncomfortable [12]. Mean temperature in cabin is 22 ℃–28 ℃, and occupants will be satisfied with thermal environment in the cabin in this temperature range [13]. When the average cabin temperature is below 22 ℃, the occupants will feel cold; when the temperature is greater than 28 ℃, the crew will feel that thermal environment in cabin is muggy [14]. Temperature difference between cabin inside and outside cabin in China is generally 8 ℃–10 ℃, when ambient temperature is high, temperature difference can be appropriately amplified to 10 ℃–12 ℃, and the appropriate temperature difference inside and outside cabin will make the occupants have a good riding experience [15]. All these fully illustrate the important role of studying thermal environment in the car interior on human comfort. This section addresses two aspects. The first section explains thermal environment in the car from the perspective of time and space. The second section compares thermal environment inside and outside car. Vehicle thermal environment analysis is complex and multiple dimensional, which relating to temperature, humidity, velocity and other factors, two aspects of this section conclude thermal analysis from aspect of time and space, and comparative analysis of thermal environment inside and outside car.

2.1. Analysis from perspective of space

Thermal environment includes the steady-state thermal environment and transient thermal environment from perspective of time, and analysis includes uniform thermal environment and non-uniform thermal environment from the spatial perspective. In summer heat, the cockpit turns on the air conditioning, and the physical activity most closely related to cockpit thermal environment is heat transfer. There are five ways of heat transfer: heat conduction, heat convection, heat radiation sweating and heat loss, and it is precisely because of the use of car air conditioning and the dynamic influence of weather that thermal environment inside the car is uneven and transient [16]. Therefore, unlike indoor buildings that use a steady-state and uniform thermal environment, interior of a car is an unsteady state and a non-uniform thermal environment based on the above characteristics. When the early researchers did not have perfect research methods, scholars from various countries analyzed thermal environment of the car cabin through numerical simulation and modeling [17].

Chien et al. [18] used numerical simulation to analyze and simulate the temperature field and flow conditions in the cabin of the automobile, and also analyzed the cooling cycle and coupling heat transfer on top, bottom and two sides of cabin, and studied the direct effect of the heat flux of the automobile air conditioning system, body maintenance structure, and the heat dissipation factors of human body on the "heat-flow" field. Influence of multiple factors on the flow field inside the cabin was analyzed. However, it did not study external climatic conditions as influencing factors. Zhang [19] conducted an internal flow field analysis on the three-dimensional model of the carriage under manned and unmanned conditions, and compared with experimental results, it was found that maximum error of numerical simulation was concentrated in the head area of the human body. Based on simulation of flow field in car, Che [20] analyzed the influence of the gap between the seat and the door on the flow field characteristics in passenger compartment.

Lu et al. [21] used computational fluid dynamics to simulate and analyze flow field in the passenger compartment of a heavy goods vehicle, and adopted the equivalent temperature evaluation standard for thermal comfort of the personnel in the vehicle, and results showed that uneven distribution of air volume in each air duct will make the airflow organization of the internal flow field of the car unreasonable, thereby reducing thermal comfort of the personnel in the vehicle. Kilic et al. [22] studied temperature and humidity features of various positions under the two working conditions of air conditioning heating and cooling in car cabin, and preliminarily discussed influence of thermal environment on the skin temperature and thermal sensation of occupants. Alahmer et al. [23] studied the overall and local thermal sensation and thermal comfort of human body under different humidity through experiment and numerical simulation, and experimental and simulation results showed that relative humidity controlled by air conditioning system in the heating and cooling process (winter and summer conditions respectively) reached human comfort zone faster than when relative humidity was not controlled, but the humidity had less influence on thermal comfort of human body in steady-state stage, and the measured temperature and the simulated temperature were compared. Results show that most significant influence of humidity on temperature and occupant thermal sensation is at the beginning of refrigeration, and when the humidity value tends to be stable, the effect is not obvious.

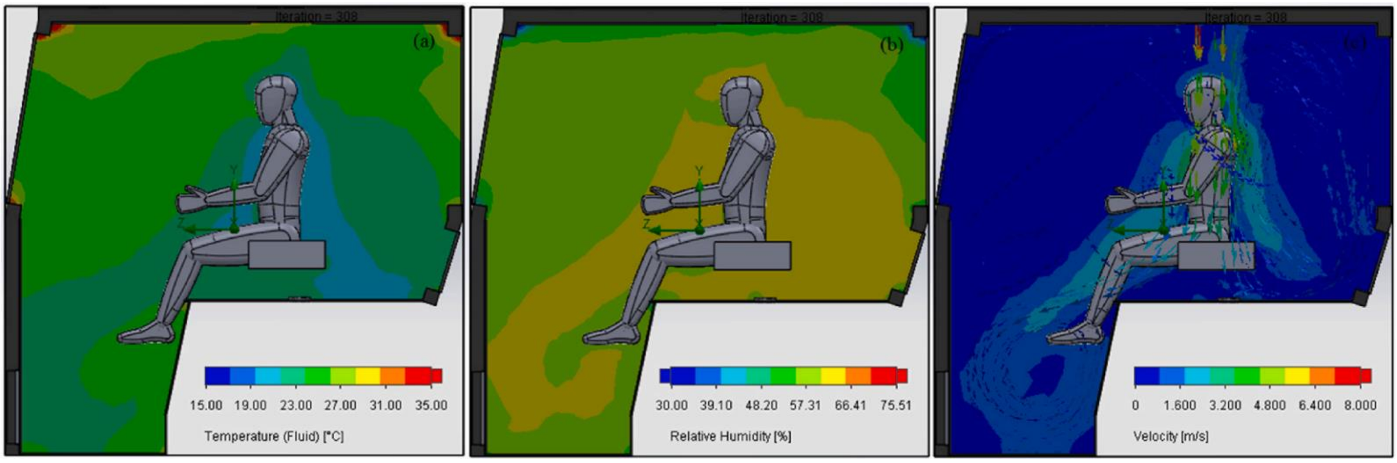
Myoung et al. [24] studied the quantitative energy-saving effect of local air conditioning system, and analyzed thermal comfort in cabin from different angles by adjusting the front and top air supply ratio, air supply temperature, air supply speed, etc. Lai et al. [25] studied the influence of uniformity of airflow at air outlet of automobile air conditioning on thermal environment of the cockpit, and found that when the air flow of the air outlet is uniform, cooling effect of cockpit is relatively good, flow field and temperature distribution in cabin are also relatively uniform, and thermal comfort level of the occupants is relatively good. Zhang et al. [26] carried out numerical simulation of the three-dimensional flow field and thermal environment in a certain car, obtained the distribution of speed field, temperature field, PMV and PPD, however PMV and PPD cannot suit for cars, and calculated the distribution of air age in the passenger compartment. Moon et al. [27] compared and analyzed the two thermal comfort evaluation indicators of PMV-PPD and equivalent temperature under multi-band and single-spectrum radiation models, and the results showed that considering effect of multi-band solar radiation, temperature near driver and passenger increased by 1 ℃–2 ℃, and equivalent temperature can predict the local change of thermal comfort level in passenger compartment.

Wang et al. [28] carried out climate experiments in Turpan to analyze climatic characteristics and study the changing characteristics of thermal environment of local automobiles under different climatic conditions, so as to provide experimental basis for research and development of automotive products in the dry heat environment of Turpan. Danca et al. [29] measured temperature and speed at various locations in the passenger compartment and calculated PMV-PPD thermal comfort evaluation indicators. However, PMV-PDD can only be used as evaluation index for building, which is not suit for cars. Giri et al. [30] applied CFD software to study two-dimensional ventilation of the cockpit in the parking stage, and studied thermal comfort of cockpit through analysis of the two-dimensional temperature field and speed field of the cockpit, and found that the air circulation in the cabin was improved with increase of air outlet speed, and temperature field distribution of cockpit tended to be uniform with increase of air outlet velocity, and heat accumulation and ventilation problems in the cabin were also greatly improved. He [31] studied influence of various crowd densities on thermal environment of cabin, evaluated thermal environment of cabin based on PMV, compared airflow velocity and occupant thermal comfort in the cabin with different crowd density, and the results showed that the different crowd density had a greater impact on thermal comfort of the cabin, which changed with the change of crowd density.

