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Thermal Comfort Models' Applicability to Automobile Cabin Environments

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ABSTRACT: This study investigates the performance of vehicle air conditioning systems by analyzing air supply temperature and velocity across different vents. Using data from a series of experiments, the research examined how side and foot vents behave under various A/C settings. The findings revealed that side vents delivered warmer air compared to foot vents, with temperatures stabilizing at approximately 40°C and 33°C, respectively, after an initial cooling phase. The study also noted a consistent 6°C temperature difference between the side and foot vents when the A/C was set to 22°C, indicating a deliberate thermal stratification within the cabin. The air supply velocity was higher at the foot vents, which became relatively stable after 30 minutes despite minor fluctuations. These results provide insights into the design and performance of vehicle air conditioning systems, emphasizing the importance of balancing temperature and airflow to enhance passenger comfort.

KEYWORDS: Indoor environment, Thermal comfort, Vehicular environment, Thermal comfort evaluation method, heating seat, personal comfort system, Vehicle cabin, Thermal environment.

I. INTRODUCTION

Research on thermal comfort in indoor environments has a long history, beginning with Fanger's thermal balance model proposed in the 1970s. This model laid the groundwork for the Predicted Mean Vote (PMV) index, which is used to assess thermal comfort in controlled environments. While the PMV index has been widely applied in climate rooms and HVAC systems globally, its applicability to car interiors has been limited. The compact and complex environment within vehicles, influenced by factors such as radiation, convective heat transfer, and varying environmental conditions across different body parts, necessitates specialized methods for evaluating thermal comfort in cars.

As industrialization has progressed, the use of automobiles has become more prevalent, leading to a growing focus on balancing two seemingly opposing goals: energy efficiency and passenger thermal comfort. Researchers are now concentrating on strategies to optimize the thermal environment inside vehicles while minimizing energy consumption to maintain good driving performance [1].

Air conditioning (A/C) is crucial for enhancing passenger comfort, but in the shift from traditional internal combustion engine (ICE) vehicles to electric vehicles (EVs), A/C systems account for a significant portion—60% to 70%—of the energy used by auxiliary systems. Consequently, using A/C has a considerable impact on the range of EVs. To address this, energy-saving strategies for EV A/C systems have evolved from merely optimizing system components to focusing on methods that improve environmental control within the passenger compartment [2]. For example, reducing A/C demand through zoned and individualized control systems has become a key approach to conserving energy while maintaining comfort.

The automotive industry is currently undergoing a significant transformation as it shifts towards new mobility concepts. The push to reduce local pollution has driven manufacturers to replace traditional internal combustion engine vehicles with electric vehicles. This change requires a re-evaluation of how thermal comfort is managed, as the energy used to maintain comfort directly affects the range of electric vehicles. Consequently, recent research in thermal comfort has intensified, focusing on developing technologies that maximize comfort within vehicle cabins while minimizing energy consumption.

In contrast to building environments, vehicle passenger compartments are characterized by their small and intricate space, which leads to highly non-uniform and transient airflow patterns. The distribution of the thermal-fluid field within these compartments dictates the heat transfer between the environment and passengers, making it difficult to predict and enhance the thermal conditions for optimal passenger comfort. Early research in this area was constrained

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by experimental limitations and primarily relied on numerical methods and simplified models to test and analyze interior heat flow fields [3,4].

Automotive environments differ significantly from building environments due to their compact and confined nature, where passengers are seated for extended periods. Unlike building environments, car cabins often experience highly variable and uneven thermal conditions. This variability is primarily due to the use of air conditioning and the effects of solar radiation.

