COMMENTARY

Journal homepage: www.the-innovation.org/energy-use

Energy Use

INNOVATION PRESS

Energy Use 1 (2026):100034

Contents lists available at INNOVATION PRESS

Thermal Environment Management of eVTOL Cabin for Future Urban Air Mobility: From Multi-dimensional Sensing to Intelligent Regulation

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Received: January 31, 2026; Accepted: March 13, 2026; Published Online: March 25, 2026; https://doi.org/10.59717/ipj.energy-use.2026.100034

Citation: Zhao J. and Cao B. (2026). Thermal Environment Management of eVTOL Cabin for Future Urban Air Mobility: From Multi-dimensional Sensing to Intelligent Regulation. *Energy Use* **2**:100034.

INTRODUCTION

The rapid rise of the low-altitude economy is reshaping future transportation systems, with electric Vertical Takeoff and Landing (eVTOL) aircraft emerging as a focal point of urban air mobility. eVTOLs are defined as innovative aircraft integrating electric propulsion with vertical takeoff and landing capabilities,[1] typically operating at altitudes below 1000 m. Owing to advantages such as low carbon emissions, compact configurations, reduced noise, and lower operating costs, eVTOLs are rapidly progressing toward commercial application. In the future, eVTOLs are expected to support various scenarios, including tourism, urban commuting, and emergency rescue.

As a focal point of research, eVTOLs have attracted increasing attention from academia and industry. Existing research has primarily focused on aerodynamic performance, configuration design, battery efficiency, navigation, and flight planning. As eVTOLs transition from laboratory validation to real-world operation, the performance of onboard subsystems in complex and dynamic operating environments has become a key indicator of technological maturity. In this context, the cabin thermal environment, which represents one of the most direct interfaces between the vehicle and the occupants, has emerged as an increasingly important yet underexplored research challenge.

However, eVTOLs differ substantially from helicopters and ground electric vehicles in power sources, structural design, weight and energy constraints, and environmental conditions. Therefore, directly applying existing mature cabin thermal management systems is impractical. Unlike helicopters, eVTOLs lack bleed air to support the air cycle machine for cabin thermal regulation. Although eVTOLs and ground electric vehicles are both electrically powered, eVTOL cabins experience markedly different external environmental conditions.[2] Moreover, lightweight requirements and high energy sensitivity driven by flight safety and endurance constraints significantly restrict the design and weight of thermal regulation systems. Consequently, acceptable thermal environments in eVTOL cabins cannot be achieved through straightforward adaptation of conventional vehicle thermal management approaches. Instead, a dedicated thermal management system is required to ensure occupant thermal comfort and energy efficiency.

THERMAL ENVIRONMENT AND BOUNDARY CONDITION IN EVTOL CABINS

The complexity of the eVTOL cabin thermal environment primarily arises from highly dynamic external boundary conditions. Unlike ground vehicles operating in relatively stable environments, eVTOLs navigate in three-dimensional airspace, where ambient conditions vary continuously with altitude, flight speed, and heading. During vertical takeoff and landing, rapid changes in ambient temperature and wind speed disturb the convective heat transfer at the airframe surface. At the same time, the large transparent canopies used to satisfy visibility requirements allow substantial penetration of solar shortwave radiation. During horizontal cruise, the aircraft operates in unobstructed airspace with minimal shading, further intensifying radiative heat gains and accumulating thermal loads within the cabin.

The influence of external boundary conditions is further amplified by the lightweight design of eVTOL airframes. To minimize takeoff weight, eVTOL structures commonly employ advanced composite materials,[3] such as carbon fiber–reinforced polymers and lightweight transparent materials including polycarbonate. While these materials provide structural and aerodynamic advantages, they also alter the thermal characteristics of the cabin. These lightweight structures exhibit reduced thermal inertia, leading to rapid responses of fuselage walls to external environmental fluctuations. As a result, the cabin thermal environment becomes highly sensitive to external changes, posing challenges for dynamic thermal regulation.