Mohammad et al. [32] conducted on-site measurements of three cars with different front windshield insulation rates, monitored the changes of thermal environment in car and dynamic thermal response of occupants, and studied effect of changes in characteristics of front windshield on thermal comfort inside the car under solar radiation. Experimental results show that improving heat insulation rate of front windshield can better improve thermal environment in car and reduce intensity of thermal shock when the occupants enter the car during the heating stage. However, in the cooling stage, due to air conditioning and cooling, improvement of heat insulation rate of the front windshield has less effect on improvement of thermal environment and thermal comfort in the car. Lü et al. [33] studied influence of the angle of the air outlet grille on thermal comfort of cockpit in extreme thermal environment, and analyzed the temperature field and speed field of the cockpit by optimizing and analyzing parameters of the air duct grille, and found that adjusting the parameters of the style grille can avoid the phenomenon of poor heat dissipation caused by the speed dead zone.

Zhong et al. [34] carried out modal behaviors and stochastic dynamics analysis of a composite cabin-like combined structure, and studied effect of aero-thermal factor on dynamic characteristics of combined structure. Riaz et al. [35] designed and installed an air-conditioned cabin on a tractor, and carried out experiment to valuate installed cabin performance under two scenarios concluding, conventional (S–I) and enhanced (S-II) air distribution. Meshing of air-conditioned cabin is illustrated in **Figure 1**, simulation results are illustrated in **Figure 2**.

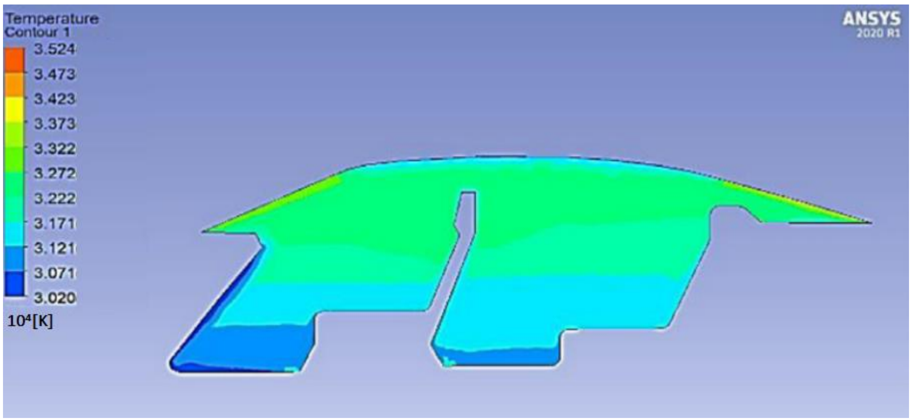
Figure 1. Diagram of meshing of the air-conditioned cabin.



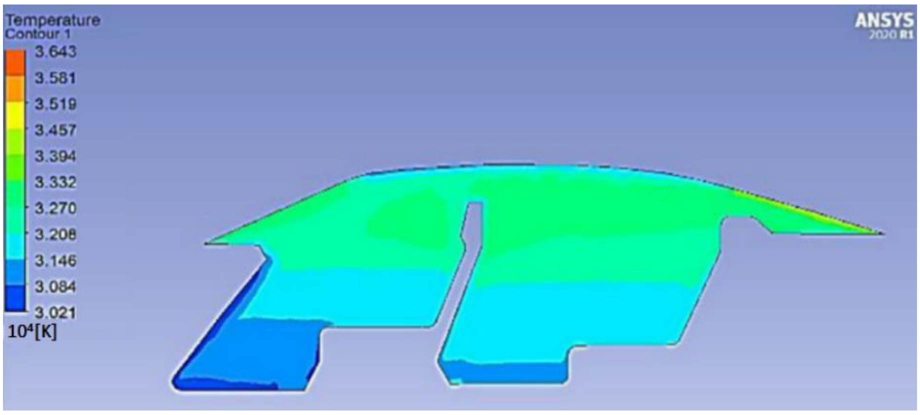
(a) **(b)** **(c)**

Figure 2. CFD simulation results of cross sectional view of the tractor cabin: **(a)** Temperature; **(b)** relative humidity; **(c)** velocity. 10^4[K]

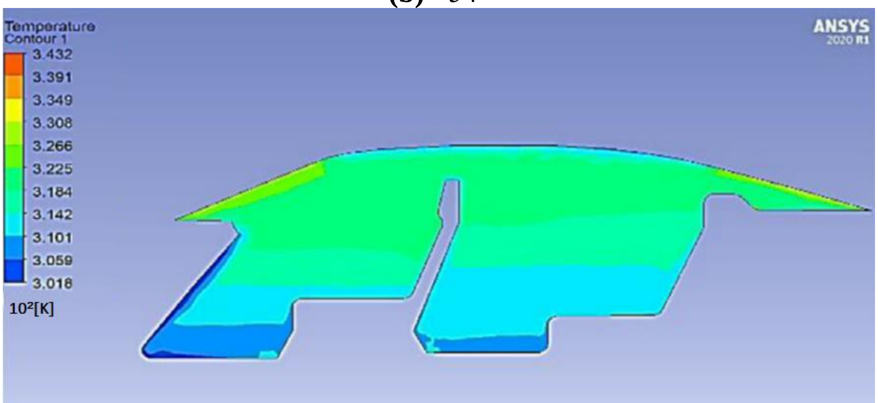
Hadi et al. [36] studied effect of solar intensity at different angles on air temperature inside a parking car based on CFD simulation. Temperature distributions at car center plane for various solar angles were shown in **Figure 3**. Due to thermal boundary layer, air temperature near heated inner surface is higher than that far away. Velocity distribution at car center plane for various solar angles is shown in **Figure 4**.



