

Study on Cabin Airflow Optimization for Improved Thermal Comfort

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Air-conditioning energy consumption has become increasingly important in electrified vehicles because it directly affects driving range. This study investigated how to reduce HVAC energy consumption while maintaining occupant thermal comfort by optimizing cabin airflow conditions based on human thermal sensation. A CFD surrogate model was developed using a Physics-Embedded Neural Network (PENNN) to enable rapid prediction of cabin airflow and temperature distributions and support efficient optimization.

The optimization focused on HVAC operating parameters, including supply air temperature, total airflow rate, airflow distribution among outlets, and airflow direction. Thermal comfort targets were defined using average air temperature and velocity in regions surrounding specific body parts, such as the head, neck, arms, and feet. These body-part-based metrics were used together with HVAC energy consumption as objective functions in the optimization process.

To build the surrogate model, CFD simulations were performed for a MAZDA MX-30 cabin under 95 different HVAC operating conditions generated through a combination of Design of Experiments and practical vehicle control modes. STAR-CCM+ was used for CFD analysis with approximately 3.4 million mesh cells, requiring about three hours per case. The resulting pressure, temperature, and velocity fields were used as training data for the machine-learning model.

The surrogate model was based on PENNN, a Graph Neural Network framework that embeds governing equations and physical operators directly into the network architecture, enabling efficient prediction of fluid flow fields. This method can handle complex geometries, maintain prediction accuracy under geometric transformations, and better represent flow physics and boundary conditions than conventional data-driven models. The developed model achieved prediction errors below the predefined targets, with maximum RMSE values of 0.47 m/s for velocity and 1.93°C for temperature. While CFD simulations required several hours, the surrogate model produced predictions in approximately 10 minutes, enabling practical optimization studies.

Thermal comfort targets were established using a thermal comfort model developed by Zhang et al. First, a vehicle thermal model was used to evaluate heat-flux ranges around each body part under winter heating conditions. Relationships between local thermal comfort and body-part heat flux were then derived. Acceptable heat-flux ranges corresponding to thermally neutral or comfortable conditions were identified and converted into target air temperatures around each body part using experimentally derived heat-transfer coefficients. Airflow velocity limits were also defined, with stricter limits applied near draft-sensitive regions near the head.

Optimization was carried out using Tree-structured Parzen Estimator (TPE), a Bayesian optimization algorithm. HVAC power consumption was expressed as a function of airflow rate and supply air temperature, while thermal comfort objectives were formulated from deviations between target and predicted temperatures and velocities around individual body parts. The optimization searched for solutions that minimized both energy consumption and comfort deviations.

The results suggested the presence of trade-off relationships between power consumption and thermal comfort metrics in the head, neck, and forearm regions. Analysis suggested that energy consumption could be reduced by lowering total airflow while increasing supply air temperature. The results also indicated that allocating some airflow to the center vents was beneficial, but directing airflow aggressively toward the head and arms was not. Increasing airflow through the center vents helped raise local temperatures near the upper body, while limiting excessive airflow prevented undesirable cooling effects in other cabin regions.

Overall, the study demonstrated that a PINN surrogate model can accurately and efficiently predict cabin airflow, enabling practical optimization of HVAC operating conditions. By combining CFD surrogate modeling with human thermal comfort evaluation, the proposed approach identified airflow control strategies that reduce HVAC energy consumption while maintaining occupant comfort, providing a promising methodology for future energy-efficient thermal management in electrified vehicles.

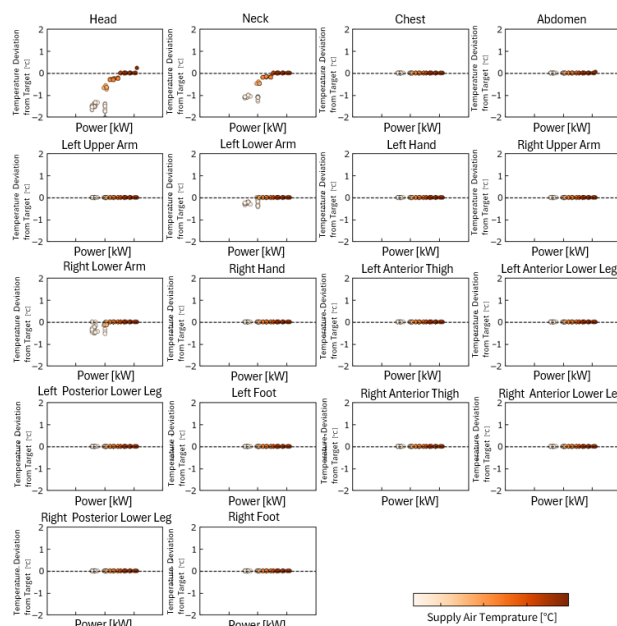


Fig.1 Pareto-optimal solutions