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NUMERICAL INVESTIGATION OF HEAT TRANSFER ENHANCEMENT IN ADDITIVELY MANUFACTURED GYROID-BASED COMPACT HEAT EXCHANGERS: A CRITICAL REVIEW

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ABSTRACT

Additively manufactured gyroid heat exchangers offer continuous, highly interconnected passages that are difficult to fabricate by conventional machining. This critical review assesses numerical methods and reported experimental evidence for heat-transfer intensification, with emphasis on the competing influence of pressure drop. A focused narrative search of peer-reviewed articles and scholarly reviews, primarily published during 2023–2026, was used to compare topology, channel design, materials, conjugate heat-transfer modeling, manufacturing effects and performance metrics. The evidence indicates that gyroid designs can outperform conventional cores under particular geometric and operating constraints; however, diamond and modified TPMS surfaces sometimes provide a more favorable hydraulic penalty. Reported CFD–experiment differences, especially for pressure losses, highlight the importance of measured surface roughness, realistic headers and model validation. The review proposes a reproducible numerical evaluation framework involving equal-duty or equal-pumping-power comparisons, grid-independence checks, uncertainty estimates and experimental calibration. It identifies fabrication-aware multi-objective optimization and generalized scaling correlations as priorities for future work. No new CFD or experimental results are claimed.

KEYWORDS: Triply periodic minimal surface; gyroid; compact heat exchanger; additive manufacturing; conjugate heat transfer; computational fluid dynamics; thermal–hydraulic performance.

1. INTRODUCTION

Compact heat exchangers are central to electronics cooling, propulsion, high-temperature recuperation and industrial heat recovery. Conventional plate-fin and printed-circuit geometries offer mature fabrication routes but constrain the flow passages that can be realized. Metal additive manufacturing (AM), particularly laser powder bed fusion, has enabled three-dimensional heat-transfer cores with curvature, branching and spatially graded density. Triply periodic minimal surfaces (TPMS) are especially attractive because a thin, continuous sheet may separate two intertwined fluid networks while retaining large contact area per unit volume [1–5].

The gyroid is commonly generated from an implicit periodic relation, $\sin(x)\cos(y) + \sin(y)\cos(z) + \sin(z)\cos(x) = c$, with scaled coordinates determining cell pitch and the iso-value c affecting phase volume. A sheet-based core uses the implicit surface as a finite-thickness wall; solid-gyroid and skeletal implementations have different hydraulic and structural behavior. The actual heat exchanger also includes manifolds, seals and connections, which are not represented by isolated periodic unit-cell simulations. Thus, comparison between studies requires careful attention to topology, fluid allocation, hydraulic diameter and boundary conditions [6–9].

This paper examines the central question: under what constraints can numerical optimization of a gyroid core yield an improvement in useful heat transfer without disproportionate pumping work? It is deliberately a critical narrative review rather than a report of newly performed numerical simulations. Only published results are attributed to prior authors, whereas recommended modeling choices and research opportunities are identified as synthesis or proposals.

2. Historical Development and Engineering Importance

Gyroid surfaces originated as mathematical minimal-surface geometries and were subsequently explored in architected materials and cellular structures. Their thermal use accelerated once printable metal channels with complex internal overhangs became practical. Earlier compact-exchanger development centered on fin passages and micromachined channels; more recent work connects CAD generation of implicit TPMS cores, CFD-based sizing, LPBF fabrication and experimental pressure-drop/heat-transfer characterization [1,2,10]. Since 2023, the field has expanded from steady numerical rankings to measured prototypes, correlations, shape modulation and data-driven optimization [6,11–15].

The importance is not confined to maximizing Nusselt number. Gyroid structures may provide low mass, compact volume, large area density and diverse flow configurations; they can also impose long tortuous paths, difficult powder removal and considerable local losses. High-temperature sCO_2 recuperators and liquid–liquid units illustrate distinct design requirements. A geometry with the highest heat-transfer coefficient is not automatically the most energy efficient, least expensive or most reliable heat exchanger [5,12,16].

