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Review Of Human Thermal Comfort In Passenger Car Cabins: A Synergistic Analysis Of CFD Simulations And Experimental Testing

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ABSTRACT
Thermal comfort significantly impacts passenger satisfaction and overall driving experience in modern vehicles. With the increasing emphasis on energy efficiency and sustainability, optimizing vehicle HVAC systems has become critical. Computational Fluid Dynamics (CFD) simulations, combined with experimental testing, offer a robust framework to analyze and enhance thermal comfort in passenger car cabins. This review explores advancements in human thermal comfort studies, focusing on CFD simulations and experimental methodologies. The paper discusses key metrics, such as Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD), and examines how airflow, temperature gradients, and radiant heat affect passenger comfort.
Additionally, this review highlights the role of advanced simulation tools like ANSYS Fluent, OpenFOAM, and STAR-CCM+ in predicting airflow patterns, temperature distribution, and heat transfer dynamics. Case studies showcasing successful integration of CFD and real-world testing are presented, providing insights into their applications in optimizing vent placement, airflow directionality, and thermal zoning. Challenges, such as the computational complexity of multi-parameter simulations and discrepancies between model predictions and real-world outcomes, are also addressed.

Keywords: *Thermal Comfort, CFD, Human Comfort, Automotive, PMV, PPD*

INTRODUCTION

Human thermal comfort is a complex phenomenon influenced by physical, physiological, and psychological factors. It refers to the condition in which individuals feel thermally satisfied and do not desire changes in their immediate thermal environment. In vehicle cabins, thermal comfort becomes even more critical due to the enclosed space, exposure to external climate conditions, and energy constraints of automotive HVAC systems. Researchers and engineers have developed various frameworks to measure, evaluate, and improve thermal comfort, with a particular focus on factors such as air temperature, humidity, airflow, and radiation.

Thermal comfort in passenger cars is not just a matter of convenience but a vital aspect of passenger safety, health, and satisfaction. An inadequately designed HVAC system can result in discomfort, fatigue, and, in extreme cases, health issues such as hypothermia or heat stress. Moreover, thermal comfort is crucial for maintaining driver alertness, which directly impacts road safety. With the rapid evolution of the automotive industry, particularly with electric and autonomous vehicles, the need for efficient and adaptable HVAC systems has become paramount. It is influenced by several factors, including air temperature, humidity, air velocity, radiant temperature, clothing insulation, and metabolic rate. In vehicles, achieving thermal comfort is challenging due to the dynamic nature of the cabin environment, where external conditions such as sunlight, wind, and ambient temperature fluctuate continuously. Modern HVAC systems incorporate zonal climate control, where different temperature settings are maintained for individual passengers. They also use eco-friendly refrigerants and energy-efficient designs to reduce environmental impact.

1. Literature Review

Koelblen et. al. [1] The development of thermal comfort indices such as PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied) has revolutionized how passenger comfort is assessed in vehicle cabins. These indices quantify thermal sensations based on six environmental and personal variables, including air temperature, humidity, air velocity, and clothing insulation. Studies have confirmed their reliability in static environments; however, challenges arise in transient conditions like vehicle interiors, where temperature and airflow fluctuate dynamically. Researchers emphasize that integrating these indices into CFD simulations enables precise prediction of comfort levels across different zones within the cabin. The inclusion of subjective factors, such as personal preferences and thermal history, remains an area for further exploration.

Lee et. al. [2] Adaptive thermal comfort models have emerged as alternatives to static models, particularly for applications in vehicles where environmental conditions are subject to rapid changes. These models consider behavioral adaptations made by passengers, such as adjusting vents or modifying seat positions, in response to discomfort. The use of adaptive models has shown significant improvements in predicting comfort under transient scenarios, such as the heat build-up in a parked car or rapid cooling during air conditioning. Researchers have validated these models using experimental and computational methods, revealing their potential to enhance HVAC designs. Incorporating adaptive features into control systems is identified as a critical step toward personalized thermal comfort solutions.

Adhikari et. al. [3]Studies focusing on real-time applications of thermal comfort metrics emphasize their importance in advanced HVAC systems. Metrics like Standard Effective Temperature (SET) and Equivalent Temperature (ET) are particularly effective in assessing the spatial and temporal variations within vehicle cabins. Experimental setups and CFD simulations have demonstrated that these metrics accurately represent the thermal sensation across different seating positions. Researchers highlight that real-time implementation of these metrics in HVAC systems can lead to responsive designs that adapt to passenger needs. Despite their effectiveness, challenges in integrating these metrics into predictive algorithms for autonomous climate control systems persist.

Zhang et. al. [4] Air distribution systems in vehicle cabins significantly influence passenger thermal comfort. Computational and experimental studies have demonstrated that improper vent placement or airflow patterns can lead to uneven temperature distribution and discomfort. Research has shown that targeted airflow from vents, combined with proper temperature control, can significantly enhance comfort levels. Using CFD simulations, researchers have optimized vent geometries and placements to achieve uniform airflow across all seating positions. However, achieving a balance between energy efficiency and comfort remains a challenge, particularly under extreme environmental conditions.

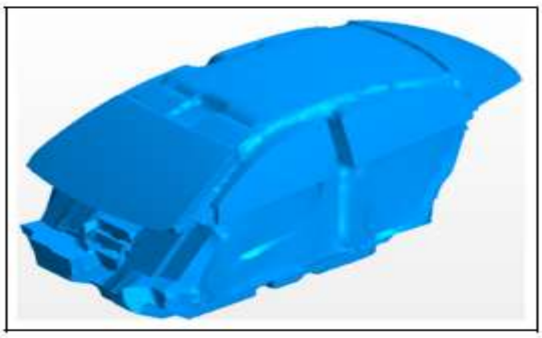

Figure 1: Schematic model for CFD analysis

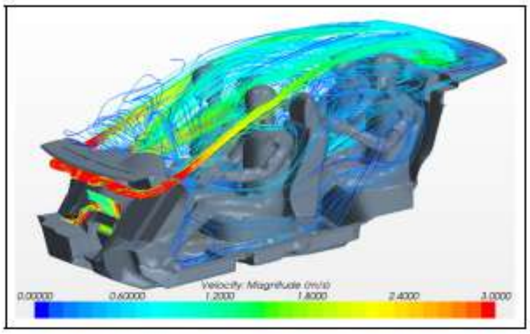

Figure 2: Streamline flow inside cabin

The direction and velocity of air have a substantial impact on human comfort. In the summer months, the air velocity experiences a slight increase, contributing to the cooling process. However, excessive wind that is directed directly at the individual may be uncomfortable. The ideal airflow velocity is approximately 0.25 m/s. The air is considered fresh when the flow velocity reaches 0.15 m/s. Nevertheless, individuals will develop apathy, even when the ambient temperature is appropriate and the flow velocity is exceedingly sluggish. Dispersion of the occupant's body surface velocity. The velocity of the occupants' front and posterior bodies is primarily between 0.3 and 0.5 m/s, demonstrating a greater degree of uniformity. The wind velocity is slightly higher than the recommended level of comfort, primarily due to the rapid chilling that occurs during the summer. Although the pilot and co-pilot can manually adjust the grid's inclination to modify the wind direction to some extent, the headwind they face is excessively strong due to the positioning of the front and centre outlets. The viability of utilising computational fluid dynamics (CFD) numerical simulation was demonstrated by the error of less than 5% when comparing the simulation and experimental findings of body surface temperature. The effectiveness of utilising numerical simulation for computational fluid dynamics (CFD) was validated by the observation that the error remained below 5%.

