
# Design and Experimental Evaluation of TPMS-Based Compact Heat Exchangers for High-Power Railway Thermal Systems

Giovani Silveira de Magalhães Martins[1]*, Mateus de Sousa Zanzi[2]
[1] *UniSenai, Joinville*
[2] *Thermal Fluid and Flow Group (T2F), UFSC, Joinville*

## 1. Introduction

The continuous demand for compact and high-performance thermal systems has driven significant advances in heat exchanger design, particularly in applications involving high heat fluxes and space constraints. Conventional technologies, such as shell-and-tube and plate heat exchangers, are widely used due to their robustness and maturity; however, they present intrinsic limitations in terms of volumetric efficiency and heat transfer enhancement [1,2].

To overcome these limitations, the use of geometries with high surface area-to-volume ratio has been extensively investigated. Among these, Triply Periodic Minimal Surfaces (TPMS) have emerged as a promising class of structures due to their interconnected topology, smooth surfaces, and ability to promote flow mixing and thermal uniformity [3–5]. These characteristics can lead to significant improvements in heat transfer performance when compared to conventional channel-based configurations.

Despite these advantages, the intensification of heat transfer is commonly accompanied by increased pressure drop, resulting in a critical thermo-hydraulic trade-off that must be carefully optimized [6,7]. Additionally, the practical implementation of such complex geometries has historically been limited by manufacturing constraints.

Recent advances in additive manufacturing (AM) have enabled the fabrication of highly complex internal structures, including TPMS-based architectures, opening new possibilities for heat exchanger design [5,8]. However, important challenges remain, particularly related to manufacturing accuracy, surface quality, sealing, and experimental validation under realistic operating conditions [9–11].

From an application perspective, the need for efficient thermal management is particularly critical in high-power-density systems. In railway engineering, the ongoing electrification of locomotives has significantly increased the demand for effective battery thermal management systems (BTMS). These systems operate under demanding conditions, including high heat generation rates, cyclic loading, and strict temperature uniformity requirements [12], [13].

Current cooling strategies, such as liquid-cooled cold plates and forced air systems, present limitations in terms of efficiency, scalability, and energy consumption [14], [15]. Moreover, issues such as thermal gradients, hotspot formation, and system complexity remain significant challenges, especially in large-scale battery packs used in railway applications [16–18].

In this context, the integration of TPMS-based geometries with additive manufacturing represents a promising approach for the development of compact and high-performance thermal management devices. Therefore, this work proposes the development and evaluation of additively manufactured compact heat exchangers, aiming to enhance thermo-hydraulic performance and enable their application in railway systems.

## 2. Experimental and Theorical Approach

The proposed methodology integrates experimental and numerical approaches for the development and evaluation of compact heat exchangers.

Initially, representative operating conditions for railway battery thermal management systems are defined, including heat flux levels, temperature limits, and flow regimes. Performance metrics such as heat transfer coefficient, friction factor, and thermo-hydraulic performance criteria (PEC) are established.

*Corresponding author: giovani.martins@edu.sc.senai.br

Complex geometries based on TPMS structures (e.g., gyroid) are designed and modeled aiming at maximizing heat transfer while controlling pressure losses. Prototypes are fabricated using additive manufacturing techniques, with emphasis on stereolithography (SLA) for initial validation.

Experimental tests are conducted using thermal-hydraulic test benches, enabling the measurement of heat transfer performance and pressure drop under controlled conditions. Numerical simulations (CFD) are used to support the analysis and to explore parameter spaces not accessible experimentally.

Finally, a comparative analysis between TPMS structures and conventional geometries is performed to assess performance gains and practical feasibility.

## 3. Results and Discussions

The expected outcomes of this study include the development and validation of compact heat exchangers based on TPMS geometries manufactured via additive manufacturing.

From a thermo-hydraulic perspective, TPMS structures are expected to significantly enhance heat transfer performance due to increased surface area and flow mixing mechanisms. However, these improvements are inherently coupled with higher pressure losses, reinforcing the importance of evaluating performance using combined criteria, such as the thermo-hydraulic performance factor (e.g., PEC).

The analysis aims to identify optimal geometrical configurations that maximize heat transfer while maintaining acceptable pressure drop levels. Parametric studies based on numerical simulations and experimental data will provide insights into the influence of geometric parameters on thermal efficiency and hydraulic performance.

In addition to performance evaluation, manufacturing-related aspects will be critically assessed. Factors such as dimensional accuracy, surface roughness, sealing capability, and repeatability of additively manufactured components are expected to play a key role in determining the feasibility of real-world applications.

From an application standpoint, the proposed devices have strong potential for integration into battery thermal management systems in railway applications. The expected benefits include improved temperature uniformity, reduction of hotspot formation, and increased overall thermal efficiency, which are critical for battery performance, safety, and lifespan.

Furthermore, this work contributes to bridging the gap between advanced geometrical concepts and their practical implementation, providing both experimental validation and design guidelines for the application of TPMS-based heat exchangers in high-performance engineering systems.

## 4. References

[1] Q. Li, G. Flamant, X. Yuan, P. Neveu, L. Luo, Compact heat exchangers: A review and future applications for a new generation of high temperature solar receivers, Renewable and Sustainable Energy Reviews 15 (2011) 4855–4875. https://doi.org/10.1016/j.rser.2011.07.066.

[2] R.K. Shah, D.P. Sekuli, Fundamentals of Heat Exchanger Design, John Wiley & Sons, Inc., Hoboken, NJ, USA, 2003. https://doi.org/10.1002/9780470172605.