Sevilgen [5] developed a three-dimensional model of a vehicle cabin to analyze airflow and heat transfer during transient heating periods. By applying constant heat flux boundary conditions to the manikin surfaces, the study found that the flow and temperature fields stabilized after about 30 minutes, revealing non-uniform temperature distributions within the cabin and on the manikin. Alahmer et al. [6] used hot soaking experiments combined with thermography to show that thermal non-uniformities in the passenger compartment result from high localized air velocities, uneven air temperature distribution, solar flux, and radiation heat from surrounding interior surfaces. In cars, the level of convective heat transfer between passengers and their surroundings is influenced by air velocities and temperature differences. Factors such as the placement of air vents, their proximity to passengers, and varying temperatures of the air they blow contribute to this uneven thermal distribution. For example, in winter, the air directed at the feet is typically warmer than the air from vents on the dashboard. Additionally, during summer, some body parts may experience significant radiative heat exchange due to direct solar radiation, while non-uniform interior wall temperatures and conductive heat exchange with seats (whether heated or ventilated) can further contribute to uneven thermal conditions. Bandi [8] conducted a 3D transient numerical simulation to examine how changes in the vertical guide vane angle affect temperature and airflow distribution under solar radiation, finding significant low-frequency oscillations (around 50 seconds) in the flow field, and highlighting the transient nature of cabin airflow. Zhang et al. [9] performed an outdoor parking temperature rise test with an SUV, providing boundary conditions and validation data for numerical simulations, and proposed an index to evaluate the average cooling rate. Thermal comfort is generally defined as the state of mind in which a person feels satisfied with the thermal environment in their occupied space [10]. Many trips cover distances of less than 18 km and last between 15 to 30 minutes, leading to frequent changes in thermal conditions. As a result, research on thermal comfort in car cabins should consider these transient conditions to accurately reflect the actual comfort levels experienced by passengers.

Thermal comfort is defined in general as the condition of mind that expresses satis-faction when considering the thermal environment in an occupied zone. The human body thermoregulatory model can theoretically study the heat exchange between the body and the surrounding environment, the human body's own thermal characteristics and the thermal responses. The human body with a model of six segments and introduced feedback mechanisms into the human thermophysiological regulation process. The Fiala model builds on this foundation by dividing the human body into 15 segments, categorized into passive and active systems, and is able to predict the thermal response in both steady-state and transient conditions. Compared with the Stolwijk model, the Berkeley Comfort Model, with its unlimited body segments and improved blood flow model, can better describe the physiological differences between individuals and predict the human responses to thermal environments, and can be widely used in transient and non-homogeneous environments. To predict human thermal comfort in transient non-uniform thermal environments such as automobiles, a thermal comfort tool that includes a 126-segment sweating manikin, a finite element physiological model of the human body, and a psychological model based on human testing to transfer data from the physiological model to the psy- chological model to predict both local and overall thermal comfort. The human thermophysiological regulation model analyzes the human body temperature regulation process through physiological data, so as to determine the heat exchange between body segments and the environment. There are many factors affecting the human body's thermal comfort and the relationship is complex, for the evaluation of comfort is mainly divided into objective and subjective evaluation.

II. LITERATURE REVIEW

Gabriel Crehan (2020) The study found that body parts have varying thermal comfort expectations depending on the overall thermal environment. For example, even in very hot conditions, the pelvis should only be lightly cooled to avoid significant discomfort. Innovative heating and cooling strategies can enhance thermal comfort in vehicles while also minimizing energy consumption. The UCB thermal sensation and comfort models offer an alternative to the traditional PMV standard, particularly for exploring cost-effective and localized solutions in electric vehicles. In this study, participants' thermal comfort ratings were recorded while they experienced transient and near-uniform conditions in simulated automotive environments. These ratings were compared with predictions from the UCB Zhang model,