Omar et. al [5] Humidity plays a critical role in human thermal comfort by influencing the body's ability to dissipate heat through sweating. Studies have shown that high humidity levels in vehicle cabins reduce evaporative cooling, leading to discomfort even at moderate temperatures. On the other hand, low humidity can cause dryness in the skin and eyes. CFD-based research has modeled the effect of varying humidity levels on comfort indices, revealing the need for precise control in HVAC systems. Advanced desiccant materials and humidity control strategies have been proposed to address these issues effectively.
Jícha et. al. [6] The effect of radiative heat transfer from vehicle surfaces, such as windows and dashboards, has been extensively studied in the context of thermal comfort. Research highlights that solar radiation through glazing materials significantly impacts the temperature distribution within the cabin. CFD models incorporating radiative heat transfer equations have been used to simulate these effects, leading to the development of advanced glazing technologies and reflective coatings. These studies suggest that minimizing radiative heat gain can reduce HVAC loads and enhance comfort simultaneously.

Iranzo et. al. [7] CFD simulations have proven instrumental in analyzing and optimizing airflow patterns within vehicle cabins. By using turbulence models like k-ε and Large Eddy Simulation (LES), researchers have visualized complex airflow dynamics, including vortex formation and dead zones. Studies show that uniform airflow distribution not only enhances thermal comfort but also reduces energy consumption. The integration of CFD results into HVAC design has led to innovations like multi-zone climate control systems, which provide customized comfort for individual passengers. However, the accuracy of these simulations heavily depends on mesh quality and boundary condition settings.

Ivanescu et. al. [8] Transient CFD simulations have enabled the study of rapidly changing thermal conditions in vehicle cabins, such as cooling upon starting the HVAC system or heating during engine warm-up. These studies have shown that dynamic temperature variations significantly affect passenger comfort, particularly during short

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trips. Researchers have developed algorithms to predict and mitigate these effects by optimizing airflow rates and vent placement. Experimental validation of transient simulations has confirmed their reliability, though challenges remain in reducing computational time for real-time applications.

Lee et. al. [9] CFD studies have extensively investigated how vent placement and geometry affect air distribution and thermal comfort in vehicle cabins. Research shows that improperly placed vents can create hot or cold spots, reducing overall comfort. Optimized vent configurations, developed through CFD simulations, ensure even air distribution across all seating zones. Studies have also examined adjustable vents and diffusers, which allow passengers to personalize airflow direction. Simulations reveal that such configurations improve thermal comfort indices while reducing energy consumption. Challenges persist in balancing airflow rates with noise levels, as excessive turbulence can lead to audible discomfort.

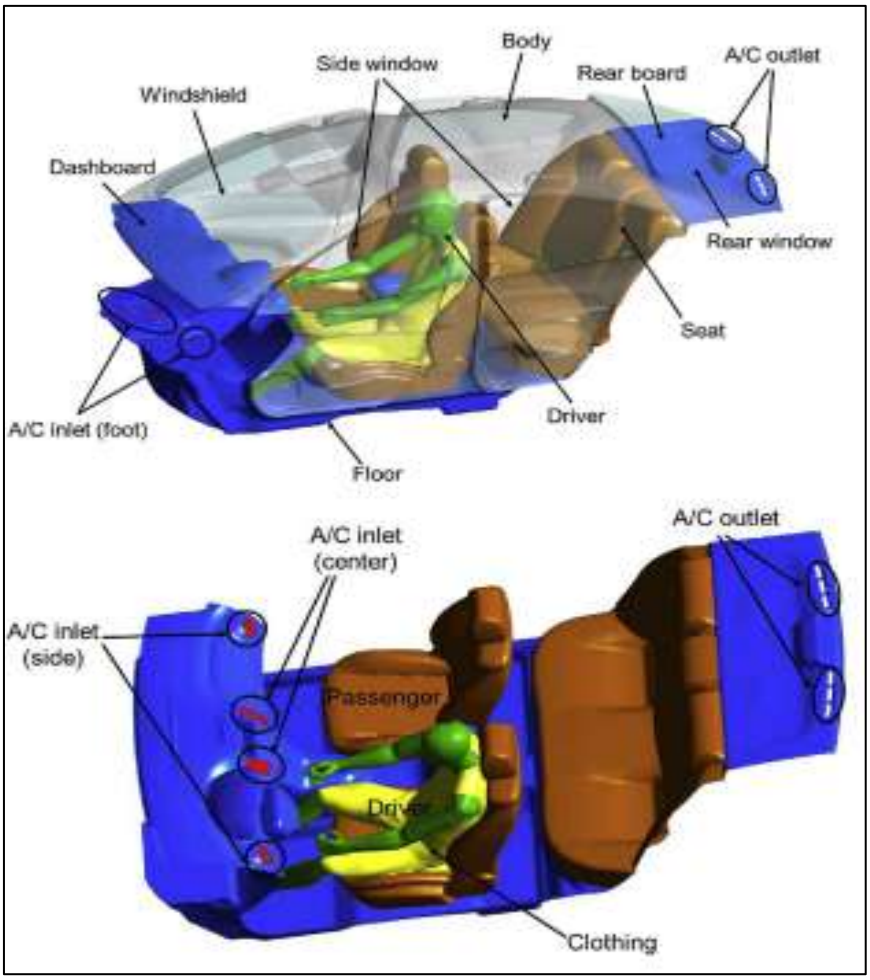

Figure 3: Computational model for passenger car [9]

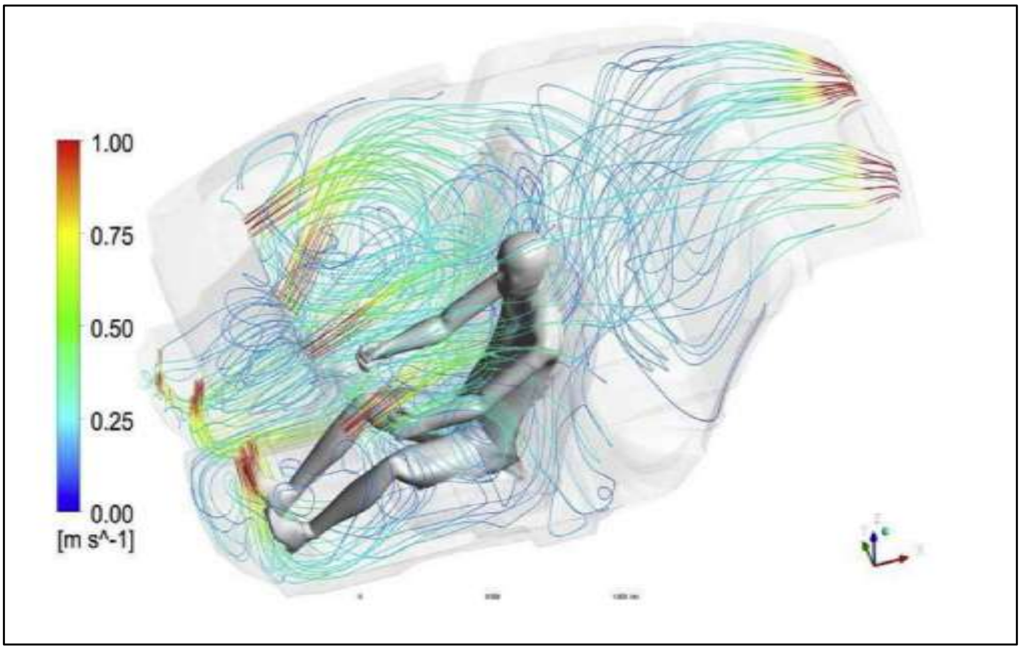

Figure 4: Streamline flow pattern obtained from CFD [9]