[3] K. Qin, N. Zhuang, C. Shao, H. Zhao, X. Tang, Gyroid-type TPMS structure optimization based on mathematical function control and its convective heat transfer performance study, International Communications in Heat and Mass Transfer 162 (2025) 108682. https://doi.org/10.1016/j.icheatmasstransfer.2025.108682.

[4] G. Yan, M. Sun, Z. Zhang, Y. Liang, N. Jiang, X. Pang, Y. Song, Y. Liu, J. Zhao, Experimental study on flow and heat transfer performance of triply periodic minimal surface structures and their hybrid form as disturbance structure, International Communications in Heat and Mass Transfer 147 (2023) 106942. https://doi.org/10.1016/j.icheatmasstransfer.2023.106942.

[5] N. Casini, L. Mazzei, R. Da Soghe, Numerical Analysis of Convective Heat Transfer Processes and Performance Assessment of Lattice and Triply Periodic Minimal Surface Geometries, in: Volume 13: Heat

*Corresponding author: giovani.martins@edu.sc.senai.br

Transfer: General Interest / Additive Manufacturing Impacts on Heat Transfer; Wind Energy, American Society of Mechanical Engineers, London, United Kingdom, 2024: p. V013T13A041. https://doi.org/10.1115/GT2024-129097.
[6] X. Zhang, M.C. Halbig, A. Almansour, M. Singh, M. Ranaiefar, Y. Zheng, Innovative 3D-printed hybrid cooling systems for thermal management of lithium-ion pouch cells, Journal of Energy Storage 142 (2026) 119469. https://doi.org/10.1016/j.est.2025.119469.
[7] Z. Deng, Y. Sun, S. Zhang, T. Li, K. Ma, Z. Wu, B. Li, Thermal analysis and optimization of high-power GPUs from heat sinks to package interfaces, Applied Thermal Engineering 280 (2025) 128008. https://doi.org/10.1016/j.applthermaleng.2025.128008.
[8] F. Ejaz, S.M. Zubair, Advancing recuperated supercritical carbon dioxide (sCO2) Brayton cycle performance: Microchannel heat exchangers vs. traditional compact designs, International Communications in Heat and Mass Transfer 163 (2025) 108693. https://doi.org/10.1016/j.icheatmasstransfer.2025.108693.
[9] C.E.B. Corrêa, G.S.M. Martins, G. Zilio, P.A. Jaskowiak, K.V. Paiva, Pressure drop prediction in gyroid triply periodic minimal surfaces structures using experimental data, computational fluid dynamics and artificial neural networks, Applied Thermal Engineering 285 (2026) 129238. https://doi.org/10.1016/j.applthermaleng.2025.129238.
[10] D.A. Ifa, D.A. Efa, TPMS-enabled architectures for heat dissipation in thermal systems: A review of current progress and future directions, International Journal of Heat and Mass Transfer 259 (2026) 128401. https://doi.org/10.1016/j.ijheatmasstransfer.2026.128401.
[11] H. Wang, C. Zhao, W. Liu, Z. Liu, H. Bian, K. Zhang, Advances in triply periodic minimal surface structures for thermal management systems: A comprehensive review, Applied Thermal Engineering 279 (2025) 127481. https://doi.org/10.1016/j.applthermaleng.2025.127481.
[12] D. Shi, Y.-L. He, S. Wang, W. Qiao, Z. Liu, Optimization design of flow path arrangement and channel structure for lithium-ion battery cooling plate based on the three-field synergy principle, Applied Thermal Engineering 264 (2025) 125372. https://doi.org/10.1016/j.applthermaleng.2024.125372.
[13] J. Deng, J. Wang, Y. Zhang, Optimal flow channel structure selection for hybrid locomotive battery pack liquid cooling system, J. Phys.: Conf. Ser. 2735 (2024) 012015. https://doi.org/10.1088/1742-6596/2735/1/012015.
[14] J. Kleiner, F. Lambauer, R. Singh, L. Komsiyska, M. Hinterberger, C. Endisch, Experimental study of cell integrated heat pipe cooling with a lithium-ion cell emulator, Journal of Energy Storage 56 (2022) 105808. https://doi.org/10.1016/j.est.2022.105808.
[15] R. Knibbe, D. Harding, E. Cooper, J. Burton, S. Liu, Z. Amirzadeh, R. Buckley, P.A. Meehan, Application and limitations of batteries and hydrogen in heavy haul rail using Australian case studies, Journal of Energy Storage 56 (2022) 105813. https://doi.org/10.1016/j.est.2022.105813.
[16] K. Elsayed Elfeky, M. Hosny, A.G. Mohammed, Q. Wang, K. Ge, Performance assessment of a novel hybrid cooling design for battery thermal management systems, Case Studies in Thermal Engineering 76 (2025) 107393. https://doi.org/10.1016/j.csite.2025.107393.
[17] A.B. Al Tahhan, M. AlKhedher, M. Ramadan, A. ElCheikh, D.S. Choi, M. Ghazal, Experimental and numerical analysis of a liquid-air hybrid system for advanced battery thermal management, Applied Thermal Engineering 253 (2024) 123754. https://doi.org/10.1016/j.applthermaleng.2024.123754.
[18] Y.S. Ranjbaran, M.H. Shojaeefard, G.R. Molaeimanesh, Thermal performance enhancement of a passive battery thermal management system based on phase change material using cold air passageways for lithium batteries, Journal of Energy Storage 68 (2023) 107744. https://doi.org/10.1016/j.est.2023.107744.

*Corresponding author: giovani.martins@edu.sc.senai.br