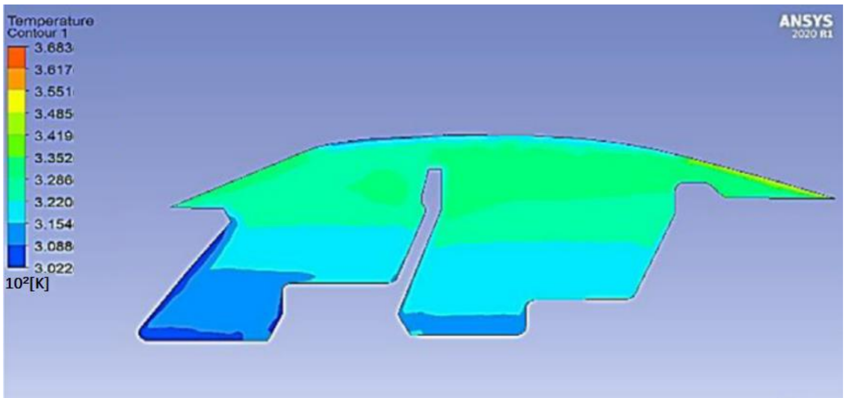
(a) 54°



(b) −54°

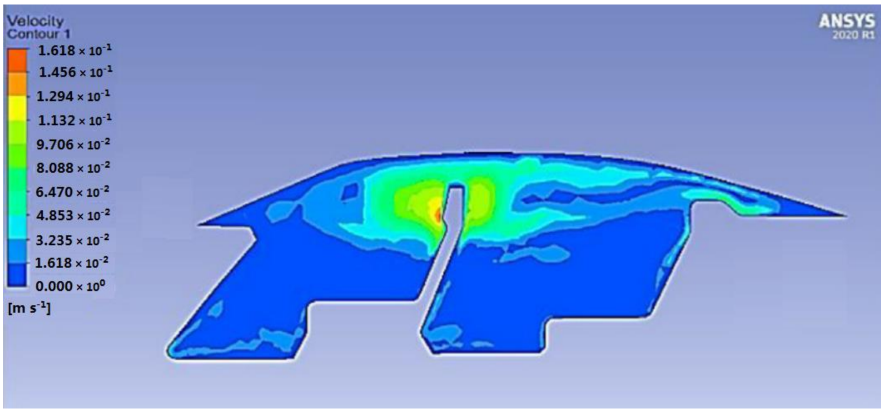


(c) 63°

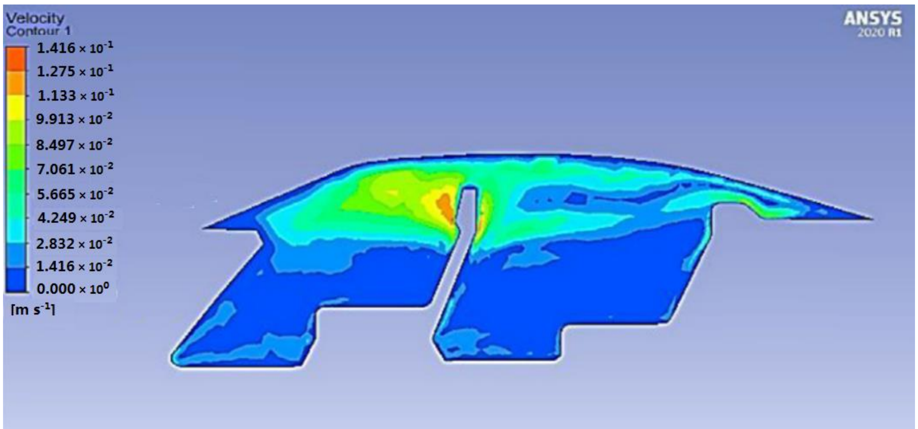


(d) −63°

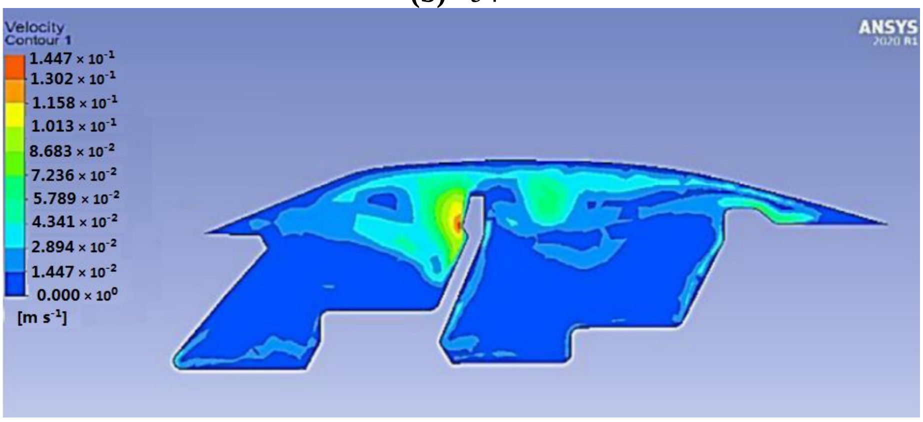
Figure 3. Temperature contours at car center plane for different solar angles.



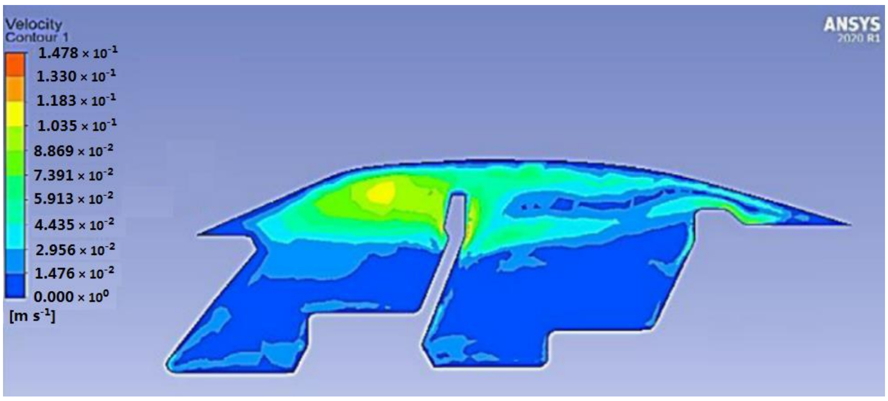
(a) 54°



(b) −54°



(c) 72°



(d) −72°

Figure 4. Velocity distribution at car center plane for various solar angles.

Wang et al. [37] carried out numerical analysis for a partitioned heat transfer wall setting of high-speed train cabin, and obtained average deviation of the airflow velocity and temperature respectively. Analysis results showed vortices in seating area, a significant longitudinal airflow and an increasing temperature near the carriage ends. Compartment's thermal environment and the acceptance of airflow were further analyzed. Longitudinal section airflow temperature fields of high-speed train cabin were shown in **Figure 5**. there is a significant temperature heterogeneity along the longitudinal direction of the cabin, with an overall low temperature in the middle and a high temperature at ends. Longitudinal section airflow velocity fields of high-speed train cabin were shown in **Figure 6**. The exhaust air influences the end airflow, so the longitudinal airflow is quite noticeable, and this longitudinal airflow may bring about the diffusion of pollutants.

As seen from existing research achievements, thermal comfort analysis of vehicle cab from aspect of time and space has been studied by many scientists, main research focuses on influence of season, weather, time (such as morning and evening, daytime), and vehicle driving status (such as stationary, driving) on the thermal comfort of drivers in terms of cabin air temperature and humidity. Following limitations are summarized:

(1) Numerical computing method is main means of analyzing thermal environment of vehicle, current numerical methods ignore natural convection heat transfer of airflow, which cause big analysis error.

(2) Experimental verification is an important means of ensuring correctness and reliability of thermal environmental analysis, however limitation of experimental conditions can cause incorrectness of analysis results.

(3) Thermal environmental analysis of vehicle is affected by many outer factors, such as temperature, wind velocity, these factors often change randomly, which are difficult to be controlled. Further exploration is needed to investigate the impact of the coupled effects of multiple factors in the driver's cabin on their thermal comfort.

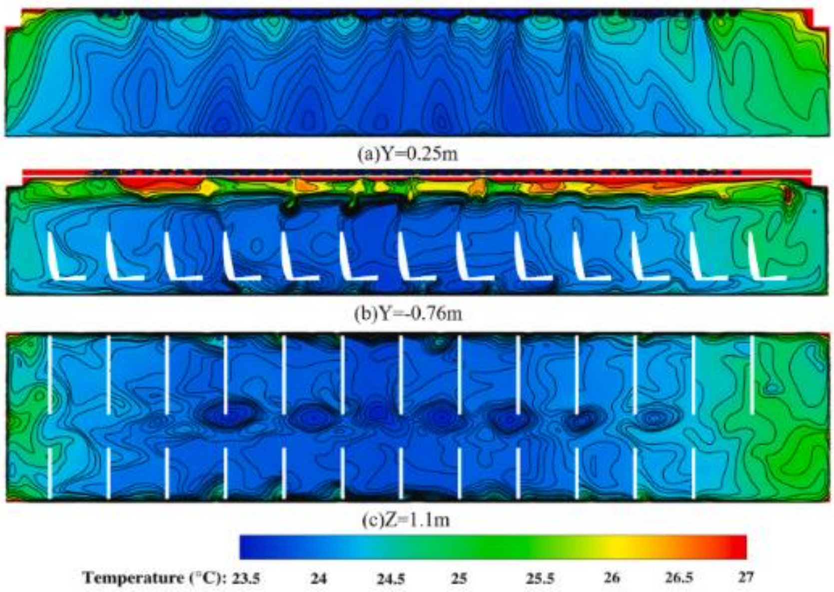


Figure 5. Longitudinal section airflow temperature fields of high-speed train cabin.

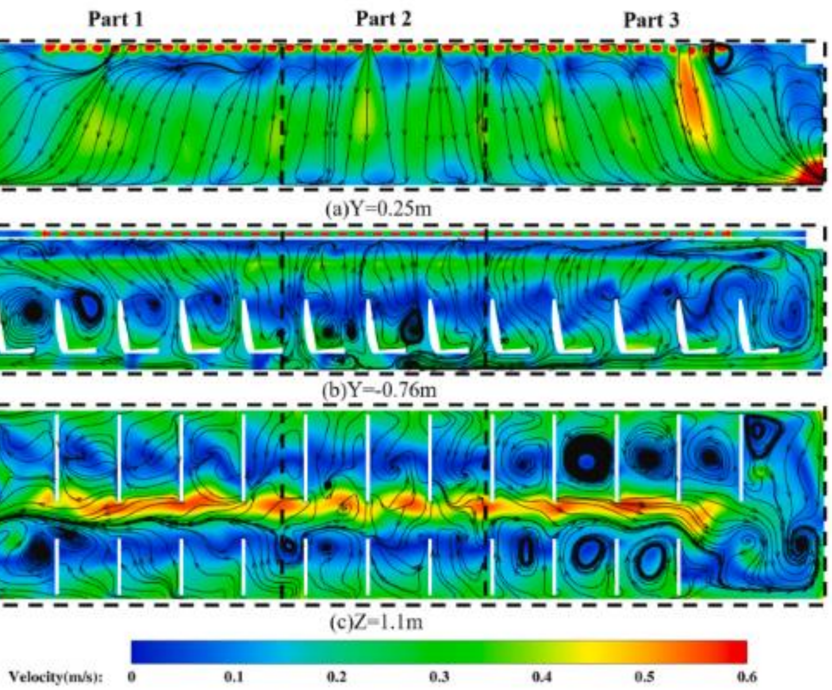


Figure 6. Longitudinal section airflow velocity fields of high-speed train cabin.

