

Porous Media-Based Thermal Design Methodology for TPMS Heat Exchangers with Genetic Algorithm Optimization: A Preliminary Study

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***Keywords:** TPMS heat exchanger, genetic algorithm, design optimization

1. Introduction

Compact heat exchangers for advanced energy systems must simultaneously provide high heat transfer capability, low pressure loss, small volume, and manufacturability. Triply periodic minimal surface (TPMS) lattices have emerged as a promising core architecture because they combine a high surface-area-to-volume ratio with smooth, continuously curved, interconnected passages, and because their self-supporting geometry is well suited to metal additive manufacturing [1]. Balanced topologies such as the Gyroid and Schwarz-Diamond divide space into two congruent labyrinths separated by a continuous wall, so a single lattice naturally forms a two-fluid exchanger. These features have motivated their application to liquid cooling, gas-liquid exchange, and supercritical carbon dioxide (sCO₂) power cycles [1,2].

Most published work has characterized local Nusselt-number enhancement, unit-cell-scale flow behavior, or topology comparisons at prescribed test geometries [3,4]. Practical development, however, requires a macroscopic step in which the overall core size, unit-cell length, flow allocation, pressure drop, and manufacturing feasibility are determined together under a specified thermal duty. Three major challenges arise in this design process. First, the geometry is strongly coupled: reducing the unit-cell size increases the surface-area density but simultaneously reduces the hydraulic diameter, increases the pressure drop, and reduces the wall thickness toward the minimum printable limit; moreover, the two flow domains may be allocated asymmetrically, giving unequal convective coefficients on the two sides [5]. Second, published friction-factor and Nusselt-number correlations cannot be used interchangeably because the definitions of hydraulic diameter, characteristic velocity, and friction factor vary among sources [3,6–8], and reported pressure drops may or may not include manifold and entrance losses [9]. Third, wall thicknesses below about 0.2 mm are generally not recommended in laser powder-bed fusion (LPBF) to avoid cracks and inter-channel leakage [10,11].

This paper presents a framework that addresses these issues by representing the periodic TPMS core through macroscopic geometric descriptors and topology-specific transport correlations. The complex periodic geometry is reduced to four threshold-dependent descriptors—porosity, surface-area density, volumetric hydraulic diameter, and minimum wall thickness—

which are coupled to friction-factor and Nusselt-number correlations regressed from screened literature data under one consistent set of definitions. The resulting one-pass sizing evaluator is embedded in a genetic algorithm (GA) and applied to an sCO₂ core to compare the Gyroid and Diamond topologies under two objectives: minimum core volume and maximum heat transfer per unit pumping power.

2. Geometric Characterization

Each topology is represented by an implicit level-set field $\phi(\mathbf{x})$ on a normalized unit cell $\mathbf{x} \in [0,1]^3$ with angular coordinates $\xi = 2\pi x$, $\eta = 2\pi y$, $\zeta = 2\pi z$:

$$\phi_G = \sin\xi\cos\eta + \sin\eta\cos\zeta + \sin\zeta\cos\xi \quad (1)$$

$$\phi_D = \cos\xi\cos\eta\cos\zeta - \sin\xi\sin\eta\sin\zeta \quad (2)$$

Two independent thresholds $t_h > t_c$ define the hot domain ($\phi > t_h$), the cold domain ($\phi < t_c$), and the solid wall ($t_c \leq \phi \leq t_h$). Because the two thresholds are separate design variables, asymmetric allocation of the flow domains within a single core is admissible (Fig. 1).

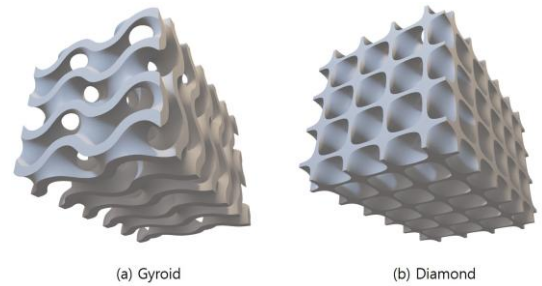


Fig. 1. Gyroid and Diamond TPMS cores.