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revealing a good qualitative match, especially in warmer conditions. Building on these findings, a parametric investigation was conducted to uncover trends in thermal preferences for different body parts. The research identified key body areas that need special attention for different thermal conditions—very cold, cold, neutral, warm, and very hot. It also provided recommendations for comfort-focused and energy-efficient strategies based on these insights [11].
Rui Wang (2023) As the automobile industry rapidly evolves and consumer expectations rise, there is an increasing demand for vehicles that offer not only energy efficiency, safety, and affordability but also superior indoor environments and enhanced thermal comfort. To address these needs, a new thermal comfort evaluation method tailored for Chinese consumers has been developed. This method establishes a relationship between equivalent space temperature and thermal sensation by gathering data on how people perceive temperature in various environments. It includes a comprehensive evaluation approach that considers both whole-body and local thermal comfort for adult Chinese males and females. The research revealed that women generally have a lower tolerance for thermal sensations and a smaller thermal comfort zone compared to men. To test the accuracy of this evaluation method, a typical non-uniform vehicle environment was used. The study involved measuring the local and whole-body equivalent space temperatures of the co-driver seat using a warm dummy, which allowed for the prediction of thermal sensation values. These predictions were then compared with subjective experiences reported by real subjects under similar conditions. The correlation between predicted and subjective thermal sensations was found to be 0.911, with statistical significance at 0.002, demonstrating that the method can accurately predict thermal sensations with a deviation of just 0.3 points. This confirms the reliability of the proposed evaluation method for assessing thermal comfort in vehicles and provides a useful tool for predicting environmental thermal comfort in automotive settings [12].

N. Martinho (2004) The study described in this article aimed to analyze airflow within a vehicle cabin, specifically one with the dimensions and design typical of a multi-purpose vehicle (MPV), to assess thermal comfort using the equivalent temperature index. Experiments were conducted using a full-scale laboratory model of the car cabin, which featured a simplified geometry. The tests varied conditions by including or excluding a thermal mannequin, adjusting air velocities and temperatures, and modifying the air inlet settings. Equivalent temperature values were measured for different parts of the body in two ways: through readings from the thermal mannequin and by assessing physical airflow parameters, such as air velocity and temperature. To map these airflow parameters within the cabin, a scanning process was employed using a traversing mechanism equipped with eight low-velocity thermal anemometer probes, which were controlled externally. Using the data collected from various points near the thermal mannequin, equivalent temperature profiles were calculated during tests conducted without the mannequin [14].

III. METHODOLOGY

Before starting the experiment, participants spent 30 minutes in a preparation room set to 26°C with 50% relative humidity. This time was used to ensure they were in a comfortable physical and mental state and that their thermal sensations were neutral.

During the main experiment, which lasted for one hour, the vehicle remained stationary. Two participants were seated in the driver’s and passenger’s seats while their skin temperatures and the thermal conditions within the vehicle cabin were monitored using thermocouples. Participants also filled out subjective questionnaires to report their experiences of local and overall thermal comfort.

The core of the experiment was carried out in a life-size model of a vehicle cabin, which was designed with a simplified geometry to replicate typical conditions in a real car. During the tests, the vehicle remained stationary to isolate the effects of the air conditioning system without interference from external factors. The cabin was equipped with specific vent configurations, including side vents (air vents 1 and 2) located by the driver’s and passenger’s windows and foot vents (air vents 3 and 4) positioned at the foot areas of both seats. Air supply temperatures and velocities from these vents were measured using thermocouples and thermal anemometer probes, respectively.

The experiment was conducted in three phases, as detailed in Table 1, with a 40-minute break between each phase. During these breaks, the vehicle's thermal environment was reset to its initial conditions using physical cooling methods. The setup of the experiment is illustrated in Figure 1.

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Table 1: Experimental conditions

Case	A/C Setting Temperature	Heating Pad Setting Temperature
1	26 °C	no
2	22 °C	33 °C
3	26 °C	33 °C

Figure 1: (a) Experiment vehicle. (b) Experiment subject. (c) Measured points in the cabin.

Environmental Parameters

The air and wall temperatures in the passenger compartment were measured with thermocouples TTK-24-SLE (±0.4% special limits of error). The air temperature measure- ment points included four air outlet temperatures, air temperatures at the breathing points, chest, and feet of the four seating positions, and outside ambient temperatures, and the wall temperatures measurement points included the instrument panel, the front windshield, and the roof of the vehicle. As shown in Figure 2, to study the effect of local heating devices on thermal sensation and thermal comfort in cold weather, the heating pads were placed on the driver's and passenger's seats, each with a rated power of 40 W and a size of 280 mm 380 mm, and five thermocouples were arranged on the pads, respectively, to measure the uniformity of the temperatures and the thermal storage situation during the experiment. Measurement of air velocity of the outlets using the Emprise im-peller anemometers with rated uncertainty of 0.5% of the readings. Temperature and air velocity data were collected with the imc SPARTAN-T128-CAN.