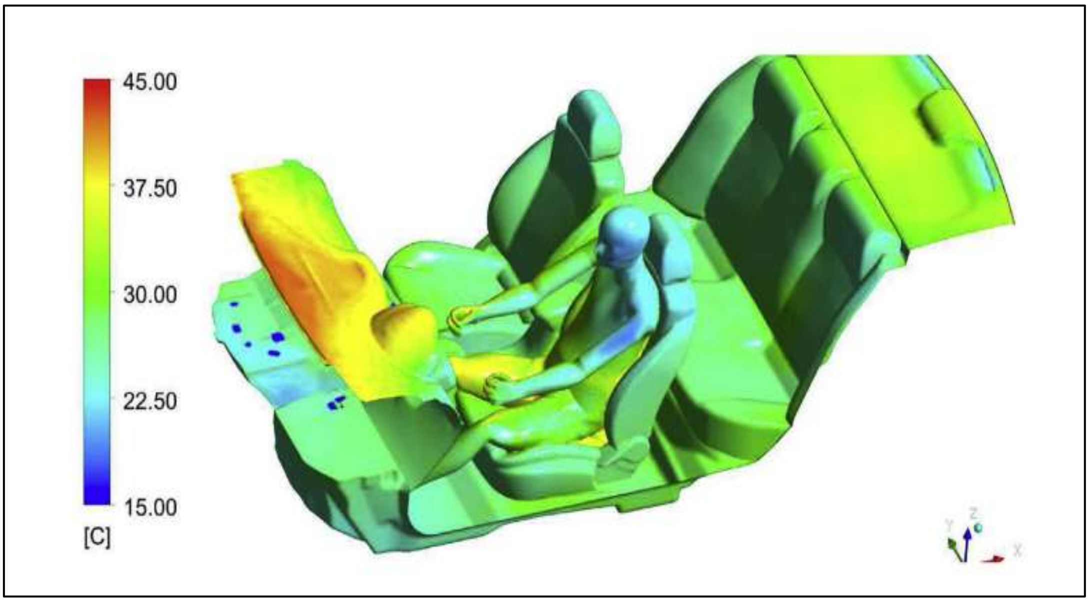

Figure 5: Surface temperature distributions obtained from CFD [9]

The temperature distribution observed in the R-Q100 scenario, which incorporated spectral radiation, demonstrated a marked improvement over the B-Q100 example, which excluded this factor, as indicated by the CFD results. This is the result of the R-Q100 example, which takes into account both absorbed and transmitted near-infrared solar radiation. This indicates that spectrum radiation needs to be considered to accurately forecast air temperature. The recirculation flow within the passenger compartment diminished as the inflow reduced, resulting in inadequate mixing of the cold air from the A/C inlets with the externally heated air. It was observed that the driver's right hand had a temperature approximately 30 degrees celsius higher than the left hand as a result of direct solar radiation and the angle of incidence.

Kim et. al. [10] Multi-phase CFD models have been applied to analyze the interaction of air, moisture, and heat transfer within vehicle cabins. These models simulate the effects of sweating, breathing, and clothing insulation on passenger thermal comfort. Research demonstrates that accounting for moisture transport improves the accuracy of thermal comfort predictions. For example, CFD simulations incorporating skin perspiration rates and evaporation have provided insights into HVAC system performance under humid conditions. Such studies pave the way for integrating moisture control technologies into modern vehicles, enhancing overall passenger well-being.

Psikuta et. al. [11] A growing number of individuals are using aeroplanes each year. However, pain is present in the majority of individuals during extended journeys. The absence of compartment temperature regulation is a substantial factor. Customising the air conditioning system to meet the thermal preferences of each passenger would enhance the overall comfort of the cabin. Consequently, aircraft necessitate their own air conditioning control system. In order to implement personal air conditioning that is customised to the individual's thermal sensibility, this research aims to clarify the optimal temperature setting in consideration of individual thermal sensation. A seat-type air conditioning system is recommended, which adjusts the temperature according to each region of the body. As a result, the thermal sensation index was utilised to determine the suitable degree of adjustment for temperature settings. Research indicated that passenger comfort increased when the temperature was modified by 2.5 ∘C in alignment with the thermal sensation scale. Furthermore, it was shown that individuals exposed to lower temperatures exhibit increased susceptibility to temperature variations. Customised air conditioning is feasible as a result of the distinctive thermal sensitivity characteristics of each individual. Conducting research on a system that autonomously predicts perceived temperature by utilising individual thermal sensitivity characteristics is essential for facilitating future advancements.

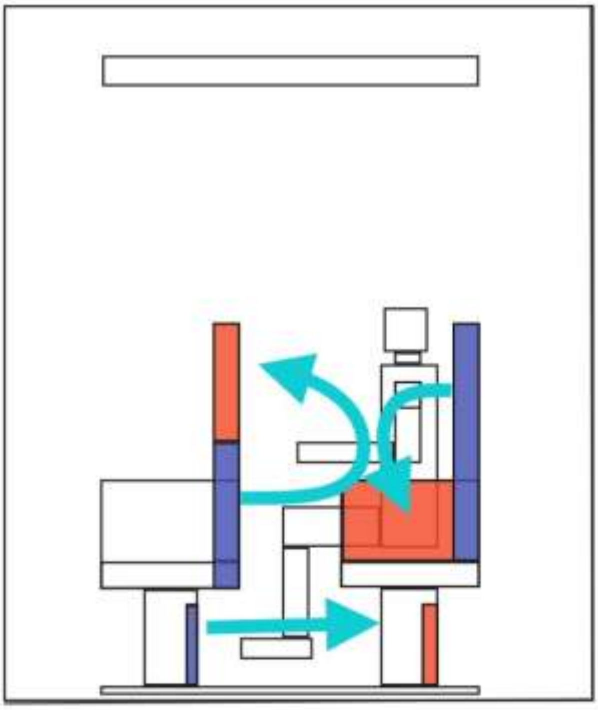

Figure 6: Predicted airflow with inlets (red-colored) and outlets (blue-colored)