For each fluid side i , the porosity ε_i and a dimensionless surface-area coefficient $C_{s,i}$ were precomputed on a 160^3 grid by voxel counting and marching-cubes surface extraction at a threshold spacing of $\Delta t = 0.01$ and stored as lookup tables. For a physical cell length t_{cell} , the surface-area density and hydraulic diameter follow analytically:

$$a_{s,i} = \frac{C_{s,i}}{t_{cell}}, \quad D_{h,i} = \frac{4\varepsilon_i t_{cell}}{C_{s,i}} \quad (3)$$

Thus, a single normalized geometry table can be used for any unit-cell size through analytical scaling. The effective flow area of each side is $A_{flow,i} = \varepsilon_i A_{core}$, and the interstitial mean velocity and Reynolds number are

$$u_i = \frac{\dot{m}_i}{\rho_i \varepsilon_i A_{core}}, \quad Re_i = \frac{\rho_i u_i D_{h,i}}{\mu_i} \quad (4)$$

with the Prandtl number $Pr_i = c_{p,i}\mu_i/k_i$ and the Nusselt number $Nu_i = h_i D_{h,i}/k_i$ based on the wetted-area-averaged coefficient h_i . These definitions are used consistently for the geometry, the correlations, and the sizing model. The zero-level surface-area coefficients, $C_s = 3.092$ for Gyroid and 3.839 for Diamond, agree with the reference values of Seddon and Templer [12] and Gandy et al. [13] to within 0.03%. The two topologies exhibit distinct sensitivities to the level-set threshold. In the Gyroid topology, porosity decreases almost linearly as the threshold magnitude increases, whereas the Diamond topology shows a more rapid and nonlinear loss of open volume. This indicates that equal threshold magnitudes do not correspond to equivalent flow-domain allocations across different TPMS topologies. Because equal thresholds correspond to different porosities in the two topologies, the design-relevant comparison is made at matched porosity. Over the matched-porosity design range considered here, particularly for $\varepsilon \geq 0.10$, Diamond consistently provides a higher surface-area coefficient than Gyroid. The relative increase is approximately 18–24%, depending on porosity. However, since $D_h = 4\varepsilon t_{\text{cell}}/C_s$, the larger surface-area coefficient also reduces the hydraulic diameter at fixed porosity and unit-cell size. The geometric area advantage must therefore be evaluated together with Reynolds number, pressure drop, and manufacturability constraints in the optimization.

The wall thickness is not equal to the threshold difference itself. Instead, it corresponds to the physical distance between the two bounding level surfaces. The minimum wall thickness was therefore evaluated from the level-set gradient within the solid band and stored as a two-dimensional lookup table in (t_h, t_c) . For the evaluated threshold pairs, Diamond generally yields a larger tabulated minimum wall thickness than Gyroid, so the two topologies approach the manufacturability constraint at different locations in the design space. A manufacturing floor of $t_{\text{wall,min}} = 0.20$ mm, representative of a minimum printable wall thickness for LPBF-fabricated 316L stainless steel [10], is imposed on the tabulated minimum wall thickness.

3. Sizing Model and Optimization

The transport closure of the sizing model consists of topology-specific $Nu(Re, Pr)$ and $f_D(Re)$ correlations obtained by regressing screened experimental [3,5,9,14,15] and computational [2,4,6,16,17] data from the literature. Because published TPMS studies employ different definitions of characteristic length, characteristic velocity, friction factor, and pressure-drop measurement domain, all reported data were first recast onto the common basis defined by Eqs. (3)–(4): the volumetric hydraulic diameter, the interstitial mean velocity, and the Darcy friction factor, $f_D = 2\Delta p_{\text{core}} D_h / (\rho u^2 L_{\text{core}})$. Only core-intrinsic pressure-drop data were retained for the friction-factor regression, thereby excluding manifold and entrance losses.

For prescribed mass flow rates, pressures, inlet temperatures, and hot-side outlet temperature, the

evaluator computes the heat duty Q and the counterflow log-mean temperature difference ΔT_{lm} , using real-fluid thermophysical properties evaluated at the respective bulk-mean state of each stream. The side-specific heat-transfer coefficients h_i are then obtained from the corresponding topology-specific Nusselt correlations. Because heat transfer occurs entirely through the continuous TPMS separating wall and no secondary finned surface is introduced, the interfacial areas are treated as primary heat-transfer surfaces and no fin-efficiency correction is required. The thermal resistance per unit core length is assembled using the side-specific surface-area densities as given in Eq. (5). The required core length and volume are then obtained directly as $L_{\text{core}} = Q R' / \Delta T_{\text{lm}}$ and $V_{\text{core}} = A_{\text{core}} L_{\text{core}}$. Thus, the core length is an output of the thermal sizing calculation rather than a prescribed input. Pressure drops are evaluated from the piecewise friction-factor correlations, with the appropriate Reynolds-number regime selected independently for the hot and cold sides. The corresponding hydraulic pumping power is $W_{\text{pump}} = \Sigma \Delta p_i \dot{m}_i / \rho_i$.

