Design and Modeling of Shipwide Navy Integrated Power and Energy Corridor Cooling System

by

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Abstract

Naval ship systems are increasingly requiring more and more electricity to power the myriad advanced offensive and defensive electrically-powered systems. The Zumwalt class destroyer was the Navy's first fully electric ship. The next generation destroyer, DDG(X), is also planned to be an electric ship. The ships of the future can thus be anticipated to employ 100 megawatts or more of electric power. This rise in electrical demand begets the need to transfer that power more efficiently through compact and robust power distribution systems.

As part of an ongoing U.S. Navy research consortium of next-generation all-electric warships, the Design Laboratory of the Massachusetts Institute of Technology (MIT) Sea Grant Program is developing the Navy integrated Power and Energy Corridor (NiPEC) to serve as the vessel's power distribution system. The corridor comprises several modular compartments capable of operating independently or as part of a network to execute energy storage, conversion, protection, control, isolation, and transfer functions [18]. The power conversion process is carried out by the corridor's integrated Power Electronics Building Block (iPEBB). The iPEBB is a comprehensive and self-contained converter configured to provide power-dense solutions to the ship's stochastic and dynamic loads [45]. The thermal management of the iPEBB is a central challenge in being able to fully realize its advanced semiconductor technology, constrained by the provision of indirect liquid cooling methods and sailor-friendly accommodations vis-à-vis handling, user interface, and operation.

Padilla et al. [36] conducted a preliminary analysis of Power Electronics Building Block (PEBB) heat dissipation strategies utilizing liquid-cooled cold plates across the dry interface of the PEBB's external surface. Reyes [39] extended this analysis in proposing a first-pass design of a NiPEC liquid cooling system capable of servicing a single nominal compartment within the larger corridor architecture. However, this most recent design presents infeasible operational and maintenance aspects given the number of cooling components required to adequately cool all envisioned NiPEC corridors, compartments, and PEBB stacks.

This thesis used a combination of first-principles thermodynamic analysis and multi-physics-based modeling to design a NiPEC liquid cooling system and architecture suitable for shipwide deployment. Using Reyes' first-pass cooling system design as a starting point, additional design iterations of the computer-modeled system were conducted and analyzed for thermal management robustness, success against key performance benchmarks, and adherence to relevant military standards. Additional modeling and analysis were conducted to determine how the cooling system could be scaled to accommodate an entire future all-electric Navy destroyer warship. This analysis examined key architectural system design considerations such as the level of component redundancy, utilization of different loop and zonal cooling schemes, and system survivability and control.

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