2.2. Comparative analysis of thermal environment inside and outside the vehicle focusing on solar radiation

Thermal environments inside and outside vehicles are two completely different systems, which have unique characteristics and influencing factors. Changes in temperature outside vehicle should be concerned for better regulating temperature inside and improve driving comfort. Comparative analysis of thermal environment inside and outside the vehicle is summarized.

Early studies are all about thermal environment inside the car, mainly studying thermophysical parameters that affect human thermal comfort, such as air temperature, relative humidity, average radiation temperature, relative air speed, etc. As well as two separate but related parameters, on the one hand, the level of activity provided by metabolism. On the other hand, it is thermal resistance of clothing. Zhou et al. [38] conducted a test of human thermal comfort under bus driving conditions, and conducted tests under indoor and outdoor parking conditions for convenience comparison. The study concluded that automotive thermal comfort studies should be conducted under transient conditions, with a good correlation between average skin temperature and average thermal sensation.

Yi et al. [39] applied a cooling film in solar spectra and high emissivity in atmospheric window, and measured inside air temperatures. Solar irradiation and heat transfer through two boxes were illustrated in **Figure 7**.

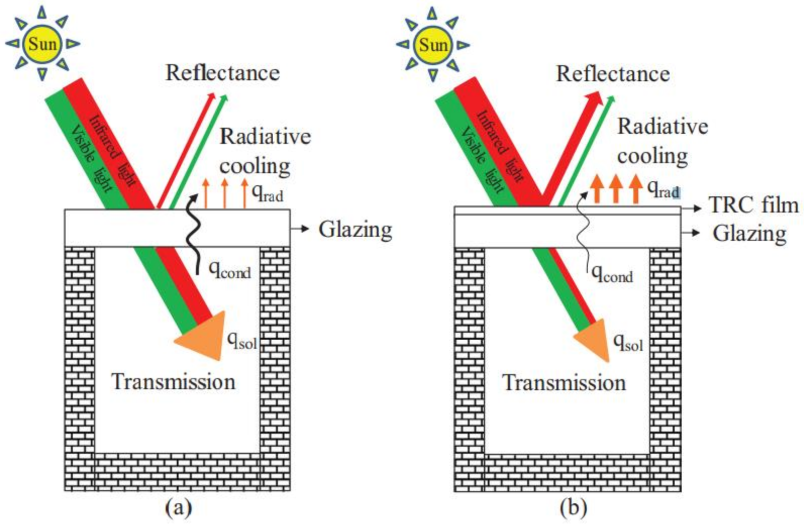


Figure 7. Solar irradiation and heat transfer through the two boxes: **(a)** silica glazing; **(b)** transparent cooling film covered glazing.

Chaiyapinunt et al. [40] studied influence of solar radiation on thermal comfort for a person near a glass window. Thermal comfort of a person is evaluated. Setiyo et al. [41] studied features of solar cells-based cabin cooler system, results showed that car cabin cooler can decrease cabin temperature by 9.8 °C. Vehicle cab is considered to be contaminated with high condition of compounds [42]. Especially in the high temperature environments of summer, it is observed that internal parts of vehicle cause more air pollutants and influence people's health [43].

Levinson et al. [44] measured the immersion temperature of two housing vehicles with high and low solar reflectance and found that solar radiation caused increased load on vehicles with low solar reflectance. Bhavsar et al. [45] grasped temperature changes in cabin of a closed vehicle under sunlight for 150 min. This environment is uncomfortable for passengers and can lead to suffocation until vehicle is completely ventilated. Some scientists analyzed thermal environment of cockpit under solar radiation and no solar radiation, and used PMV-PPD to evaluate thermal environment. PMV is not suitable for cars.

Yang et al. [46] studied human thermal comfort needs with standing and treadmill workstations based on experiment, results showed that temperature changing from 20 to 26 °C could meet most occupants. Zhang et al. [47] established CPMV* index based on CPMV model, considering solar diffusion coefficient, which further improved the accuracy of thermal environment evaluation model under solar radiation conditions. Huang et al. [48] sorted out and compared 8 thermal sensory evaluation indicators and models under effect of solar radiation effects, and proposed a SC-PMV model, which is analogous to outdoor comprehensive air temperature, which regards solar radiation as a component of air temperature, and calculates and analyzes the measured data in Lhasa in winter, and finds that the SC-PMV model has good predictability. Yang et al. [49] of Tongji University used a combination of experiment and numerical simulation to study thermal comfort of the cockpit, and studied that the solar altitude angle and solar radiation intensity have a great influence on thermal comfort level of the cockpit, and found that the temperature in the cabin increased with the increase of solar radiation, indicating that solar radiation intensity has an important effect on thermal comfort.

Hirn et al. [50] studied effect of radiation intensity and wavelength on cockpit thermal comfort, results shows that solar radiation has a great effect on thermal comfort. The above is a comparative analysis of thermal environment inside and outside the car, but there is little research on the interior wall of the car, but in fact, multiple walls in the cabin have an important effect on thermal comfort. Second, although thermal environment in the car cabin has been extensively studied, there are still some problems. If there is no comparative analysis of thermal environment in the car when parking and driving. Failed to relate wall temperature to space temperature field. Considering the quantitative effect of automotive window glass materials on the ability to absorb sunlight, it has little quantitative effect on thermal environment inside the car. Regarding the latest progress of windshields, Kong [51] and others of Chongqing University studied the influence of thermal insulation rate of the front windshield on thermal comfort level of the cockpit, and carried out the test of three different thermal insulation coefficients of glass on thermal environment of the cockpit and the dynamic thermal response of the occupants, and found that improving thermal insulation coefficient of the front windshield can improve thermal environment of the cabin in the warming stage and improve thermal comfort level of the cockpit. Zhang et al. [52] studied the influence of characteristics of the window on thermal environment of cockpit, and analyzed effect of various heat conduction methods on temperature in the cockpit, and the results showed that influence of solar radiation on thermal environment in cockpit was relatively large, different types of glass had different transmittance, the transmittance had a greater impact on thermal comfort of cockpit, and the absorption rate of the glass surface had little effect on the cockpit.

There is no reference to the measurement techniques used to evaluate microclimate conditions in cars compared to buildings. Cars are heterogeneous environments where no single microclimatic parameter can be deemed homogeneous. This is particularly true for mean radiant temperature, which necessitates specialized instruments for accurate evaluation.

According to existing achievements, research trend of thermal environment inside and outside vehicle cab mainly reflects in equal emphasis on health and comfort, application of intelligent technology, integration of thermal management systems, and adaptability to extreme weather conditions. These trends will drive continuous development and innovation of automotive industry, providing drivers with safer, more comfortable, and environmentally friendly travel experiences. Vehicle climate measurement technology uses a series of sensors and control systems to measure and adjust real-time parameters such as temperature, humidity, and air quality inside the car, creating a comfortable and healthy riding environment. With the continuous development of technology, future car climate measurement systems will become more intelligent, integrated, and environmentally friendly, providing passengers with a more comfortable and healthy riding environment.

3. Factors influencing thermal comfort in car

Factors effecting thermal comfort can be divided into thermophysical parameters and human physiology, psychological factors and clothing thermal resistance. Among them, human physiology, psychology and clothing thermal resistance are independent but interrelated. The thermophysical parameters contain four aspects: air temperature, humidity, air velocity, and mean radiation temperature.

3.1. Thermophysical parameters

(1) Air temperature

Temperature inside the car is the main indicator of thermal environment and main factor affecting thermal comfort, which directly affects the heat exchange between human body and air through convection and radiation, air temperature is affected by the heat transfer by radiation (transparent and opaque walls), not vice versa [53]. When ambient temperature rises, perspiration increases, and subjective thermal sensation will be biased towards the direction of heat.

