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Multi-Disciplinary and Multi-Scale Framework for the Design of Additively Manufactured TPMS-based Advanced Heat Exchangers

By

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Declaration

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2026

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Multi-Disciplinary and Multi-Scale Framework for the Design of Additively Manufactured TPMS-based Advanced Heat Exchangers

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Advances in additive manufacturing (AM) enable the production of architected lattice materials, often referred to as metamaterials, whose effective properties can be tailored by geometry. Their use in compact heat exchangers (HXs) and lightweight structures is, however, limited by the prohibitive computational cost of high-fidelity simulations: thousands of unit cells and intricate topology make direct modeling infeasible, especially when simulations are employed in optimization frameworks. Therefore, this thesis presents a validated multiscale framework, that bridges micro and macro-scale analyses to assess both structural and thermo-fluidic performance.

On the modeling side, an in-house software, Lattice Designer, has been developed to generate strut-based and TPMS lattices via CAD and implicit representations. The tool supports uniform and graded architectures, user-defined domains, and mesh-ready export, offering a GUI and API for seamless integration with scripted workflows.

For structural mechanics simulations, representative volume element (RVE) analyses are used to compute homogenized elastic and damping properties under static and dynamic loading while enforcing energetic consistency (Hill–Mandel principle). Multiple boundary-condition schemes are implemented and compared, mesh and size convergence criteria are established, and a de-homogenization procedure is provided to recover local stress states in critical regions from macroscopic fields. The homogenized models reproduce global stiffness and stress distributions of fully resolved lattices with small errors while reducing computational time by orders of magnitude.

For computational fluid dynamics (CFD) and conjugate heat transfer (CHT) assessments, a two-stage approach is formulated: micro-scale RVE simulations to extract Darcy–Forchheimer flow resistance and Nusselt-based heat-transfer correlations, and macro-scale porous-medium simulations of full HXs, including conjugate heat transfer. The porous representation accurately predicts pressure drop and thermal performance relative to high-fidelity resolved CFD at a fraction of the cost, enabling component-scale studies that would otherwise be unfeasible.

The framework is implemented with open-source solvers and fully automated through to ensure reproducibility and scalability. The results demonstrate that the multi-scale approach, coupled with robust geometry generation, provides a practical route to the accurate and efficient

analysis of AM lattice components. The procedures were designed for future embedding in multi-disciplinary design environments and can be extended to other thermal-management and structural applications where architected materials offer system-level advantages.