Moreover, the eVTOL cabin thermal environment is characterized by pronounced spatial non-uniformity and temporal dynamics. Temporally, thermal field distribution transient variations across different flight mission phases. Spatially, the compact cabin geometry combined with extensive transparent surfaces gives rise to temperature gradients and radiative asymmetries within the occupant zone. Under such conditions, conventional single-point environmental monitoring approaches are insufficient to capture the true thermal exposure experienced by occupants. This highlights the need for more advanced sensing strategies capable of characterizing the spatiotemporal complexity of eVTOL cabin thermal environments.

MULTI-DIMENSIONAL SENSING TECHNOLOGIES FOR HUMAN-ENVIRONMENT INTERACTION

To comprehensively characterize the interaction between occupants and the environment in eVTOL cabins, monitoring systems must evolve from conventional single-parameter environmental monitoring toward multi-dimensional sensing that integrates physical environmental fields, thermal physiological feedback, and occupant information.

Environmental sensing relies on mature and minimally intrusive methods that enable straightforward system deployment and integration with negligible weight impact. It provides fundamental measurements of the cabin thermal environment, including air temperature, humidity, airflow velocity, and solar radiation. However, these parameters represent only the external drivers of human thermal state. Due to individual differences in thermal physiological and psychological responses, occupants may experience different thermal sensations under identical physical environments.

Consequently, physiological monitoring is essential for capturing physiological signals of the thermoregulatory process. As wearable sensing tech-