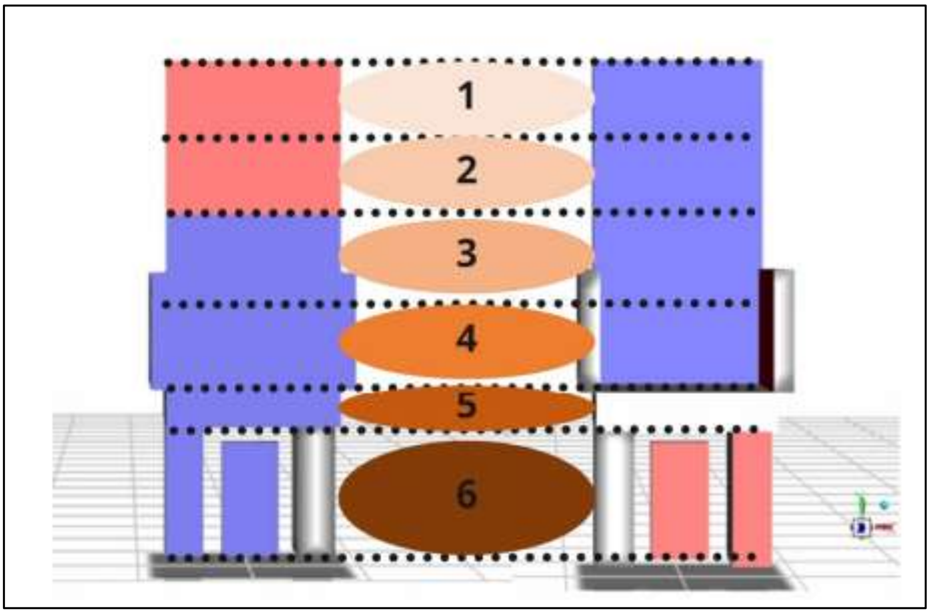

Figure 7: Inlets (red-colored) and outlets (blue-colored) for personal air-conditioning system; outlets are positioned in six different

The air conditioning system proposed in this study demonstrates a notable difference in the volume of ventilation provided to different body areas and its effect on temperature perception. The analysis concluded that the proposed air conditioning system requires enhancements to guarantee consistent ventilation across all areas of the body. Additionally, the subjective assessment was conducted in this study to determine the temperature sensation. The optimal method for minimising passenger discomfort involves the implementation of a system capable of autonomously detecting and responding to thermal sensations. Future research in this field should also incorporate a strategy for predicting thermal sensations that considers the thermal sensitivity characteristics. The adjustment of the optimal temperature setting may be modified based on the results of this investigation.

Jiang et. al. [12] Defining accurate boundary conditions is crucial for reliable CFD simulations of vehicle cabins. Studies have emphasized the importance of realistic inputs, such as external temperatures, solar radiation, and passenger heat loads, in producing meaningful results. Research has shown that inaccurate boundary conditions can lead to deviations between simulated and experimental results. Advanced methods, such as using weather data and thermal mannequins as boundary inputs, have improved the reliability of CFD models. However, integrating these complex inputs into simulation workflows remains a challenge.

Lee et. al. [13] Research has increasingly focused on the energy implications of HVAC system designs optimized using CFD. Simulations have demonstrated that efficient airflow distribution reduces the energy required to achieve thermal comfort. Studies also highlight the trade-offs between energy efficiency and passenger comfort, particularly under extreme climate conditions. Strategies such as zonal climate control and energy recovery ventilation have been proposed and validated through CFD, showcasing their potential to enhance both comfort and efficiency.

Duan et. al. [14] Extreme climate conditions, such as desert heat or Arctic cold, present unique challenges for vehicle HVAC systems. CFD models have been used to simulate these scenarios, revealing the limitations of traditional HVAC designs. Studies show that innovative solutions, such as phase-change materials and advanced insulation, can mitigate these effects. CFD simulations incorporating real-world climate data provide valuable insights into designing systems that maintain comfort under extreme conditions. Experimental validation of these models remains a critical step in ensuring their reliability.

Jazizadeh et. al. [15] Airflow recirculation zones can significantly impact the thermal comfort of passengers in vehicle cabins. CFD studies have identified areas where airflow stagnates, creating zones with higher or lower temperatures. Research shows that modifying vent placement or airflow direction can eliminate these recirculation zones. Simulations have also explored the use of active airflow management systems, such as movable louvers, to dynamically adjust airflow patterns. These innovations have been shown to improve comfort levels and reduce HVAC energy consumption.

Ugurlu et. al. [16] Thermal mannequins have been extensively used to validate CFD simulations and test HVAC systems under controlled conditions. Research highlights their effectiveness in mimicking human heat dissipation and measuring localized thermal comfort. Studies show that combining mannequin data with CFD results provides a comprehensive understanding of cabin thermal performance. Advances in sensor technology have improved the accuracy of mannequin-based testing, though challenges in replicating dynamic passenger movements persist.

Xia et. al. [17] Field tests conducted in actual driving conditions have provided critical insights into the performance of HVAC systems. Research shows that factors such as road speed, engine heat, and external weather significantly influence cabin comfort. Testing protocols have been developed to measure temperature and airflow across different seating zones during varied driving scenarios. These tests validate CFD predictions and reveal discrepancies caused by real-world factors not accounted for in simulations.

Za et. al. [18] Studies have compared passive cooling methods, such as ventilated seats, with active cooling provided by HVAC systems. Research demonstrates that combining these techniques enhances passenger comfort while reducing energy consumption. CFD simulations and experimental tests show that ventilated seats improve local airflow, reducing the load on the central HVAC system. However, challenges in integrating these systems without compromising cabin aesthetics remain an area of ongoing research.

Megri et. al. [19] Research has examined the rapid heat build-up in vehicle cabins parked under direct sunlight. Experimental studies show that cabin temperatures can exceed 60°C within minutes, posing significant risks to passengers. CFD simulations have been used to analyze heat transfer mechanisms, while experimental data validate these findings. Innovations such as reflective coatings, sunshades, and advanced glazing materials have been proposed to mitigate heat build-up.

Warey et. al. [20] Predicting thermal comfort within the asymmetric and dynamic thermal conditions of an automobile compartment is crucial for the advancement of energy-efficient heating, ventilation, and air conditioning (HVAC) systems. This study integrates high-fidelity Computational Fluid Dynamics (CFD) simulations with machine learning algorithms to predict the thermal comfort of vehicle occupants across diverse environmental conditions, glazing characteristics, and HVAC configurations, including flow rate and discharge air temperature. A computational fluid dynamics (CFD) model of a vehicle cabin was utilised to produce training data that included the complete spectrum of boundary conditions influencing occupant thermal comfort. The data underwent validation through comparison with climatic wind tunnel measurements. Three machine learning techniques were applied to the simulation data: stochastic gradient descent, random forests, and artificial neural networks (ANN). The methods employed facilitated the prediction of the volume-averaged compartment air temperature and the Equivalent Homogeneous Temperature (EHT) for each passenger. The machine learning models that were trained were assessed utilizing unobserved data produced by the CFD model. The developed machine learning model achieved a test error rate of under 5% in predicting ambient air temperature and EHT. The estimated Effective Heat Temperature (EHT) serves as a basis for deriving thermal comfort metrics, such as the Predicted Percentage of Dissatisfied (PPD) and the estimated Mean Vote (PMV). These metrics are calculated considering the metabolic rates and clothing levels of a varied group of passengers. The machine learning algorithms utilized in this study demonstrate the ability to produce real-time predictions of thermal comfort across various boundary conditions, eliminating the necessity for resource-intensive CFD simulations.