(2) Relative humidity

Past studies have shown that relative humidity of the air has little influence on human thermal comfort at 30%–70% [54]. Therefore, the influence of air humidity has often been overlooked in previous studies of passenger compartment thermal comfort. But in fact, air humidity directly or indirectly affects thermal comfort. Zhang et al. [55] studied effect of different driving states on thermal comfort of occupants, and results showed that different driving states influence temperature distribution in cabin, and relative humidity of the cockpit also changes relative. Air humidity also affects the moisture diffusion of the skin and the balance of the body's energy metabolism. MO et al. [56] study influence of relative humidity in passenger compartment on human thermal comfort based on PMV-PPD. Results illustrate that when cabin air temperature is fixed, the relative humidity change will cause the change of human heat, and the higher cabin temperature, the more obvious influence of relative humidity on thermal comfort.

(3) Air velocity

Air velocity affects thermal comfort of human body by affecting convective heat transfer and air evaporation. Experimental studies that different wind speeds have significant differences in human body temperature, and under low temperature conditions, wind speed increases, human body temperature decreases, and the greater wind velocity, the lower body temperature [57].

(4) Average radiation temperature

Ambient radiation temperature inside the car includes solar radiation and heat exchange between human body and interior surface of car in form of radiation. Zhang [58] of Jilin University pointed out in study of thermal environment of automobile space that the temperature of the part of the car exposed to direct sunlight can be as high as 90 ℃ or more in summer under solar radiation heat transfer, Wang Weijian also verified through experiments that the air temperature in the car can quickly rise to 60 ℃–70 ℃ when exposed to the sun for 30 min.

3.2. Human physiological factors

Human body has a self-regulating function and can cope with various thermal conditions. When people move from a warm environment to a cold environment, body will be suit for new environment through a series of complex physiological processes, including vasoconstriction, shivering. At the same time, heat transfer between human body and thermal environment is also a complex. The human thermoregulatory system dynamically responds to its environment, keeping body's main temperature.

The physiological model of the human body concludes two parts: passive system and active system. Passive systems describe heat transfer to human body and its surfaces. The rate of thermoregulation reaction depends on the actual deviation of the core temperature and skin temperature from the set temperature. The classification of human thermoregulation models takes into account single-node, two-node, multi-node, 3D models with up to thousands of nodes [59,60]. At the present only these models can be considered suitable for cars: 3D models like: JOS-3 model, but it has been validated on naked subjects, but it has been validated on naked subjects, open source is developed [61]. Fiala Ergonsim model, but it is not a free software. THERMODE 2023, specifically designed to account for microclimatic inhomogeneities (potentially suitable for cars), provided with a thermal sensation model [62] and UCB model [63].

3.3. Clothing thermal resistance

Clothing also plays a very important role in human heat comfort by keeping warm and slowing down the evaporation and diffusion of sweat on the body surface in the heat exchange of the human body. Zhang et al. [64] studied the influence of clothing resistance and activity level on thermal comfort level of the cabin based on PMV evaluation indicators, and the results showed that clothing resistance and thermal comfort of clothing had a related effect, resulting in different perceptions of thermal environment of the occupants. Common winter clothing thermal resistance is shown in **Table 1**.

Table 1. Common winter clothing thermal resistance.

Clothing	Thermal resistance/clo
sweater	0.28
Regular long sleeve	0.25
Down jacket	0.55
Regular pants	0.10

Regular pants 0.10 The current calculation of clothing thermal resistance is often a warm body dummy as a test tool, and there are generally three models: parallel model, serial model and global model. These three types of calculation methods use different calculation methods due to different modes of application. Both the parallel model and the serial model are related to the local thermal resistance of the garment. The total thermal resistance of the garment is the weighted average of the local thermal resistance of each region. Among them, the parallel model is the reciprocal of the sum of the reciprocal thermal resistance weights of each segment, and the serial model first finds the local thermal resistance of each segment of the dummy, and then weights thermal resistance value of the clothing.

Table 2 selects several typical dummies for analysis from the development process of various warm body dummies, and summarizes whether they can test the local thermal resistance of clothing.

Table 2. Various types of warm body dummys and their characteristics.

Year	Name	Dummy type	Country	Key character	Whether thermal resistance of clothing can be tested
1942	SAM	Cell segment dummy	United States	It does not reflect the temperature distribution characteristics of the human body.	No
1969	The first generation of warm body dummy improvement	Non-sweating manikin	United States	Simulated sweating is realized by spraying water heating of the fabric covered by the surface of the dummy, but it is limited by the experimenter's different experience of spraying water and heating time, which is not very accurate and has poor repeatability, but it provides ideas for the future development of dummy simulation sweating.	No
2002	Walter	Sweating manikin	China	Improved two-part test method, using one-step test, the world's first simultaneous test of thermal resistance and wet resistance [61].	Yes
2011	Newton	Sweating manikin	United States	Separately control heating and sweating in the first interval, which is more commercial [62].	Yes

Effect of body movements and air action on the clothing's thermophysical properties as described in ISO 9920 should be considered. When human body is in motion, thermal resistance of clothing decreases due to an increase in convective heat dissipation. Air action during human movement on thermal properties of clothing is multifaceted, including increased convective heat dissipation, changes in the air layer under clothing, sweat evaporation and humidity regulation, as well as the influence of clothing materials and structure. These factors work together to determine the insulation and breathability of clothing during human movement.

3.4. Other secondary factors

There are also factors that are widely believed to affect a person's thermal comfort, including age, gender, race, region, etc. [65,66]. The basic metabolic rate of people body will gradually decrease with age, but evaporation rate of sweat on skin also decreases with age, which is reflected in the heat balance equation for the human body's heat production and heat dissipation to reduce simultaneously, so the part affected by age cancels each other. The relationship between gender and human comfort has been studied and analyzed by many scholars.

Fabbri et al. [67] analyzed thermal comfort in kindergarten environment of 4- and 5-year-olds. Experiments have shown that children can clearly distinguish thermal comfort and can express their thermal sensation in terms of thermal comfort, and under same conditions, children have higher PMV than adults.

Li et al. [68] conducted experimental studies on more than 28,000 subjects from different climatic regions in China, and more than 500 subjects conducted simulated climatic conditions in the laboratory. The experimental results show that the same thermal comfort value means different things to people in different climatic regions, so thermal comfort standard needs to be divided by region.

4. Thermal comfort evaluation index

At present, most of thermal comfort evaluation models are suitable for the construction field, that is, suitable for steady-state, uniform indoor thermal environment. Li et al. [69] will conduct detailed research on the authoritative standards currently applied to thermal comfort evaluation in buildings, clarify the scope of application and evaluation accuracy of each standard, and clearly classify and organize the standards and performance evaluation. The study concludes the future development trend of human thermal comfort and advantages and disadvantages of thermal comfort evaluation standards, which provides a theoretical basis for the use of thermal comfort evaluation in China's building environment [70].

However, for automobile unsteady state, the evaluation index research of non-uniform thermal environment is relatively late compared with the development of the construction field. In this paper, different thermal comfort evaluation methods will be explained from two aspects: uniform thermal environment and non-uniform thermal environment. Among them, there are 4 uniform thermal environment evaluation indicators. They are PMV-PPD evaluation method, effective temperature ET evaluation index, and standard effective temperature SET evaluation index. There are three evaluation indicators for the comfort of non-uniform thermal environment. They are weighted PMV index, equivalent temperature EQT evaluation method and equivalent temperature EHT evaluation method. Common evaluation indicators are illustrated in **Table 3**.

Table 3. Thermal environment comfort evaluation indicators.

Evaluation index	Founder	Limitations
PMV-PPD	Fanger	Non-uniform thermal environments cannot be evaluated
Weighting PMV	Matsunagc Ingcrsoll	Weights do not accurately reflect the impact of this factor on overall comfort
EQT	SAE J2234-2001	Overall thermal comfort cannot be evaluated, AEQT metrics are required
EHT	Wyon	Overall thermal comfort cannot be evaluated
TSV	UC-Bcrkclcy	It is necessary to use warm body dummy experiments, which are costly

4.1. Evaluation method of thermal comfort in uniform thermal environment

(1) ASHRAE seven-point scale subjective evaluation method ASHRAE seven-point scale evaluation method is a subjective thermal comfort evaluation model, which divides the body's thermal sensation of thermal environment into 7 levels of heat (+3), warm (+2), slightly warm (+1), neutral (0), slightly cool (−1), cool (−2) and cold (−3), as shown in **Table 4**, by organizing a certain number of evaluators to make 7 according to their own thermal sensation of the evaluation target is evaluated in one of the grades, and finally thermal comfort of target under different operating conditions is obtained.

