Coupling Additive Manufacturing with Triply Periodic Minimal Surface Enable Next-Generation Aero-Engine Heat Exchangers

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The aero-engine, characterized as a highly complex and advanced thermodynamic machinery, experience a heightened thermal load on its on-board heat exchangers due to the elevating pre-turbine temperature and thrust-to-weight ratio. Triply periodic minimal surfaces (TPMS) are regarded as holding potential for constructing the next-generation heat exchangers.

Since 2021, our research group[1] has been actively engaged in exploring the applicability of TPMS as configurations for on-board heat exchangers in aero-engines, specifically focusing on fuel cooling oil cooler (FCOC). This study presents a comprehensive exploration of the TPMS-HX, covering multiple perspectives including design, manufacturing, experiment, simulation, and post-processing.

TPMS is a collection of mathematically defined surfaces that exhibit local area minimization and extend periodically in three-dimensional space. TPMS structure could effectively partitions the three-dimensional space into two interconnected yet separate domains. Among the TPMS family, the Gyroid structure is the most renowned and widely acknowledged for its suitability in constructing heat exchangers. The experimental prototype investigated in this study consisted of Gyroid structures, with a unit cell size of 4 mm and a uniform wall thickness of 0.5 mm. The prototype was manufactured using stainless steel 316L via a selective laser melting process.

Surface roughness poses a significant challenge in the application of AM-ed heat exchangers. The experimentally measured ΔP_c surpasses the theoretical performance by 69.82% for $\dot{m}$=500 kg/h. The experimentally measured $\dot{Q}_{ave}$ consistently exceeds the numerical results, with this advantage progressively magnifying as Re_c increases. Notably, the largest relative deviation occurs at Re_c of approximately 1350, reaching 8.52%.

To address this issue, this study employed abrasive jet polishing technique to finish the internal surface of the prototype. The samples were characterized using an Olympus DSX-1000. Prior to polishing, the internal surface exhibited uneven distribution with rough raised microstructures ranging from 20 to 200 μm in diameter. These structures were attributed to partially melted metal powders adhering to the internal surface. Following the polishing process, there was a noticeable reduction in the density of microstructures, this outcome signifies a substantial decrease in surface roughness.

The *PEC* (performance evaluation criteria) value represents the comprehensive performance of studied prototype. At *Re* of 300, the pre-polishing sample exhibits an 8.08% higher *PEC* compared to the baseline. However, at *Re* of 3000, this prototype demonstrates a 12.10% lower *PEC* than the baseline, indicating no comprehensive performance advantage at high *Re*. Remarkably, after the polishing process, the Gyroid configuration consistently outperforms the baseline by 12.94% to 26.09% across *Re* range of 300-3000.

The findings and insights obtained from this work will serve as a valuable guidance and references for the development and implementation of TPMS-HX in next-generation aero-engine.

[1] Yan, K., Wang, J., & Deng, H. (2023). "Numerical investigation into thermo-hydraulic characteristics and mixing performance of triply periodic minimal surface-structured heat exchangers." *Applied Thermal Engineering*, *230*, 120748.
[2] Yan, K., Deng, H., Xiao, Y., Wang, J., & Luo, Y. (2024). "Thermo-hydraulic performance evaluation through experiment and simulation of additive manufactured Gyroid-structured heat exchanger." *Applied Thermal Engineering*, *241*, 122402.