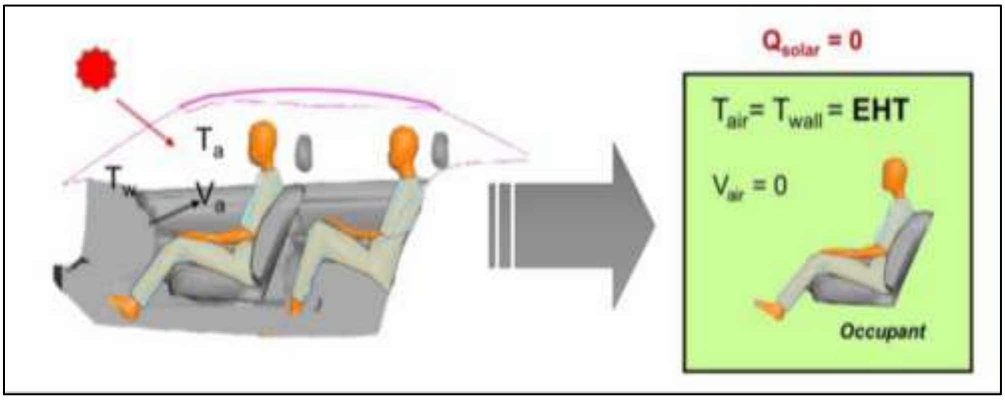

Figure 8: Schematics for total body heat balance in a vehicle cabin and a uniform environment [20]

Farhan et. al. [21] Hypothermia and hyperthermia, which are life-threatening conditions, may result from impairments in human temperature perception within an environment. This is particularly relevant to elderly individuals, as the human perception of climate changes as we age. We suggest a decision support system that forecasts human thermal comfort in real-time and recommends appropriate interventions, utilizing a variety of environmental factors, psychological attributes, and physiological traits, in order to significantly enhance the overall thermal comfort and health of individuals, particularly the elderly. Accurate thermal comfort modelling is essential for accomplishing this objective. We suggest a novel machine learning method for determining an individual's thermal comfort profile. This method first defines the optimal feature set and subsequently trains a classifier to take a feature vector as input and provide a class that corresponds to a thermal experience (e.g., "feeling warm," "feeling cold," or "neutral""). Our approach, which employs Support Vector Machines (SVM) classifiers, achieves an accuracy of 76.7%, surpassing that of the widely used Fanger's model, which achieves an accuracy of only 35.4%. This evaluation was conducted on a substantial dataset of publicly available information. Additionally, our research suggests that thermal comfort is substantially influenced by two factors that are not included in Fanger's model: an individual's age and external temperature. This is a significant discovery in its own right. Real-time predictions and corresponding recommendations could considerably enhance overall thermal comfort and health, particularly for the elderly, as ageing frequently results in diminished and delayed thermal perception. In order to achieve this objective, we suggested a unique machine learning approach to determine an individual's thermal comfort model.

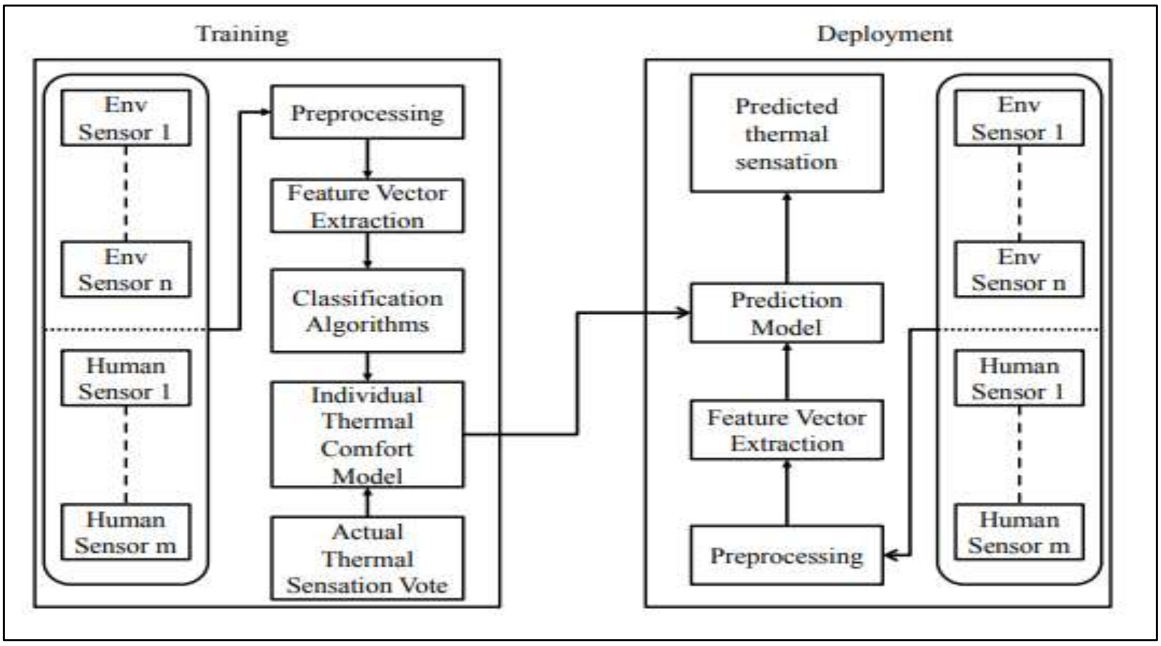

Figure 9: High-level overview of our approach [21]

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This method first identifies the optimal feature set and subsequently trains a classifier that accepts a feature vector as input and outputs a class based on the thermal experience. In contrast to Fanger's model, which achieved an accuracy of 35.4%, our technique achieved an accuracy of 76.7% using SVM classifiers on a publicly available large-scale data set. Additionally, hypothesis tests demonstrate that our methodology outperforms Fanger's model. Our feature selection study ultimately demonstrated that thermal comfort is substantially influenced by two factors that are not included in Fanger's model: an individual's age and external temperature. This finding is noteworthy in its own right.

Schweiker et. al. [22] The advent of autonomous vehicles has led to new considerations in HVAC system design, as the need for driver-focused thermal comfort decreases. Research has focused on creating more personalized HVAC systems for passengers, using individual climate control systems in autonomous cars. CFD simulations have modeled the effects of multiple, independent HVAC zones, each with sensors that adjust airflow and temperature. Experimental validation shows that these systems provide enhanced comfort, particularly in ride-sharing and multi-passenger scenarios. As autonomous vehicles continue to evolve, integrating adaptive HVAC systems into the user experience remains a crucial area of research.