At the same time, Santos Silva et al. evaluated and analyzed the low-speed and high-speed models according to ASHRAE Standard 55 to obtain different long-term indices [71]. Simulation experiments are used to show that different indicators can lead to different results, but the trend is not much different. The subjective evaluation method is suitable for both steady and transient conditions, which is applied for both overall thermal comfort evaluation and local thermal comfort evaluation of the human body, but the method has greater subjectivity, and its evaluation results will be largely affected by the evaluators' own reasonable judgment of thermal comfort, and must face the real thermal environment, so it is difficult to apply to thermal comfort research work in the automobile development stage.

Table 4. Subjective evaluation index of human thermal sensation.

	Bedford	ASHRAE	Gagge & Hardy
1	cold	cold	comfortable
2	cool	cool	Slight comfort
3	Comfortable and cool	slight	uncomfortable
4	Neutral comfort	neutral	Very uncomfortable
5	Cozy and warm	Mild warmth	
6	warm	warm	
7	hot	hot	

(2) PMV-PPD evaluation method

Human thermal comfort equation and the ASHRAE seven-point scale as the starting point were taken, and curved and analyzed thermal sensory data under the four metabolic rates were obtained by the subjective sensory test conducted, and PMV-PPD thermal comfort evaluation system was obtained. PPD indicator is defined as percentage of people who are dissatisfied with thermal environment. Therefore, its value ranges between 0 and 1, and the lower the value, the more people are satisfied with thermal environment. This method comprehensively considers six factors: human activity, clothing thermal resistance, air temperature, average radiation temperature, air flow rate and relative air temperature. Corresponding to the ASHRAE temperature sensing range, the indexing of PMV, as illustrated in **Table 5**, PMV indicates feeling of heat and cold in vast majority of people in same hot environment, using a total of 7 stages of comfort evaluation from −3 (cold feeling) ~ 0 (intermediate feeling) ~ +3 (heat feeling). The correlation between PMV and PPD populations and predicted average turnout is shown in **Figure 8** [72].

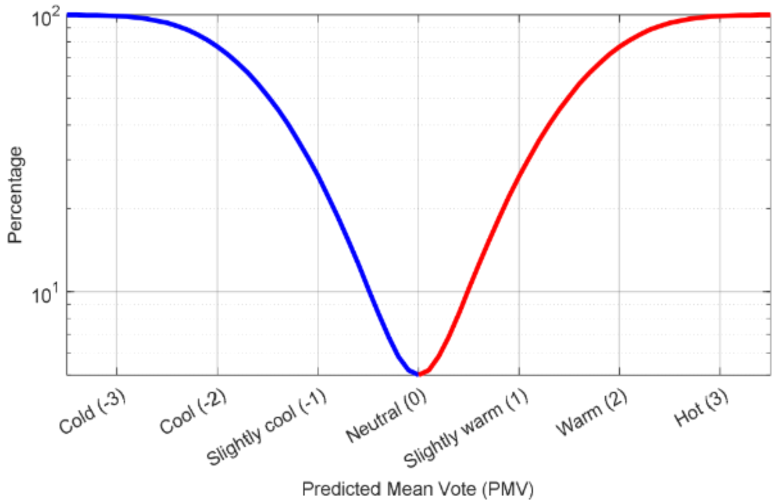


Figure 8. Correlation between PVD prediction average turnout.

Table 5. PMV thermal comfort index.

Thermal sensation	Hot	Warm	Slightly warm	Neural	Slightly cool	Cool	Cold
PMV	+3	+2	+1	0	−1	−2	−3

Human thermal comfort equation and PMV-PPD evaluation index have always been the theoretical basis of international research on human thermal comfort, and have been widely used by ISO 7730 as indoor thermal environment comfort evaluation index. Zhang [73] found that PMV can be used correctly to predict thermal comfort of car. Thermal environment in a mobile car is uneven due to rapid changes in solar radiation and an uneven air temperature. Therefore, there are four shortcomings in the PMV-PPD evaluation method: Because theory is based on test results in thermal environment close to human comfort zone, and the non-test area is predicted by formula, the use of this index in environment far from the comfort zone will obtain inaccurate conclusions; The method does not consider the influence of regional, age and sex differences, but many scholars believe that differences in metabolism due to differences in sex and age, and different regional climates will also cause people’s adaptability to thermal environment and different psychological expectations, which all lead to the limitations of the method. The method is an overall evaluation method of thermal environment, the parameters used in the PMV index are some average quantities, such as treating people as a whole, taking the average of the temperature and pressure around the human body, M and W are also averaged, this simplification is suitable for a uniform thermal environment with a large space, and local thermal comfort problem of occupants that is common in non-uniform thermal environment of car seating space is not applicable; This method is a steady-state thermal comfort evaluation method, which is not applicable to transient environments in the car, such as air conditioning refrigeration and heating processes.

Although PMV indicators have been widely used in building thermal comfort assessment, their application in vehicle environments is limited. Main reason is that internal environment of a vehicle is a highly uneven and non-stationary environment and interior space of the vehicle is relatively small. Therefore, in the assessment of vehicle thermal comfort, multiple factors such as passenger expectations, individual differences, environmental parameters, etc. need to be comprehensively considered to provide more accurate and reliable evaluation results.

(3) Effective temperature (ET) evaluation index Effective temperature (ET) human body thermal comfort evaluation index comprehensively considers the influence of dry bulb temperature, humidity and air flow rate on human thermal comfort, it is numerically equal to the temperature of static saturated air that produces the same feeling, this index has been used by HVAC engineers in the field of building environment for nearly 50 years, but because this indicator overemphasizes the influence of humidity at low temperatures, and the influence of humidity at high temperatures is not emphasized enough. It caused the inherent defects of the effective temperature index and was gradually replaced by a new effective temperature index [74].

(4) Standard effective temperature (SET) evaluation index

SET is defined as the subject’s wearing standard clothing (clothing thermal resistance of 0.6clo) in a thermal environment, and subject’s average skin temperature and skin temperature are same as thermal resistance of a certain real thermal environment and clothing of the actual clothing. It is believed that human body has same amount of heat dissipation in standard thermal environment and the actual thermal environment.

(5) Thermoregulation model JOS-3

Thermoregulation models that accurately consider factors such as clothing, sweating, and microclimatic variations should be concerned. Some scientists developed a thermoregulation model JOS-3 based on JOS-2. Human physiological responses and body temperatures are calculated using the backward difference method. JOS-3 has a higher accuracy for heat production in young and older subjects and mean skin temperature in older subjects than JOS-2 under cold environmental conditions.

4.2. Evaluation of comfort in non-uniform thermal environment

(1) Weighted PMV index Weighting

There are two weighting methods for PMV indicators. Including equivalent temperature weighting and body segment area weighting, it is an evaluation method for weighted average of environmental parameters in non-uniform environment in PMV indexes and then referring to PMV, but the weight of thermal comfort in local parts of human body to the overall thermal comfort of human body cannot be accurately obtained, and Han et al. [75] used weighted PMV for main evaluation parameters of human thermal comfort in non-uniform thermal environment. The index and the weight value of the local heat sensitivity of the human body to overall heat sensitivity studied by Crawshaw et al. [76] analyzed the influence of different distribution of air return outlets in the car on human thermal comfort.

(2) Equivalent temperature (EQT) evaluation method

Equivalent temperature EQT index refers to an ideal space environment with a relative humidity of 50%, when real ambient temperature and heat dissipation of a certain part of the dummy’s body are equal, air temperature is defined as equivalent temperature of the part [77]. Equivalent temperature considers air temperature, air velocity and radiation influence, divides the human body into 15 segments. Human effective radiation area coefficient is listed in **Table 6**.

Table 6. Human effective radiation area coefficient.

	Fanger	**Guibert&Taylor**
Sitting position	0.70	0.70
Standing posture	0.72	0.78
Semi-vertical posture	-	0.72

(3) Equivalent uniform temperature (EHT) evaluation method

Huang et al. [78] proposed equivalent uniform temperature (EHT). First set an ideal uniform environment, air temperature is equal to mean radiation temperature, no temperature gradient and air flow, in the case of the same amount of clothing and metabolic intensity, if a part of body in a non-uniform environment is equal to its heat dissipation in uniform environment, the air temperature in uniform environment is called EHT in a non-uniform environment.