$$R' = \frac{1}{h_h a_{s,h} A_{\text{core}}} + \frac{t_{\text{cond,rep}}}{k_s a_{s,rep} A_{\text{core}}} + \frac{1}{h_c a_{s,c} A_{\text{core}}} \quad (5)$$

Two constrained optimization problems were solved using the real-coded genetic algorithm implemented in the EES Min/Max facility, with a population of 128 over 256 generations, a mutation rate of 0.7, and ten independent seeds for each case. Problem P1 maximizes Q/W_{pump} , with A_{core} fixed at 0.01 m² and design vector $(t_{\text{cell}}, t_h, t_c)$, where $t_{\text{cell}} \in [1, 20]$ mm. Problem P2 minimizes V_{core} , with t_{cell} fixed at 3 mm and design vector $(A_{\text{core}}, t_h, t_c)$, where $A_{\text{core}} \in [0.001, 0.1]$ m². Both problems are subject to $\Delta p_i \leq 50$ kPa on each fluid side, $t_{\text{wall,min}} \geq 0.2$ mm, and $L_{\text{core}} \leq L_{\text{allow}} = 1.0$ m, together with the requirement of a positive thermal driving force. Each TPMS topology was optimized independently rather than treated as a categorical design variable, allowing the optimum achievable by each topology to be compared directly under identical operating conditions and constraints.

4. Results and Discussion

4.1 Core volume minimization

All twenty P2 runs terminated with feasible solutions, and both topologies showed reproducible convergence. Over ten independent seeds for each topology, the final core volumes were 1.554 ± 0.033 L for Diamond and 2.216 ± 0.029 L for Gyroid. Most of the volume reduction occurred within the first ten generations, followed by slower, seed-dependent refinement within a relatively shallow near-optimal region. Although the final frontal areas varied by approximately 19%, the corresponding core volumes differed by only about 4%, indicating that a range of geometrically distinct designs provided nearly equivalent objective values. Residual variability was primarily associated with utilization of

the available hydraulic budget: the final volume decreased as the combined pressure-drop utilization increased ($r = -0.92$), indicating that more compact designs were obtained when a larger fraction of the allowable pressure drop was exploited. The same tendency was observed for both topologies, as shown in Fig. 2(b). The optimized threshold pairs also remained close to the symmetric locus, $t_c \approx -t_h$, indicating that strongly asymmetric partitioning of the two flow passages was not favored under the present operating conditions.

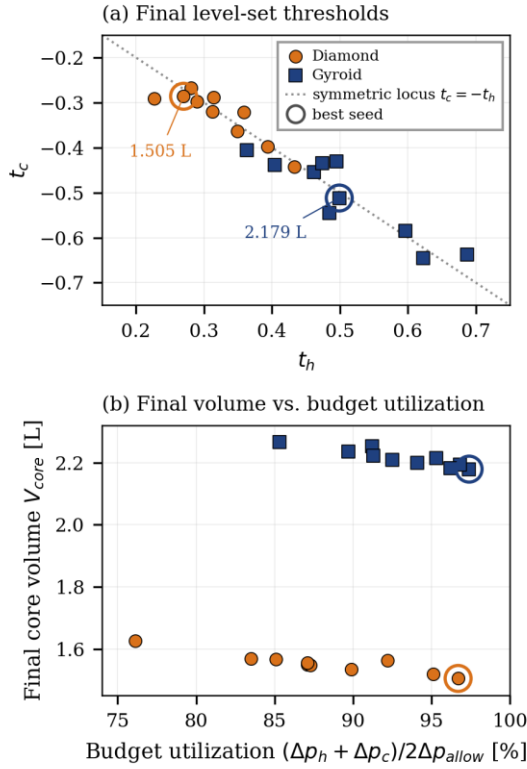


Fig. 2. Final designs from the twenty P2 runs for Diamond and Gyroid: (a) level-set thresholds with the symmetric locus $t_c = -t_h$; (b) final volume versus combined pressure-drop budget utilization.