Choi et. al. [23] The majority of modern temperature and sensory models depend on established formulas or empirically derived recommendations, often overlooking individual physiological characteristics. The models exhibit considerable limitations in evaluating the heat sensitivity of individuals, often neglecting the varied physical characteristics present within the population. The human body's heat exchange with its external environment is regulated by skin temperature, which is essential for thermoregulation. This study examined the potential applications of skin temperature and its technological components to generate a thermal sensation. This study utilized advanced sensor technology and established thermal regulation models to identify and validate seven anatomical sites as significant local segments for the evaluation of overall heat sensation.

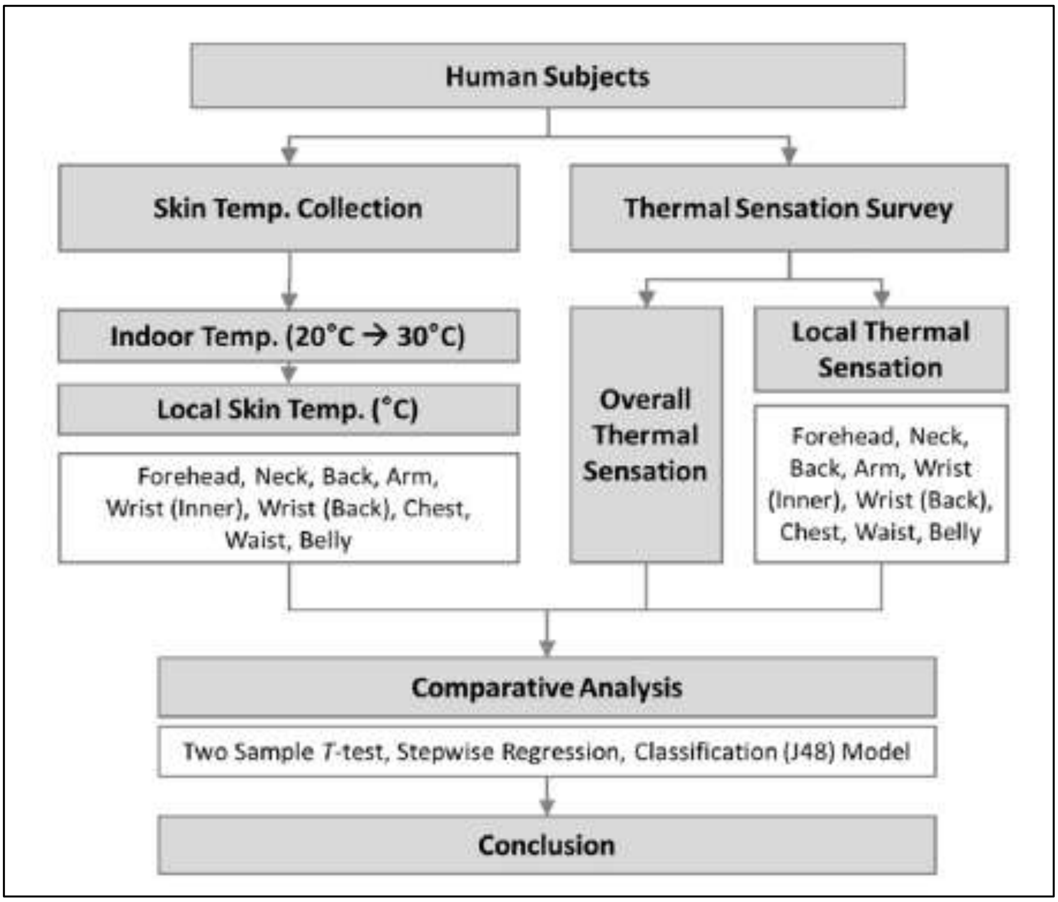

Figure 10: Human experiment workflow chart [23]

A series of environmental chamber experiments were conducted for a duration of two hours. The internal temperature varied between 200 and 300 degrees Celsius, while the thermal sensation and comfort assessment was employed to measure the skin temperatures of seven designated body areas. The investigation's findings indicated that the combinations of skin temperatures measured from the wrist, back, and arm constituted the essential data necessary for an accurate assessment of each user's thermal sensations. Both wrists yielded valid data in approximately 94% of cases, which is a significant finding.

Ravindra et. al. [24] Evaluating the thermal comfort of the vehicle in a hot and humid climate is essential due to potential adverse health effects. This study assessed the thermal comfort of a virtual passenger through real-time monitoring of temperature and relative humidity (RH%) in the automotive interiors of different car models. The relative humidity varied from 8.3 to 60.4 percent, and the temperature within automotive interiors experienced fluctuations between 26.7 and 64.9 degrees Celsius throughout the monitoring period. Data from meteorological stations was collected to develop a scenario assessing the thermal comfort of occupants outside the vehicle. The PMV range for ambient conditions was 3.24–7.41 for the front end of the vehicle, 8.36–11.87 for the rear end, and 11.5–18.04 for the front end, in accordance with the ASHRAE 55-2017 guidelines. The thermal comfort experience was consistently classified as heated and met the standards of EN15251 category IV.

Figure 11: Model car and air quality and meteorological parameter monitoring set-up

The PMV for both the front and rear of the vehicle were assessed to be the least favorable, in compliance with ASHRAE 55-2015 and EN12521 standards. The PPD recorded a consistent 100% across all instances, signifying a complete dissatisfaction with all categories of vehicles. The CO2 and CO concentrations at the front of the vehicle were measured at 113 to 1127 ppm and 0 to 3.9 ppm, respectively. The threshold values for thermal comfort measures, as defined by ASHRAE Standard 10,001:2016, were evaluated against the results and found to be acceptable. The thermal comfort of automotive occupants may be significantly impacted by temperature extremes caused by climate change, as car interiors are heated and function as a closed microenvironment. As a result, this study recommends the implementation of design standards for vehicles that prioritize thermal comfort, as well as the creation of a sensor that can detect the thermal comfort of passengers in order to prevent negative health consequences during high temperatures.
Lahimer et. al. [25] Humidity levels in the vehicle cabin play a critical role in passenger comfort. High humidity can make a cabin feel warmer than it actually is, while low humidity can cause discomfort. Research has explored

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the interaction between temperature, humidity, and airflow using CFD simulations. Experimental testing has shown that controlling both temperature and humidity can significantly enhance the overall comfort level. Some studies have investigated the use of dehumidifiers integrated into HVAC systems, which have been shown to improve comfort, particularly in humid climates. While the integration of such systems shows promise, they need to be optimized for energy efficiency.

Zhou et. al. [26] It is imperative that automobile manufacturers promptly ensure that their vehicles are equipped with an interior that is adequately comfortable for brief excursions. The driver's perception of thermal comfort and the thermos-fluid conditions in parking lots or laboratory environments are likely to be different from those in outdoor situations, as numerous previous thermal comfort trials for passenger vehicles conducted this way. This investigation investigated the thermal perception of the driver, the air and surface temperatures within a vehicle, and the driver's epidermis temperature in the context of external driving conditions. Data indicates that in the first fifteen minutes after the air conditioner was activated, the car's air and surface temperatures exhibited inconsistency and a rapid decline. The thermal comfort parameters of the vehicle exhibited instability for a duration of two hours. It is essential to perform an analysis of the thermal comfort within a vehicle under transient conditions. A significant relationship identified between the average cutaneous temperature and the average thermal sensation. The investigation revealed that the driver's perception of heat varied between the conditions of travelling outside and being stationary.