4.3. Thermal comfort research methods

Currently, there are three main models of thermal comfort. One is experimental research, the second is theoretical analysis, and the third is numerical simulation methods. This section will elaborate on the above three aspects.

(1) Experimental research

Experimental research is guided by scientific principles, establishing an experimental platform that matches research topic, and finally obtaining experimental results by changing the set parameters [79]. Experimental methods can often test the comfort of human body in a real environment or a specific space in a thermal environment, and offer a factual basis for theoretical research. Experimental methods include the climate simulation room experimental method and the field test record analysis method, both of which require a statistical analysis of the subjective thermal comfort of the person being tested. Although the experimental method is convincing, it often requires repeated experiments many times, and generally has high requirements for experimental conditions. And when measuring experimental data, there will be experimental errors. If the measurement results are affected by human factors, such as when measuring the surface temperature of human skin with a thermocouple, the thermocouple is not well bonded to the skin and affects the measurement results, or the assembly of personalized heating equipment and heat insulation devices does not ensure sufficient airtightness, which will have a certain impact on the temperature measurement value and the time for the human body to achieve thermal comfort.

Since the experiment is a subjective questionnaire survey of local and overall thermal sensation and thermal comfort of experimenter, the survey results will be affected by the gender, psychological factors, cold tolerance and other factors of the experimenter. Therefore, the development of a psychological scale on thermal comfort to estimate the reliability and validity of questionnaires will minimize errors.

Currently, there are generally three experimental data collection techniques—invasive, semi-invasive, and non-invasive measurements [80]. Traditionally, invasive measurements are performed directly on the human body with lab equipment. Although the data obtained from invasive measurements is fairly accurate, current predictive models based on invasive measurements generally perform well. For example, Kong et al. [81] provide a new method for assessing personal thermal comfort. This method computes inspection index to infer subtle changes in blood flow on facial skin.

In recent years, experimental research methods have mainly studied thermal comfort of vehicles during actual driving through measurement and electroencephalogram (EEG), skin temperature, heart rate variability.

Electroencephalogram (EEG) is a physiological and neuroscientific method that quickly reflects electrophysiological activity throughout cortex and scalp surface [82]. EEG can record brain's central nervous system [83]. EEG can be applied to judge various neurological disorders [84]. EEG signal is weak [85]. Related studies are experiments in which electroencephalograms (EEGs) are collected by placing specialized electrodes. EEG data is used to develop models that classify thermal comfort state of subjects. Wang [86] studied the effect of vehicle temperature on cognitive ability and EEG on the basis of evaluating EEG characteristics. Results illustrated that cognitive ability of driver decreased with increase of temperature.

Park et al. [87] proposed a method to predict individual thermal status by measuring different human body indexes. Liu et al. [88] proposed a method that could identify 12 human poses to predict thermal discomfort. Luo et al. [89] presented a thermal image-based means to evaluate thermal comfort by measuring facial skin temperature. Qavidel et al. [90] used wearable sensor to obtain skin temperature data. Čulić et al. [91] studied differences between heat map pairs and introduced a personal thermal comfort prediction method. Mehnatkesh et al. [92] proposed a personal thermosensory index by measuring physiological parameters. Bode [93] proposes a new electric vehicle seat heating strategy based on the heat sensitivity of human skin. A new method using deep neural networks to extract gray information of face thermal images and predict individual thermal comfort states. A deep learning-based ResNet34embedded spatial attention mechanism is established for extracting features from facial thermal images. **Figure 9** shows a preliminary frame design for predicting personal thermal comfort [94].

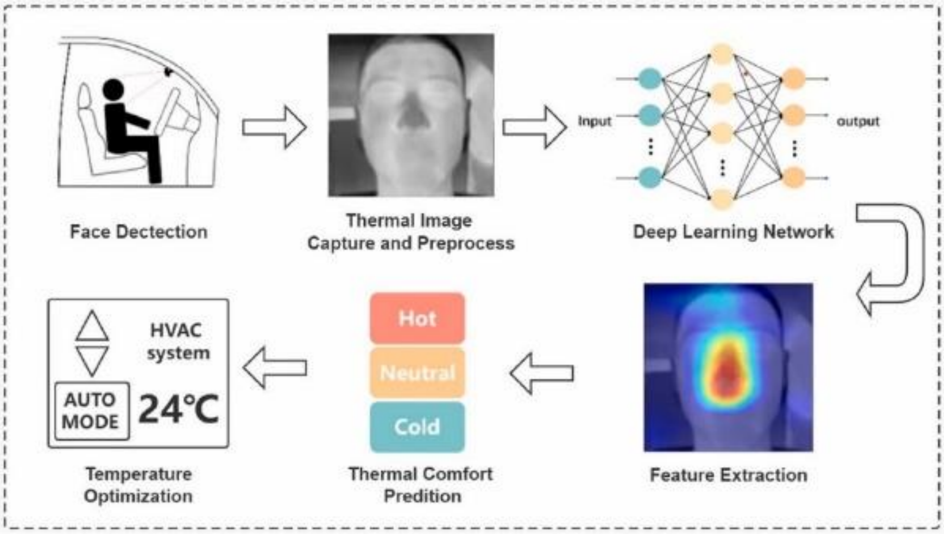


Figure 9. Preliminary framework for thermal comfort prediction and temperature optimization.

Zhang et al. [95] used six models to predict the driver's facial temperature of a specific series of vehicles, namely support vector regression (SVR), artificial neural network (ANN), and gated recurrent unit (GRU). The results of MAE show that when tested using both trained and untrained test datasets, the performance of ANN is the best among the 6 models. In addition, the accuracy of these models is lower when test data sets are collected under new operating conditions. Based on the above results, ANN may be the preferred method for predicting facial air temperature for vehicle drivers. **Figure 10** shows the flowchart for optimizing and evaluating the SVR, ANN, GRU models.

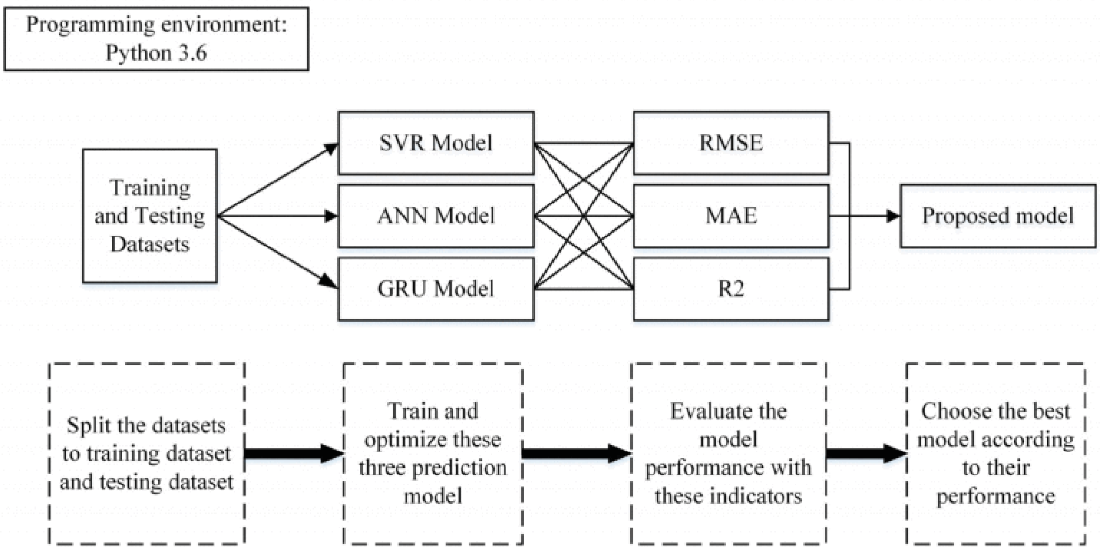


Figure 10. Flow chart for optimizing and evaluating SVR, ANN, GRU models.