Table I summarizes the best design obtained for each topology. Both P2 optima were pressure-drop-limited, utilizing approximately 97% of the combined allowable pressure-drop budget, whereas the core-length and minimum-wall-thickness constraints remained inactive. The optimized Diamond core required a volume of 1.505 L, compared with 2.179 L for Gyroid, corresponding to a 30.9% reduction at the same thermal duty. The comparison based on the ten-seed means yielded a consistent reduction of 29.9%, and the two distributions of final volumes did not overlap.

The volumetric advantage of Diamond results from the combined effects of heat-transfer area and convective performance. At the optimized porosity of approximately 0.33, Diamond provides about 24% greater fluid–solid interfacial area per unit core volume. In addition, the adopted topology-specific Nusselt correlations, together with the corresponding geometric hydraulic diameters,

yield higher convective heat-transfer coefficients for Diamond under the optimized conditions. Meanwhile, the predicted friction factors of the two topologies remain of comparable magnitude. Consequently, the thermal advantage of Diamond is obtained without a proportionally large hydraulic penalty. Because the optimized frontal areas are also similar, 46.7 cm² for Diamond and 50.5 cm² for Gyroid, the shorter required core length of Diamond (322 mm compared with 431 mm) translates directly into a smaller core volume.

Table I: Optimized designs for P2 and P1 at $L_{\text{allow}} = 1.0$ m

	P2 Diamond	P2 Gyroid	P1 Diamond	P1 Gyroid
V_{core} [L]	1.505	2.179	9.98	9.98
A_{core} [cm ²]	46.7	50.5	100*	100*
L_{core} [mm]	322	431	998	998
t_{cell} [mm]	3.0*	3.0*	7.38	5.81
t_h	0.270	0.499	0.093	0.189
t_c	-0.286	-0.512	-0.116	-0.185
Δp_h [kPa]	46.8	48.1	5.98	7.00
Δp_c [kPa]	50.0	49.3	6.46	7.05
$t_{\text{wall,min}}$ [mm]	0.217	0.279	0.200	0.200
Q/W_{pump}	71.2	70.7	553.4	489.4

*Fixed in the corresponding problem.

4.2 Heat transfer per pumping power

Under P1, the governing constraints changed fundamentally. All twenty runs terminated with $t_{\text{wall,min}} = 0.200$ mm to within 0.0001 mm and with L_{core} within 0.5% of L_{allow} , whereas only approximately 12–14% of the available pressure-drop budget was utilized. Thus, unlike P2, the P1 solutions were governed primarily by the minimum-wall-thickness and packaging constraints rather than by pressure drop.

Within the narrow optimal region, activation of the wall-thickness constraint strongly restricted the admissible combination of threshold separation and unit-cell size. For Diamond, for example, the quantity $(t_h - t_c)t_{\text{cell}}$ remained within approximately 1.538–1.539 mm while t_{cell} varied from 7.26 to 7.38 mm. The optimized solutions therefore clustered within a narrow region of the design space, leaving the relative allocation of the threshold magnitudes between the two fluid passages as the main remaining degree of freedom. A small but reproducible asymmetry, $|t_c| > |t_h|$, was observed. This tendency is consistent with the slightly greater density of the cold stream: for equal mass flow rate and pressure drop, the pumping-power contribution $\Delta p_{\text{mi}}/\rho$ is lower on the denser side, making a modest redistribution of hydraulic resistance toward the cold passage energetically favorable. The convergence was highly reproducible, with relative scatter of only 0.09% for Diamond and 0.03% for Gyroid. The two topologies nevertheless selected different physical unit-cell sizes, approximately 7.4 mm for Diamond and 5.8 mm for Gyroid.

At $L_{\text{allow}} = 1.0$ m, Diamond achieved $Q/W_{\text{pump}} = 553.4$, compared with 489.4 for Gyroid, representing a 13.1% improvement. Because the thermal duty is identical, this corresponds to approximately 11.6% lower core hydraulic pumping power for Diamond. Repeating the

optimization over $L_{\text{allow}} = 0.5\text{--}3.0$ m showed that the Diamond advantage persisted throughout the common design range, remaining between 10.7% and 15.6%, with no intersection between the two topology-specific trajectories (Fig. 3).