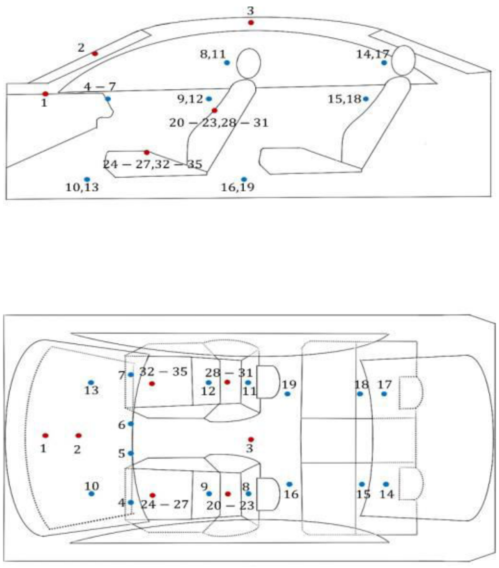

Figure 2: Experimental measuring points in the cabin.

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Human Body Temperature

The thermocouple TT-K-36-SLE (0.4% special limits of error) was used to measure the occupant's body temperature. The human body was divided into 17 sections, with three measurement points on the back, the right under-thigh and the left under-thigh in contact with the heating pad, and the other sections were divided into the head, the chest, the right upper arm, the right lower arm, the right hand, the left upper arm, the left lower arm, the left hand, the right upper-thigh, the right calf, the right foot, the left upper-thigh, the left calf, and the left foot, and the temperature measurement points were arranged at the center of each section with adhesive tapes conducting heat. Mean skin temperature (MST) is an important parameter reflecting the status of heat exchange between the human body and the environment, to show the effect of localized heating of the human body on the overall skin temperature, 13-point formula. was chosen to calculate the MST, and the 13-point calculation method involves the temperature measurement parts and weighting factors as shown in Equation (1).

$$T_{sk} = 0.06T_{head} + 0.07T_{R,upperarm} + 0.05T_{L,forearm} + 0.0225T_{L,hand} + 0.0225T_{R,hand} + 0.18T_{L,back} + 0.2T_{L,chest} + 0.1025T_{R,upper-thigh} + 0.1025T_{L,under-thigh} + 0.0625T_{R,calf} + 0.0625T_{L,calf} + 0.0325T_{R,foot} + 0.0325T_{L,foot}$$

IV. RESULTS

The measurement of the external ambient temperature is shown in Figure 3, where the range of the external ambient temperature is 0.8–1.5 ◦C.

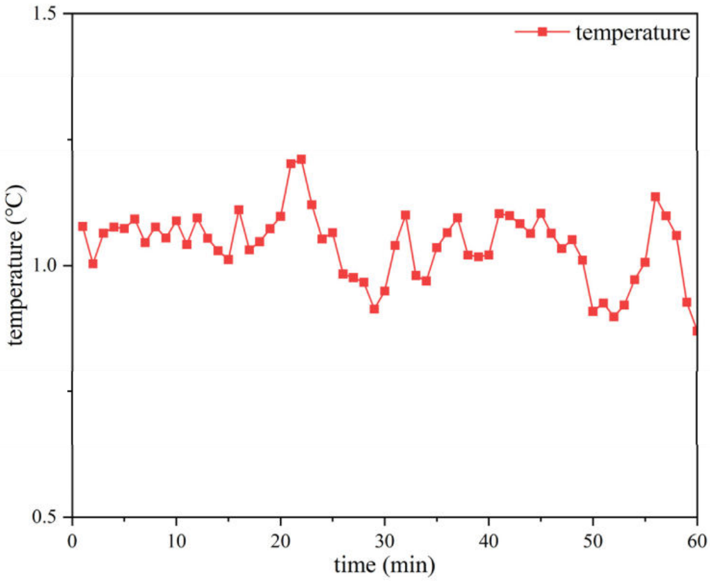

Figure 3: External ambient temperature.