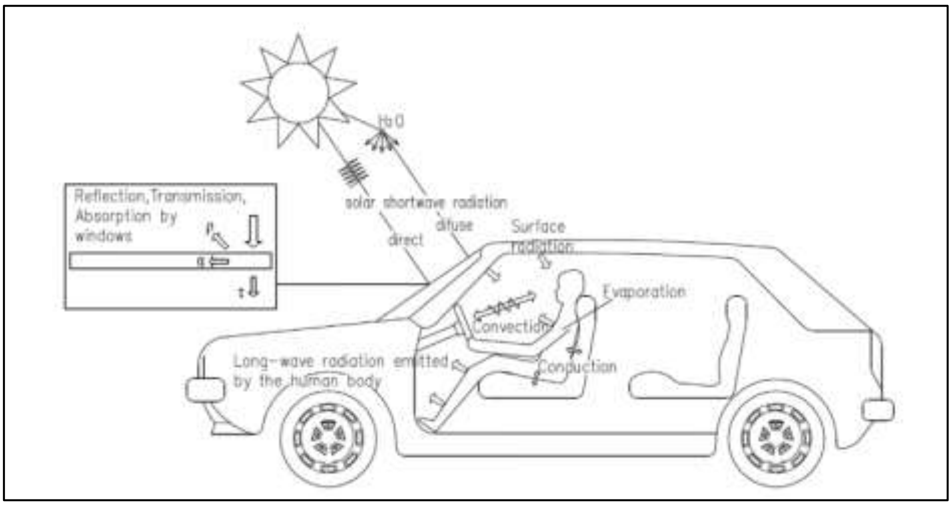

Figure 12: Heat transfer between a human body and its surroundings in a car

This study experimentally investigated the thermal comfort of a passenger car under midsummer driving conditions, as well as during interior and outdoor parking scenarios. The investigation gathered a substantial amount of experimental data regarding the external environment, the car's air and surface temperature distributions, the skin temperatures of participants, and their thermal sensation ratings. The following results were derived from the analysis: The exterior and interior air temperatures of the vehicle were transient and variable. Surface temperatures exhibited more pronounced fluctuations in outdoor driving conditions when compared to the other two sets of circumstances, due to the rapid variations in solar radiation. There was a significant correlation between the subjects' heat perception and their mean cutaneous temperature. The mean epidermis temperature is a critical variable influencing the thermal comfort within a vehicle. The correlation coefficients for outdoor driving, outdoor parking, and indoor parking were recorded as 0.89, 0.68, and 0.93, respectively. When parking, the subjects demonstrated a greater sensitivity to the temperature inside the vehicle than when travelling.

Chen et. al. [27] One of the lesser-studied but critical aspects of HVAC systems is the noise and vibration generated by the system's operation. Studies have used CFD simulations to model the airflow inside the HVAC components, identifying the sources of turbulence and vibration that lead to unwanted noise. Experimental testing has been conducted to measure sound levels at different airflows and ventilation modes. Research indicates that reducing the noise produced by HVAC systems is crucial for improving passenger comfort,

particularly in luxury vehicles. New technologies, such as noise-canceling ventilation ducts, are being explored to minimize these disturbances.
Marshall et. al. [28] With the rise of connected technologies, integrating HVAC systems with the Internet of Things (IoT) has become a focal point for improving vehicle thermal comfort. Research has explored the use of smart sensors that detect and respond to changes in passenger activity, such as adjusting the airflow based on real-time body temperature data. CFD simulations have been employed to model the interactions between various smart systems within the vehicle cabin. Experimental testing of IoT-enabled HVAC systems has shown that they can adapt to the preferences of individual passengers, offering a more personalized experience. However, the integration of IoT technologies must ensure data security and seamless communication between devices.
Tan et. al. [29] The quality of the air entering the vehicle from outside plays a significant role in maintaining a comfortable cabin environment. CFD simulations have been used to model the influence of external air quality, such as pollution or pollen levels, on interior air comfort. Studies have shown that vehicles equipped with advanced filtration systems can mitigate the effects of poor external air quality, reducing the need for higher airflow rates. Experimental tests using air quality sensors have confirmed that cabin air quality control is essential for both thermal comfort and passenger health, especially in urban areas with high levels of air pollution.
Gagan et. al. [30] Long-distance travel can present unique challenges for maintaining passenger thermal comfort, as passengers are exposed to the HVAC system for extended periods. Studies have used CFD simulations to assess the performance of HVAC systems in long-duration driving scenarios, where the primary concern is maintaining stable, comfortable temperatures over long periods. Experimental validation of these simulations has shown that ensuring uniform temperature distribution throughout the cabin is crucial for preventing discomfort. Research suggests that the optimal balance between heating, cooling, and ventilation systems can significantly enhance comfort during extended trips.
Brusey et. al. [31] Passengers of different ages and health conditions may experience varying levels of thermal comfort within the same environment. Research has explored adaptive HVAC systems designed to respond to the specific needs of children, elderly passengers, and those with medical conditions. CFD simulations have been used to model the effects of personalized temperature control systems that adjust airflow to individual passengers. Experimental validation shows that such systems improve overall comfort and well-being, particularly for vulnerable populations. Further studies are needed to explore the feasibility and practicality of implementing such adaptive systems in everyday vehicles.
Walls et. al. [32] The appropriate sizing of HVAC systems is critical for ensuring both comfort and energy efficiency. Research has applied CFD simulations to optimize the sizing of HVAC systems based on vehicle type and usage. Studies show that over-sizing or under-sizing HVAC systems can lead to inefficiencies and discomfort. Experimental validation has confirmed that proper system sizing, based on accurate simulation data, leads to more efficient temperature regulation and reduced energy consumption. Additionally, optimally sized HVAC systems can reduce the wear and tear on components, prolonging system lifespan.
Hintea et. al. [33] Car cabins are non-uniform and asymmetric environments in relation to both air velocity and temperature. Estimating and controlling vehicle occupant thermal comfort is therefore a challenging task. This paper focuses on evaluating the suitability of four existing thermal comfort models, namely the Predicted Mean Vote (PMV), Taniguchi's model, Zhang's model and Nilsson's model in a variety of car cabin conditions. A series of comfort trials were performed ranging from controlled indoor trials to on-road driving trials. The outputs of all four models were compared to the sensation index reported by the subjects situated in the driver seat.

