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Modelling, Design and Optimisation of New Cooling Architectures for Fuel Cell, Hybrid-Electric Aircraft

By

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Declaration

I hereby declare that the contents and organisation of this dissertation constitute my own original work and do not compromise in any way the rights of third parties, including those relating to the security of personal data.

This dissertation has been carried out in collaboration with Leonardo S.p.A., co-funding the assigned PhD scholarship. All data and results reported in the manuscript are updated to the submission date. The data used in the present dissertation have been obtained from the available literature.

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Modelling, Design and Optimisation of New Cooling Architectures for Fuel Cell, Hybrid-Electric Aircraft

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Recent advances in aircraft electrification and novel propulsion architectures introduce new challenges associated with substantially increased thermal loads, requiring innovative approaches to system design and integration to ensure effective onboard thermal management.

This dissertation addresses these challenges in the context of a hybrid-electric regional transport aircraft with a 20% fuel-cell power contribution, developed in collaboration with Leonardo Company at the Innovation Labs in Torino. A systems engineering approach is adopted to structure the investigation and ensure design traceability throughout the process. Within this framework, a system-oriented methodology for aircraft Thermal Management System (TMS) assessment is developed within the Industrial Systems Engineering and Design (ISED) group at Politecnico di Torino, integrating dynamic TMS models tailored to the selected industrial use case.

The developed methodology is applied to investigate emerging fuel-based TMS architectures (F-TMS) and evaluate their performance over representative mission profiles. The approach captures key transient effects, including fuel depletion, thermal inertia, and buoyancy-driven convection, to quantify the capabilities and limitations of fuel as a heat sink. Subsequently, air-based (A-TMS) configurations are developed and evaluated alongside a novel integrated air-fuel (AF-TMS) architecture. The AF-TMS exploits fuel thermal inertia for active thermal buffering under peak thermal loads, enabling reductions of up to $\sim 17\%$ in TMS mass and $\sim 30\%$ in air intake requirements.

At the component level, a physics-based modelling framework for compact, additively manufactured heat exchangers is developed within the Institute for Advanced Automotive Propulsion Systems (IAAPS) at the University of Bath. The framework integrates numerical models that are validated against literature data and extended to account for manufacturing-induced geometric deviations, improving the accuracy of pressure-drop predictions. A genetic algorithm-based routine is then coupled with the developed simulation framework to support design optimisation while satisfy-

ing application-specific performance requirements, enabling the identification of lightweight, high-performance configurations with mass reductions of up to $\sim 78\%$.

The optimised heat exchangers are ultimately integrated into the dynamic simulation models, closing the design loop and linking component-level designs to system-level performance. This integration yields substantial improvements, including up to a $\sim 64\%$ reduction in TMS mass relative to early design assumptions, alongside reduced intake-induced drag for both A-TMS and AF-TMS configurations.

Overall, the dissertation provides a comprehensive framework for the early-stage design of TMSs for hybrid-electric aircraft, combining dynamic system modelling, component-level simulation, and multidisciplinary optimisation. The results define the operational limits of fuel-based cooling, quantify the benefits of integrated air–fuel architectures, and demonstrate the critical role of tightly coupled system–component design in advancing efficient thermal management for next-generation electrified aircraft.