(2) Theoretical analysis

Theoretical analysis is to establish a mathematical model related to practical problems, use relevant theories to analyze and study the problem, summarize the law, this method not only requires the established mathematical model to be very accurate, but also requires the theoretical knowledge of researchers to be very deep, so that the results obtained have reference value. There are 4 commonly used thermal sensing models, including the Predictive Average Voting (PMV) model, the Dynamic Thermal Sensing (DTS) model, the UCB model developed by the University of California, Berkeley, and the Outdoor Thermal Comfort (Lai's) model. At present, there are 3 kinds of virtual cockpit models, virtual mannequins and dummy models. The details are as follows:

1) Virtual cockpit model

The human microenvironment is highly influenced by convection and radiant heat transfer between the body surface and the surrounding environment, and correct turbulence modeling is one of the keys to obtaining repeatable and reliable results [96]. Due to the limitation of computer level, it is difficult to solve the complex turbulence problems encountered in engineering by direct numerical simulation (DNS) of turbulence from the N-S equation, and in this case, the N-S equation (RANS) method for solving the Reynolds mean has become a more effective and feasible means to solve engineering problems. For cockpit modeling, K-ε models and K-ε models with low Reynolds numbers are commonly used. But the drawback of the RANS model is that sometimes the accuracy is insufficient. Compared to the RANS model, large eddy simulation (LES) provides more dynamic details of heat and mass transfer, but relies on computational resources that make this method still unsuitable for human-scale research. Some researchers also use the Separation Vortex Simulation (DES) method. Comparative studies of DES, LES and RANS models show that DES has the potential to be an accurate turbulence model. However, this method needs further research before it can be widely used to simulate the indoor environment of automobiles [97].

2) Virtual mannequin

The establishment of virtual mannequins is the key to thermal comfort simulation research. The virtual mannequin started with an early simplified 2D model and gradually transitioned to a 3D model that was closer to the real world. Shape-based virtual mannequins do not have the same thermoregulation function as the human body can respond to the microenvironment, so researchers have developed more complex thermophysiological models of the human body [98]. The human thermophysiological model is a mathematical representation of the human body and includes: 1) passive systems, which simulate the physical and dynamic heat transfer of the human body and its surroundings (through heat equilibrium equations or biothermal equations); 2) Active system, simulating the physiological regulatory response of the human body to vasoconstriction, vasodilation, and trembling to maintain the stability of core temperature. The human thermos-physiological model can not only represent the heat exchange parameters between the human body and the environment, but also extract some thermal comfort indices such as equivalent temperatures. Thermophy-siological models can be further divided into single-node models, two-node models, and multi-node models according to complexity. Both the single-node model and the two-node model are limited to a unified environment, while the multi-node model considers the composition structure and thermophysiological characteristics of the human body, simulating the heat transfer process inside and on the surface of the human body. The more complex the model, the more suitable it is to simulate thermal response of the human body in complex environments.

Toader et al. [99] present the details of a recently designed and created thermal model consisting of 79 surface areas with independent neurofuzzy thermoregulation. The components of the model and the acceptance strategy are described. A flexible heating element is used to control the temperature, on which five digital sensors are located. To determine the relationship between heat loss and ambient temperature, thermal model was calibrated in a climate chamber. Thermal models are able to predict local sensations through the so-called equivalent temperature concept of predicting average voting.

3) Dummy models

Human trials are demanding due to high costs and ethical limitations, and differences within and within subjects are often difficult to explain. In comfort studies, a large number of participants are needed to achieve sufficient statistical significance. To reduce this burden, dummies have been used to conduct standardized studies of human thermal comfort [100]. Use of thermal mannequins compared to actual human experimental subjects and tests different scenarios were discussed [101]. The results show that dummy models can provide accurate invasive measurements of human thermal sensory predictions, including questionnaires, monitoring of environmental parameters and human physiological parameters, which have been widely used and integrated with technologies such as IoT, artificial intelligence, and machine learning. At present, there are some new sensors, such as glasses, watches, etc., these wearable devices avoid potential foreign body sensation to a certain extent, but still have a certain degree of invasiveness. Studies have begun to attempt to use infrared thermography to achieve non-contact measurement [102]. Thermal imaging measurement of infrared thermal imaging cameras is a non-contact and relatively cutting-edge imaging method, using infrared thermal imaging detectors to measure the temperature of interior surface of cockpit, the surface of clothing and visible body parts of human body in real time. This experimental method overcomes the shortcomings of traditional single-point temperature measurement technology and visual observation methods, and this new measurement method is expected to gain large-area applications in the future automobile cockpit.

Evaluation results show that none of models can correctly predict thermal sensation in driving condition in the car, because they do not take into account influence of changing solar radiation on thermal sensation. A study of existing international standards that can be used for thermal comfort methods in automotive interiors shows that there are currently no international standards that can accurately assess thermal comfort specific to a vehicle's ambient space.

(3) Numerical simulation

Numerical simulation is to combine the concepts related to finite elements, simulate and calculate the finite element model through electronic computers, and study the problems encountered [103]. The characteristics of the flow field in the cockpit are studied by computational fluid dynamics CFD (CFD) technology, which can analyze air flow, temperature distribution and air velocity in cockpit, and obtain their distribution patterns. Most of the modeling analysis studies focus on how to generate thermal comfort and mechanism of thermal comfort, and at the same time carry out the prediction and analysis of thermal comfort under different working conditions [104]. Numerical simulation provides an effective basis for engineers to study cockpit thermal comfort, and can also reduce number of experiments, thereby improving efficiency of practical problem research.

Zhou et al. [105] of Donghua University studied the numerical simulation of cockpit thermal comfort, compared the influence of the setting of the second and third boundary conditions on the human surface temperature distribution in the numerical simulation, analyzed the speed field, temperature field and PMV index evaluation of cockpit, and found that different boundary conditions had a certain impact on simulation results of the cockpit, and selection of appropriate boundary conditions in the process of cockpit thermal comfort research had an important impact on the simulation results [106]. Li et al. [107] established a model that integrates human body thermal regulation mechanism and dynamic environmental features. Kim and Jung [108] validated influence of steering wheel heating system on enhancing hand heat.

Croitoru et al. [109] evaluated effect of turbulence intensity at inlet of the air distribution system on local airflow sensation and thermal discomfort under different ventilation conditions. Jamin et al. [110,111] proposed a complex experimental and numerical study to better understand air distribution in carriage.

5. Conclusion and outlook

The first chapter of this paper introduces research background on thermal comfort in the interior of the car. The second chapter discusses thermal environment in the interior, the influencing factors of thermal comfort in the interior, the evaluation index of thermal comfort, and research methods of thermal comfort.

At the same time, it is also pointed out that the current research on thermal comfort of the interior wall facing the human body is insufficient. At the same time, the wall temperature is not closely related to the temperature field in the space, and the optical characteristics of automobile window glass have insufficient influence on thermal comfort of automobile personnel. Regarding the experimental data, since the experiment uses a subjective questionnaire, it is bound to be due to differences in age, gender, cold tolerance, etc. At present, there is no psychological scale on thermal comfort to support the reliability and validity of the questionnaire. This is also one of the problems that currently exists.

Thirdly, for the automotive field, thermal comfort of the cab in a non-uniform, high-transient environment is still far from fully understood, and there is no universally accepted theory. There is no established industry specification, including test methods, evaluation indicators, etc., and there is currently no international standard that can accurately assess thermal comfort specific to the vehicle's environmental space. The current state of the art is methodologically inconsistent.

Lastly, from aspect of energy saving in car air conditioning, future development prospects of electric vehicles will be very good. To improve energy economy of electric vehicles and reduce the attenuation of low-temperature heating performance, three heat pump air conditioning system solutions for low temperature environments are proposed and analyzed:

(1) Waste heat recovery: Waste heat from batteries, motors and electronic control systems is recycled, and the energy consumption of whole vehicle is optimized while improving performance of heat pump air conditioning system.

(2) Steam jet heat pump air conditioning system: steam jet heat pump air conditioning system of R1234yf refrigerant was tested and studied. Results show that heating COP of heat pump system with steam injection is about 10%–30% higher than that of the heat pump system without steam injection, and the lower the ambient temperature, the more obvious the improvement of heating COP.

(3) CO_2 refrigerant heat pump air conditioning system: Studies have shown that due to the characteristics of CO_2 refrigerant, heat pump system can heat stably and effectively at ambient temperature −20 °C. It is concluded that the current use of steam jet heat pump air conditioning system is an effective means to solve the low-temperature heating of new energy electric vehicles, and in the future, the use of natural refrigerant CO_2 is an inevitable trend. For electric vehicles, targeting specific small body areas with high temperature sensitivity and direct contact heating solutions (resistance heating) can improve thermal comfort and reduce energy consumption at the same time. Therefore, research of new electric vehicle seat heating strategies and development and use of thermal sensitivity test devices are one of the future development trends.

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