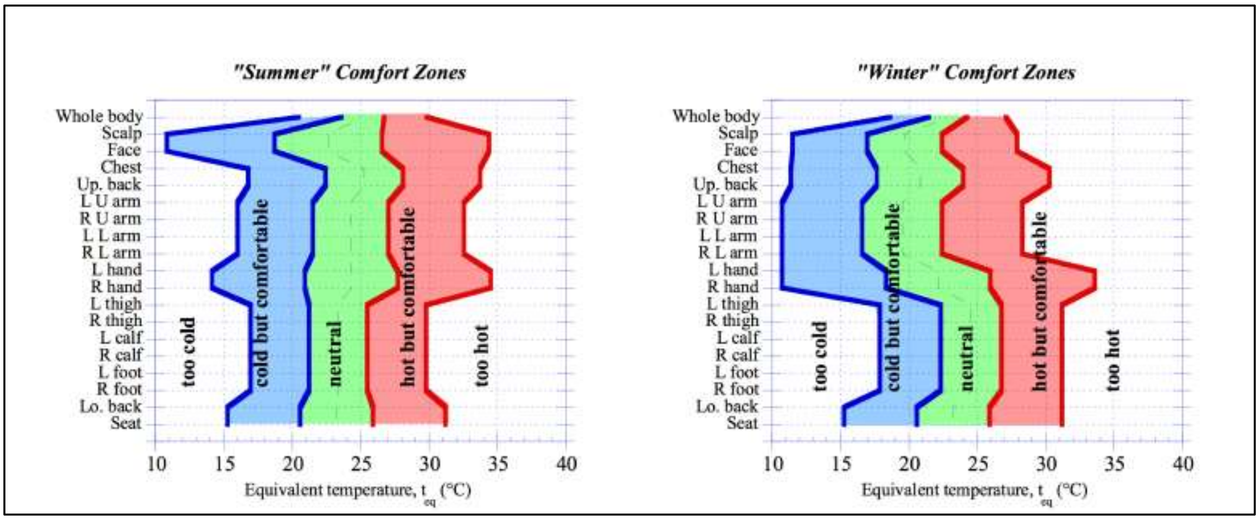

Figure 13: Nilsson's clothing independent thermal sensation diagrams [33]

The results show that PMV and Nilsson's model are generally applicable for the car cabin environment, but that they are most accurate when there is a small air temperature rate of change (of under 1.5 °C per minute), giving correlation levels of 0.91 and 0.93 for the two models respectively. Taniguchi's and Zhang's models were found unsuitable for all conditions, with correlation levels ranging between 0.03 and 0.60. Nilsson's model is recommended by the authors based on the level of agreement with the subjective reports, its ability to estimate both local and overall thermal sensation and the smaller number of input parameters.
Helian et. al. [34] Research has explored the use of energy recovery systems in vehicle HVAC designs to increase overall system efficiency. Studies show that using waste heat from the engine or exhaust system can reduce the load on the HVAC system, improving energy usage. CFD simulations have modeled the potential for integrating energy recovery systems into the HVAC design, demonstrating a reduction in overall energy consumption while maintaining comfort. Experimental testing has validated the results, with energy savings observed in both heating and cooling modes. However, technical challenges remain in integrating these systems without adding weight or complexity.

Danca et. al. [35] Air filtration and ionization technologies have been explored as complementary solutions to improve air quality and thermal comfort in vehicle cabins. CFD simulations have been used to model the airflow through advanced filters and ionizers, which can remove particulate matter and neutralize pollutants. Experimental validation has shown that these systems contribute to both comfort and health by improving air quality, particularly in urban areas with high levels of particulate pollution. Research suggests that integrating these systems with the HVAC system can further optimize passenger well-being.

Discussion

The review highlights significant advancements in the field of thermal comfort in vehicle cabins, particularly through the use of computational fluid dynamics (CFD) and advanced thermal models. PMV and PPD indices have proven invaluable for assessing thermal sensations under static conditions, but their accuracy diminishes in transient environments like vehicle cabins. Adaptive models and real-time metrics such as SET and ET have emerged as promising alternatives, addressing dynamic changes in cabin conditions and enabling more precise HVAC system designs. Additionally, the role of environmental factors, such as humidity, radiative heat transfer, and airflow patterns, has been extensively studied, demonstrating their critical influence on passenger comfort. The integration of CFD tools into HVAC design has enabled significant advancements, including optimized vent placement and multi-zone climate control systems.

Challenges and Open Issues

Despite these advancements, several challenges persist:

1. **Accuracy and Validation of CFD Models**: Achieving accurate simulations remains a challenge due to the reliance on realistic boundary conditions, mesh quality, and the complexity of transient scenarios.
2. **Energy Efficiency vs. Comfort Trade-offs**: Optimizing HVAC systems to balance energy consumption with passenger comfort is particularly challenging under extreme environmental conditions.
3. **Integration of Subjective Factors**: Incorporating personal preferences, thermal history, and individual sensitivity into predictive models remains underexplored.
4. **Real-Time Implementation**: The integration of real-time data for predictive algorithms in HVAC systems is hindered by computational costs and processing times.
5. **Advanced Materials and Technologies**: While innovations like phase-change materials and reflective coatings have been proposed, their practical implementation in vehicles requires further research and validation.
6. **Dynamic Vent Control**: Adjusting airflow to individual preferences in real-time poses technical and computational challenges.

Future Directions

To address these challenges, the following areas merit further exploration:

1. **Enhanced CFD Techniques**: Developing more robust turbulence models, mesh generation techniques, and transient analysis methods will improve simulation accuracy.
2. **Integration of AI and Machine Learning**: AI-driven algorithms can be used to predict passenger comfort dynamically, based on environmental and physiological data.
3. **Personalized Thermal Comfort Systems**: Advancing adaptive HVAC systems with localized control for individual passengers is essential.
4. **Energy Optimization Strategies**: Incorporating energy recovery ventilation and advanced insulation materials can help balance energy efficiency with comfort.
5. **Experimental Validation**: More comprehensive experimental studies are needed to validate CFD simulations under diverse environmental and operational scenarios.
6. **Multi-Phase Modeling**: Continued development of multi-phase CFD models that account for human perspiration, respiration, and clothing insulation will enhance predictive accuracy.
7. **Predictive Thermal Sensation Models**: Research into autonomous systems that detect and adjust to passengers' thermal sensations can drive innovation in HVAC systems.

Conclusion

Achieving optimal thermal comfort in vehicles and built environments is a complex task that requires advanced technologies and refined models tailored to diverse user needs. Traditional thermal comfort models often lack precision due to their inability to incorporate critical factors such as age, physiological differences, and varying environmental conditions. Novel approaches, including machine learning-based methods, have demonstrated superior accuracy by integrating these factors, providing a more individualized understanding of thermal sensation.

Personalized HVAC systems have emerged as a pivotal solution, especially in autonomous vehicles and multi-occupant settings, where adaptive climate control can significantly enhance user experience. Research has highlighted the importance of addressing factors such as humidity, airflow, and cabin asymmetry, with studies demonstrating that precise control over these parameters can improve comfort, particularly in extreme climates. Integrating technologies like dehumidifiers, energy recovery systems, and advanced filtration further optimizes air quality and comfort while improving energy efficiency.

Advances in sensor technology and real-time monitoring have enabled more accurate evaluations of thermal comfort by capturing data on skin temperature and environmental fluctuations. These developments allow HVAC systems to dynamically adjust to changing conditions, providing enhanced comfort during transient scenarios like long-distance travel or extreme outdoor conditions. Overall, integrating these innovations into HVAC systems promises significant advancements in thermal comfort, energy efficiency, and occupant health.

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CONFLICT OF INTEREST STATEMENT
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