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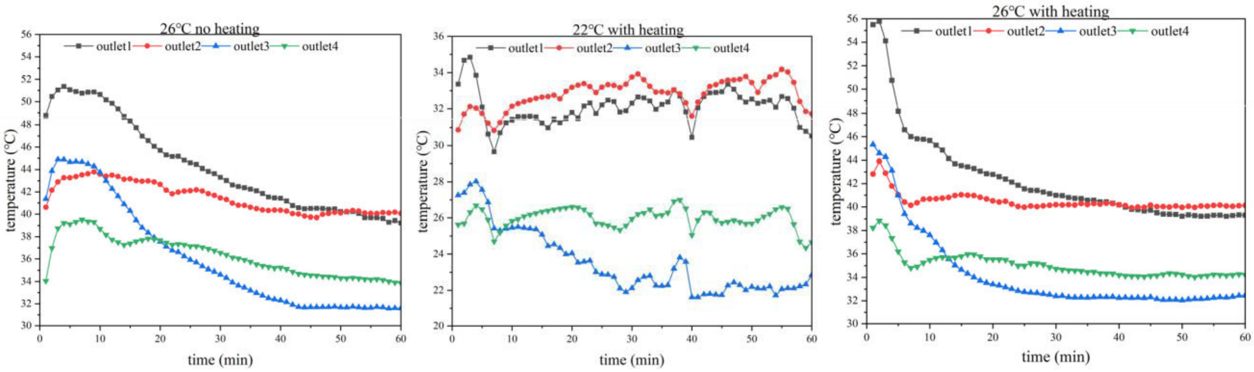

Figure 4: Air supply temperature at different heating modes. (a) 26 ◦C no heating. (b) 22 ◦C with heating. (c) 26 ◦C with heating.

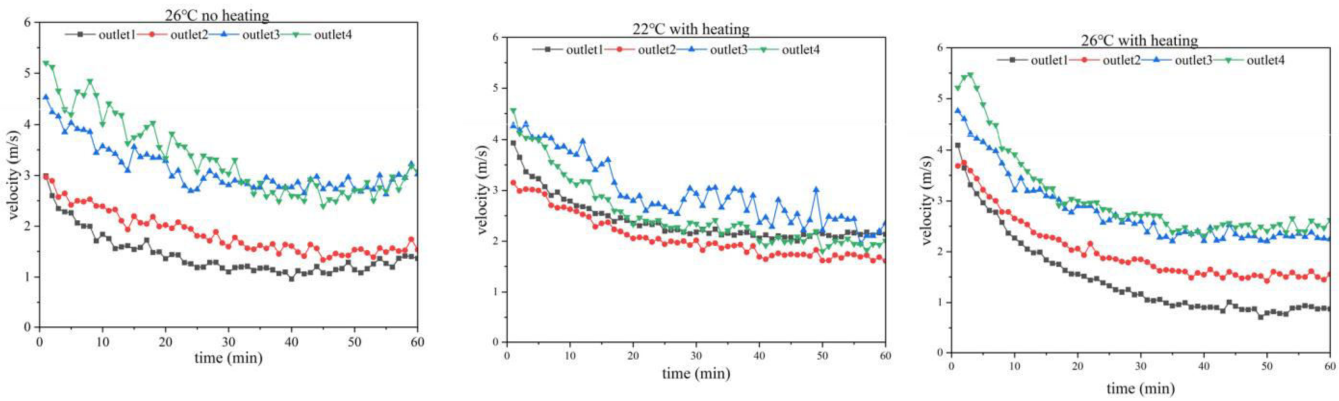

Figure 5: Air supply velocity at different heating modes. (a) 26 ◦C no heating. (b) 22 ◦C with heating. (c) 26 ◦C with heating.