The mechanism responsible for this ranking differs from that governing P2. At the P1 optima, both topologies operate near $Re \approx 3500$ and $\varepsilon \approx 0.44$, with similar surface-area densities and nearly identical required thermal resistance per unit length, R' . The hot- and cold-side film resistances each account for approximately one half of the total resistance, whereas the wall-conduction contribution is only about 1%. Under these conditions, the principal discriminator becomes the hydraulic performance. The adopted correlations predict a friction-factor ratio of approximately $f_{D,G}/f_{D,D} \approx 1.10$, which is consistent with the corresponding hydraulic-power ratio of approximately 1.13. This indicates that the P1 ranking is driven primarily by the lower predicted hydraulic resistance of Diamond.

Increasing the allowable core length produced pronounced diminishing returns. For Diamond, successive increases in the envelope yielded improvements in Q/W_{pump} of approximately 9.6%, 2.0%, and 0.4%. The envelope sweep further indicated an internal optimum at approximately $t_{\text{cell}} \approx 11.5$ mm for Diamond and 12.1 mm for Gyroid, beyond which additional available core volume was not fully utilized. Notably, a 5.0-L Diamond design achieved $Q/W_{\text{pump}} = 505$, which is within 1.4% of the highest Gyroid value obtained in the envelope sweep at a core volume of approximately 28 L. Within the present model and design space, changing the topology therefore provides a substantially greater improvement in hydraulic economy than simply enlarging a Gyroid core.

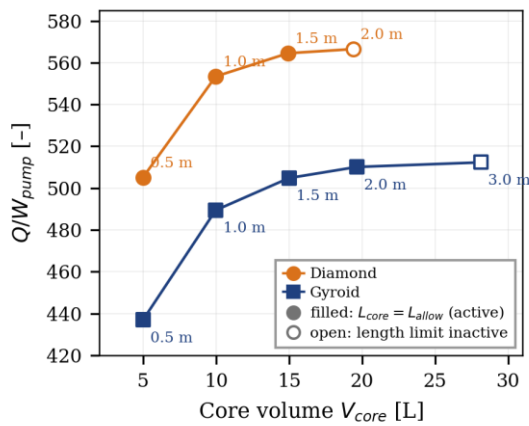


Fig. 3. Compactness-hydraulic-power trade-off from the P1 envelope sweep at a fixed $0.1\text{ m} \times 0.1\text{ m}$ frontal area.

4.3 Overall trade-off

The two problems probe the same evaluator from complementary directions. Compactness was governed

by the pressure-drop budget, whereas hydraulic economy was governed by the minimum-wall-thickness constraint and the packaging envelope. Although the wall limit contributed only about 1% of the thermal resistance, it was geometrically decisive because it strongly constrained the admissible combination of threshold separation and unit-cell size. The two Diamond optima differ by a factor of about 6.6 in volume and 7.8 in Q/W_{pump} , and extending the envelope beyond 1.0 m yields only a further 2.4% improvement in hydraulic economy while nearly doubling the volume. A practical exchanger should therefore be selected along this trade-off rather than at either single-objective extreme.

5. Conclusions

A standardized, manufacturability-aware framework for the macroscopic sizing and constrained optimization of two-fluid TPMS heat exchangers was developed by representing the TPMS core using threshold-based macroscopic geometric descriptors coupled with topology-specific transport correlations. For an $s\text{CO}_2$ core, Diamond was preferred under both objectives—30.9% smaller volume at fixed 3 mm cell size, and 10.7–15.6% higher heat transfer per pumping power at fixed frontal area—but for different reasons: a surface-area and heat-transfer advantage under volume minimization, and lower predicted friction under hydraulic-economy maximization. The persistence of this ranking under two distinct mechanisms indicates a consistent preference for Diamond within the adopted model. However, this conclusion is based on the nominal correlations, and future work will address correlation uncertainty and extend the framework to multi-objective optimization of compactness and hydraulic performance, with frontal area, unit-cell size, and level-set thresholds treated simultaneously as design variables.

ACKNOWLEDGEMENT

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning(KETEP) and the Ministry of Climate, Energy & Environment(MCEE) of the Republic of Korea (No. RS-2026-25537883). This work was also supported by the Technology Innovation Program (Materials and Components Technology Development Program) (RS-2025-24536111, Development of 3D Printing-Based Fabrication Technology for Printed Circuit Heat Exchangers(PCHE) for Micro Reactors) funded by the Ministry of Trade, Industry and Resources(MOTIR, Korea).

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