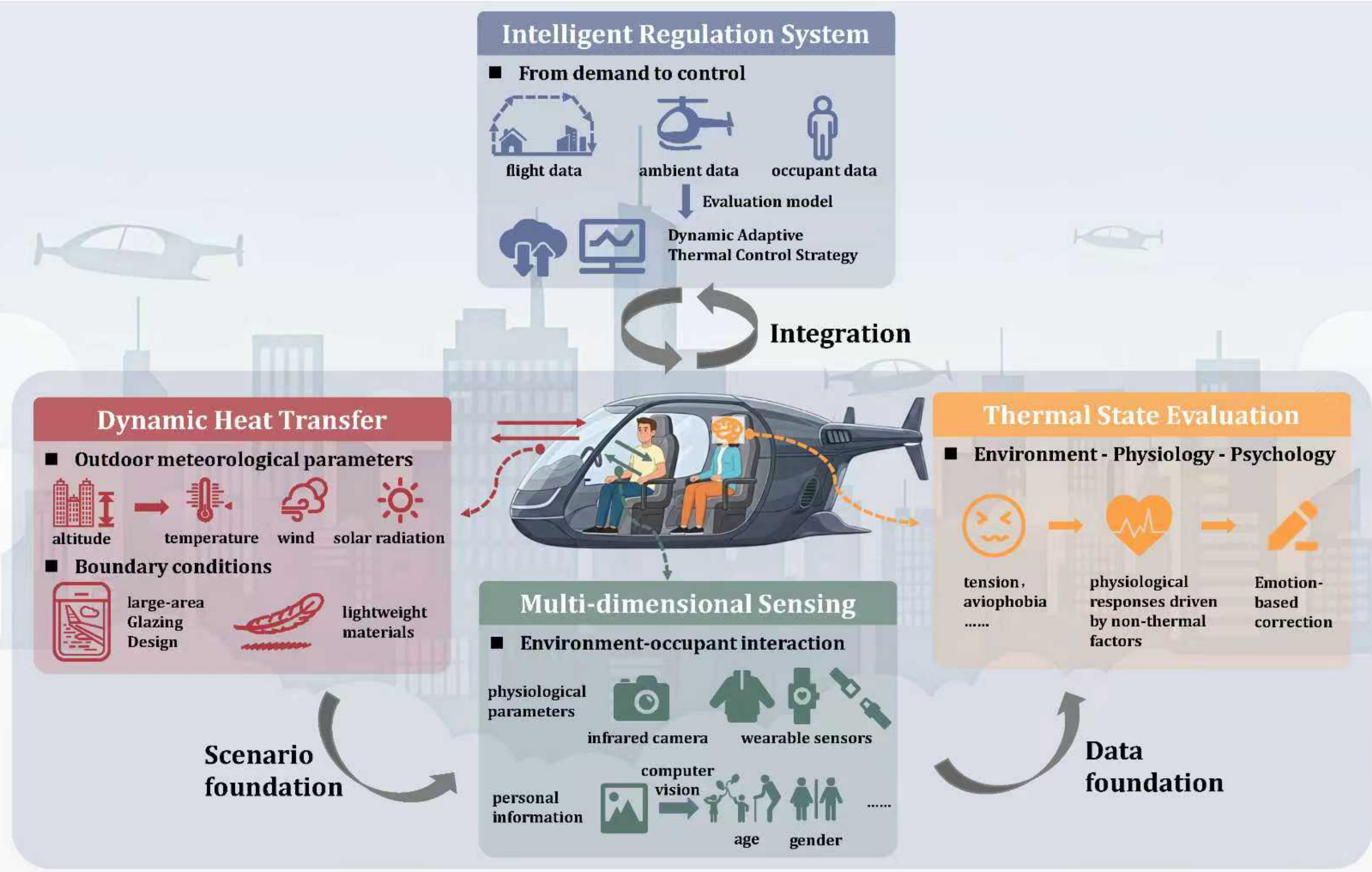

Figure 1. Integrated framework of intelligent cabin thermal environment regulation for eVTOL

nologies transition from laboratory studies toward practical engineering applications, approaches for monitoring physiological responses have expanded considerably. Flexible sensors integrated into clothing, wristbands, or seatbelts enable continuous acquisition of physiological indicators such as skin temperature, heart rate, respiratory rate, and skin conductance. By distributing sensing functions to wearable devices, part of the sensing hardware weight can be transferred away from the aircraft structure. These signals exhibit high sensitivity and provide valuable insights into occupants' dynamic thermal responses. However, their deployment in commercial operations may face challenges related to user compliance and data privacy.

In contrast, non-contact sensing technologies, particularly infrared sensors, demonstrate significant potential for application in compact cabins where occupant positions and postures are relatively fixed. This sensing approach can reduce deployment complexity and improve practical feasibility. With infrared sensors on dashboards or headliners, surface temperature distributions of exposed skin regions or clothing can be continuously monitored. Temporal variations and rates of change in skin temperature can then be correlated with individual thermal states.

Furthermore, most eVTOL platforms are equipped with onboard cameras and processing units. Based on existing onboard hardware, non-contact measurement methods combined with computer vision can identify individual characteristics such as age, gender, and metabolic rate, providing an additional dimension for personal thermal state assessment. Therefore, the system can classify occupants according to group-specific thermal preferences and establish differentiated reference baselines for thermal state identification. While algorithmically promising, their practical deployment should carefully consider real-time processing capability, privacy protection, and system reliability.

ADVANCED EVALUATION MODELS FOR OCCUPANT THERMAL STATES

An accurate thermal comfort model is fundamental for intelligent regulation of cabin thermal environments. Mainstream thermal comfort research has progressively established a relatively comprehensive evaluation framework that integrates environmental index assessment, human thermal physiological regulation simulation, and subjective evaluation of thermal sensation and comfort. These modeling approaches provide a solid theoretical basis for evaluating human thermal state under complex conditions. In recent years, extensive research has refined and adapted classical models for automotive cabins and developed dedicated models for applications in the cabin.[4]