Figures 4 and 5 illustrate the average air supply conditions for different test modes, focusing on air supply temperature and velocity. Air vents 1 and 2 are positioned by the windows on the driver's and passenger's sides, while air vents 3 and 4 are located at the foot area for both seats.

Under various test conditions, the air supply temperature at the side vents was consistently higher than at the foot vents. When the auto A/C was set to 26°C, the air temperature at the side vents initially dropped sharply in the first 20 minutes, eventually stabilizing around 40°C. In contrast, the temperature at the foot vents stabilized at about 33°C. When the A/C was set to 22°C, the temperature difference between the side vents and the foot vents was approximately 6°C. Regarding air supply velocity, the foot vents delivered air at a higher speed compared to the side vents. After 30 minutes, the air supply speed at both locations became relatively stable, although some fluctuations were still observed.

V. DISCUSSION

The data presented in Figures 4 and 5 offer valuable insights into the performance of vehicle air conditioning systems under different conditions, highlighting how air supply temperature and velocity vary across different vents. The higher temperatures observed at the side vents compared to the foot vents under all tested conditions suggest a design choice aimed at providing greater warmth to the upper body, which is typically more sensitive to temperature changes. The significant drop in air supply temperature from the side vents during the first 20 minutes of the experiment, followed by stabilization at around 40°C, indicates an initial cooling phase that likely aligns with the system's start-up dynamics. In contrast, the foot vents, which stabilized at a lower temperature of about 33°C, appear to provide a steadier and cooler airflow, possibly to maintain comfort at the lower extremities. When the A/C was set to 22°C, the consistent 6°C difference between the side and foot vents highlights the thermal stratification within the cabin, which could affect passenger comfort depending on their seating position. The air supply velocity data reveal that the foot vents deliver air at a higher speed than the side vents, which is consistent with the need for more rapid air movement to balance

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temperature disparities and enhance overall comfort. The stabilization of air supply speed after 30 minutes, despite some remaining fluctuations, reflects the system's adjustment period as it seeks to maintain consistent airflow and temperature control. These findings underscore the complexities of managing thermal comfort in vehicle cabins, where variations in air supply temperature and velocity must be carefully balanced to meet passenger needs and preferences effectively.

VI. CONCLUSION

The analysis of air supply conditions in vehicle cabins reveals significant insights into how temperature and velocity variations impact passenger comfort. The observed higher temperatures at the side vents compared to the foot vents suggest a design strategy to address the thermal comfort of the upper body, which is more sensitive to temperature fluctuations. The initial rapid cooling followed by stabilization at the side vents, and the consistent lower temperature at the foot vents, indicate the system's effective adaptation to different comfort needs. The 6°C temperature difference between the side and foot vents at lower A/C settings underscores the importance of considering thermal stratification within the cabin. Additionally, the higher air supply velocity at the foot vents aligns with the need for more dynamic airflow to achieve balanced thermal conditions. Despite some fluctuations, the stabilization of air velocity after 30 minutes reflects the system's capability to maintain comfort over time.

Experiments were conducted to assess how these factors influence thermal comfort in both the driver's and passenger's seats. The results showed that side vents, positioned near the windows, delivered warmer air compared to the foot vents, which are located at the lower part of the cabin. Specifically, air temperatures at the side vents stabilized around 40°C after an initial cooling period, while temperatures at the foot vents stabilized at about 33°C. When the A/C was set to 22°C, a consistent temperature difference of approximately 6°C between the side and foot vents was observed, illustrating the thermal gradient within the cabin. Furthermore, the air supply velocity was higher at the foot vents than at the side vents, which reached a relatively stable rate after 30 minutes, although some fluctuations were noted. This study highlights the complexities involved in optimizing vehicle air conditioning systems to achieve balanced thermal comfort. It underscores the need for careful design and calibration of temperature and airflow settings to address varying passenger comfort needs effectively. The findings suggest that both temperature control and airflow management are crucial for enhancing overall passenger comfort in vehicle cabins.

