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Doctoral Dissertation

Doctoral Program in Energy Engineering (38th cycle)

**Triply Periodic Minimal Surfaces as
structured porous media cooling
systems for the removal of high heat
fluxes**

By

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2025

Declaration

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

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2025

* This dissertation is presented in partial fulfillment of the requirements for **Ph.D. degree** in the Graduate School of Politecnico di Torino (ScuDo).

Abstract

Many engineering applications in energy and non-energy sectors require advanced thermal management systems for proper operation. The development of innovative enhanced heat removal systems is therefore essential. The rise of Additive Manufacturing (AM) in recent years has enabled the exploration of structures that were previously impossible to achieve with traditional manufacturing methods, including cellular lattice structures, among which Triply Periodic Minimal Surfaces (TPMS) stand out. TPMS are periodic, non-intersecting and highly interconnected surfaces, with no sharp angles and large specific surface area, arising in many fields for thermal, structural, biomedical, or chemical applications. Discovered in the late 1800s as mathematical combinations of trigonometric functions in 3D space, they are now extensively studied due to their recent manufacturability. Many researchers have attempted to develop TPMS-based systems, for example for heat-exchangers or heat sinks applications, and compare them with more traditional devices. Studies aiming at modeling TPMS in order to analyze their thermal and hydraulic performance are present in the literature, too. Notwithstanding the enormous amount of work on TPMS, most current literature lacks generalizability or repeatability, frequently based on questionable assumptions or providing insufficient detail in the descriptions or inconsistent definitions of descriptive parameters.

The objective of the present thesis is thus to provide a solid basis on the hydraulic and thermal characterization of TPMS at low Reynolds numbers, by starting from simple and generalizable models (such as the porous medium framework) that can be employed in other problems, and investigating a significant range of geometric parameters, such as porosity and different topologies. At the same time, this work does not only intend to study TPMS from a theoretical point of view, but also aims to exploit their analysis for real-use purposes, specifically in a solar application as volumetric solar receivers for Concentrated Solar Power (CSP), and, for the first time,

in a nuclear fusion application as cooling system for mirrors reflecting high-frequency electromagnetic beams.

For the hydraulic characterization of Triply Periodic Minimal Surfaces, the Darcy-Forchheimer equation was approached, and other common frameworks such as the Ergun equation, considering TPMS as a structured porous medium. The developed models correlated the hydraulic impedance of diverse topologies to their porosity and tortuosity, proving successfully also in different geometries than those used for the development. The hydraulic phenomena were related to the energy transport within TPMS, enabling the building of correlations between the thermal and hydraulic variables. Concerning the use of TPMS for heat removal, problem-specific devices were designed, compliant with the working conditions, investigated from a numerical point of view, manufactured with AM and tested, both thermally and hydraulically. The performance assessment of these TPMS-based devices was successful, as the volumetric receiver filled with TPMS proved outstanding compared to other traditional receivers in terms of thermal efficiency, and the mirror cooled by TPMS structures was thermally superior to other proposed cooling options. The comparison between simulation and experimental results highlighted the reliability of numerical models for large structures printed in polymeric materials, but significant discrepancies occurred with metal samples, probably due to the residual roughness of the prototypes. Furthermore, these differences increased as the characteristic hydraulic size of the TPMS decreased, thereby making any porosity or printing defects more significant. In theory, the large roughness of the samples should also raise heat exchange, by increasing the effective heat exchange surface area. However, thermal tests on the mirror filled with TPMS failed to detect this phenomenon, probably due to the inadequacy of the experimental setup - an issue that could be resolved by testing the prototype in a facility more suitable for delivering high heat fluxes, such as the solar simulator used for the receivers.