Despite these advances, the direct application of existing thermal comfort models to eVTOL cabins remains challenging due to their special operational modes and application scenarios. During flight, occupant thermal states are more susceptible to psychological factors, imposing additional requirements on thermal comfort models. Unlike passengers in conventional driving or routine transport with relatively stable psychological expectations, occupants during eVTOL flights may experience heightened tension, anxiety, or fear of flying due to uncertainty under highly automated flight conditions. Such emotional fluctuations modulate the nervous system and may induce non-thermally driven variation in physiological responses. These effects are difficult to disentangle in conventional thermal comfort models and may bias thermal state assessments. Consequently, thermal comfort models for eVTOL occupants should incorporate psychological state recognition and correction mechanisms tailored to this specific scenario. Standardized emotion assessment scales can be employed to quantitatively characterize psychological states. By integrating environmental parameters, behavioral characteristics, physiological signals, and historical occupant data from multi-dimensional sensing systems, data-driven algorithms can be used to establish quantitative mappings between psychological factors and thermal sensation. Subsequently, an emotional correction factor can be formulated and introduced into thermal comfort models to dynamically adjust thermal sensation predictions. This approach can mitigate evaluation bias induced by non-thermal factors and improve model applicability in eVTOL cabin environments.

INTELLIGENT REGULATION PLATFORMS SYNERGIZED WITH FLIGHT-OCCUPANT DATA

Unlike the relatively independent and enclosed environmental control systems employed in automotive operations, eVTOL flights are highly automated with operational scheduling and control decisions integrated into the overall urban air mobility system. In practical scenarios, eVTOL control strategies must balance multiple objectives, including energy efficiency, passenger safety and comfort, and noise impacts on the urban environment.[5] During vertical takeoff, hover, and landing phases, priority is given to safety and energy efficiency to preserve range and power margins. In cruise phases, when power demand becomes stable, control priorities can shift toward thermal comfort and noise reduction while satisfying safety and energy constraints. Within this framework, an intelligent cabin thermal management system can leverage urban-scale low-altitude meteorological data and real-time flight information, guided by personal thermal comfort models (Figure 1).

Leveraging urban low-altitude flight data service platforms with minute-level updates and sub-kilometer spatial resolution, the system can access real-time microclimatic information along planned flight trajectories. Integrating these data with real-time flight parameters enables anticipatory assessments of cabin thermal conditions, allowing potential thermal disturbances to be identified before major environmental changes occur. This predictive approach shifts thermal management from reactive to proactive control, satisfying occupant thermal demands while minimizing unnecessary system operation caused by delayed responses and improving overall energy efficiency. In parallel, multi-dimensional perception modules enable continuous identification and evaluation of occupant thermal states. This supports targeted, time-resolved, and personalized regulation, aligning the energy use of thermal regulation with occupant demand. To manage computational load and communication latency, large-scale learning and parameter optimization are conducted offline in the cloud. The onboard system performs real-time computation and limited adaptive updates, maintaining operation even under network delays or temporary disconnections. With continued operation, the system can evolve into a self-learning digital twin of the cabin thermal environment. Through long-term data accumulation, both model parameters and weighting schemes in personal thermal comfort models can be iteratively updated and refined. This enables dynamic optimization of thermal control strategies that satisfy both eVTOL operational demands and thermal comfort requirements of occupants.

CONCLUSION

As eVTOLs become a central vehicle in future urban air mobility systems, balancing energy efficiency and thermal comfort in cabin thermal management has become a critical challenge for large-scale deployment of eVTOLs. Future advances in eVTOL cabin thermal environment management are expected to rely on coordinated development of multi-dimensional sensing, personal thermal state evaluation, and intelligent control strategies. By integrating cabin environmental data with occupant physiological responses and applying thermal comfort models specifically adapted to eVTOL cabins, occupant thermal states can be more accurately characterized and predicted under dynamic conditions. These capabilities provide the foundation for embedding cabin thermal management into intelligent control platforms, supporting adaptive and learning-based thermal regulation that addresses both eVTOL operational constraints and thermal comfort requirements.

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FUNDING AND ACKNOWLEDGMENTS

The study was supported by Tsinghua-Toyota Joint Research Fund and National Natural Science Foundation of China (No. 52578134).

DECLARATION OF INTERESTS

The authors declare no competing interests.