REFERENCES

1. Zhang, Z.; Wang, J.; Feng, X.; Chang, L.; Chen, Y.; Wang, X. The solutions to electric vehicle air conditioning systems: A review. Renew. Sustain. Energy Rev. 2018, 91, 443–463.
2. Marshall, G.J.; Mahony, C.P.; Rhodes, M.J.; Daniewicz, S.R.; Tsolas, N.; Thompson, S.M. Thermal Management of Vehicle Cabins, External Surfaces, and Onboard Electronics: An Overview. Engineering 2019, 5, 954–969.
3. Komoriya, T. Analysis of vehicle passenger compartment ventilation using experimental and numerical model. SAE Trans. 1989, 98, 392–400.
4. Lin, C.-H.; Lelli, M.A.; Han, T.; Niemiec, R.; Hammond, D.C. An Experimental and Computational Study of Cooling in a Simplified GM-10 Passenger Compartment. In Proceedings of the SAE International Congress & Exposition, Detroit, MI, USA, 25 February–1 March 1991.
5. Sevilgen, G.; Kılıç, M. Transient numerical analysis of airflow and heat transfer in a vehicle cabin during heating period. Int. J. Veh. Des. 2010, 52, 144–159.
6. Alahmer, A.; Abdelhamid, M.; Omar, M. Design for thermal sensation and comfort states in vehicles cabins. Appl. Therm. Eng. 2012, 36, 126–140.
7. Torregrosa-Jaime, B.; Bjurling, F.; Corberán, J.M.; Di Sciullo, F.; Payá, J. Transient thermal model of a vehicle's cabin validated under variable ambient conditions. Appl. Therm. Eng. 2015, 75, 45–53.
8. Bandi, P.; Manelil, N.P.; Maiya, M.P.; Tiwari, S.; Thangamani, A.; Tamalapakula, J.L. Influence of flow and thermal characteristics on thermal comfort inside an automobile cabin under the effect of solar radiation. Appl. Therm. Eng. 2022, 203, 117946.
9. Zhang, Y.; Li, Z.; Liu, S.; Wang, G.; Chang, H. A Study of Passenger Car Cabin Pre-Ventilation under the Sun. Energies 2023, 16, 7154.
10. ANSI/ASHRAE Standard 55-2013; Thermal Environmental Conditions for Human Occupancy. ASHRAE: Peachtree Corners, GA, USA, 2013.
11. Rachelle Abou Jaoude, Ilango Thiagalingam, Roch El Khoury, Gabriel Crehan, Berkeley thermal comfort models: Comparison to people votes and indications for user-centric HVAC strategies in car cabins, Building and Environment, Volume 180, 2020, 107093, ISSN 0360-1323, https://doi.org/10.1016/j.buildenv.2020.107093.

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| Volume 6, Issue 10, October 2023 |

| DOI:10.15680/IJMRSET.2023.0610017 |

12. Chaoqing Feng, Fengge Ma, Rui Wang, Wei Li, Jianfeng Gao, A thermal comfort evaluation on vehicular environments based on local human body thermal sensations, Results in Engineering, Volume 17, 2023, 100907, ISSN 2590-1230, https://doi.org/10.1016/j.rineng.2023.100907.
13. V. Mohan & S. Senthilkumar, "IoT based fault identification in solar photovoltaic systems using an extreme learning machine technique", Journal of Intelligent & Fuzzy Systems, vol. 43, no. 3, pp. 3087-3100, 2022. DOI: 10.3233/JIFS-220012.
14. Martinho, N. & Gameiro da Silva, Manuel & Ramos, João. (2004). Evaluation of thermal comfort in a vehicle cabin. Proceedings of the Institution of Mechanical Engineers Part D Journal of Automobile Engineering. 218. 159-166. 10.1243/095440704772913936.
15. S. Senthilkumar, V. Mohan, S. P. Mangaiyarkarasi & M. Karthikeyan, "Analysis of Single-Diode PV Model and Optimized MPPT Model for Different Environmental Conditions", International Transactions on Electrical Energy Systems, Volume 2022, Article ID 4980843, 1-17 pages, January 2022, DOI: https://doi.org/10.1155/2022/4980843.

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