3. Review Methodology and Scope

A focused narrative literature survey was assembled through topic-specific searches for "gyroid heat exchanger", "TPMS heat transfer", "additive manufacturing", "CFD", "pressure drop" and related combinations. Publisher landing pages, DOI records and accessible abstracts were checked for the included bibliographic entries. Priority was assigned to peer-reviewed experimental–numerical comparisons, numerical correlation studies, geometry optimization and authoritative reviews from 2023–2026, supplemented by adjacent TPMS heat-sink and two-phase research. The reference list is a traceable selection, not an exhaustive census; no database hit counts or PRISMA screening totals are asserted.

For synthesis, each investigation was classified by device type, geometry, working conditions, method, principal performance observation and limitation. Quantitative claims are retained only with their study-specific comparators. For example, a percentage improvement against straight tubes is not equated with an improvement against a brazed plate heat exchanger. The review also differentiates whole-exchanger tests from unit-cell calculations, and experimental measurements from CFD predictions. These choices prevent misleading pooling of incompatible outcomes.

4. Literature Survey and Critical Synthesis

Yan et al. [6] developed a three-dimensional conjugate model in OpenFOAM for multiple TPMS exchanger configurations and described helical or sinusoidal flow paths with repeated merge–split behavior. Their numerical comparison with a printed-circuit exchanger demonstrated substantial potential for intensification at Reynolds numbers around 200–500. The result is important mechanistically: secondary flow and repeated boundary-layer redevelopment contribute to improvement beyond surface area alone. Nevertheless, the performance ratios depend on the chosen printed-circuit reference and the normalization method; they cannot be generalized to every compact exchanger or Reynolds-number regime.

Yan et al. [7] subsequently manufactured a 316L gyroid unit by selective laser melting and investigated single-phase water performance experimentally and numerically. At 500 kg/h, the reported measured overall coefficient and cold-side pressure difference exceeded corresponding theoretical predictions by 9.70% and 69.82%, respectively. This discrepancy is particularly significant for CFD verification, because an apparently acceptable thermal match may conceal a poor hydraulic representation. The authors also developed an experimental Nu–Re correlation. The study supports explicit measurement of as-built roughness and inlet/outlet geometries rather than reliance on nominal CAD alone.

Renon and Jeanningros [8] calculated Nusselt and friction-factor correlations for Gyroid and Diamond channels and found broadly comparable thermal behavior but a lower pressure penalty for the Diamond configuration within their model domain. Their treatment makes correlations more useful for preliminary design, yet geometry-specific definitions and property variations remain important. Coe et al. [17] explored stretching of TPMS cells; for selected comparison criteria, the altered geometry improved the thermal–hydraulic balance dramatically. Taken together, these works show that “gyroid” is not a single design but a tunable family whose anisotropy and hydraulic pathway affect any claimed advantage.

Kus et al. [18] combined a gyroid heat-exchanger prototype with numerical calibration and reported that surface roughness strongly influenced pressure drop. This reinforces the evidence from Yan et al. [7] that model discrepancies are not merely numerical error. Kus et al. also emphasized the role of cell size in exergy destruction. Separately, Wang et al. [9] used numerical and experimental methods across several TPMS structures, including flow-path analysis. Their comparisons demonstrate that channel topology and asymmetry should be studied at the scale of the entire exchanger, including how the two fluid domains are supplied and collected.

Yu et al. [12] integrated surrogate modeling, genetic optimization, LPBF and high-temperature supercritical-carbon-dioxide testing in a Haynes 282 gyroid recuperator. At the reported operating conditions, the optimized exchanger delivered 51.8 kW and improved heat transfer by 26.4% relative to a straight-pipe comparator, with lower measured pressure drop. This is stronger deployment-oriented evidence than geometry-only CFD because it includes fabrication and high-temperature testing; however, the benefit is specific to the baseline, operating conditions and optimized parameters. It does not establish gyroid superiority over all competing TPMS or conventional architectures.

Kim et al. [19] experimentally compared a printed gyroid exchanger with a commercial brazed plate exchanger and found that flow direction influenced duty; a flow arrangement

gave up to 15% enhancement, while overall coefficients were up to 4.4% higher and friction factors up to 30.5% lower over a comparable Reynolds-number range. The result is directly relevant to commercial benchmarking. In contrast, studies of functional surface modulation [20], anisotropic lattice manipulation [21] and porosity [22] demonstrate that thermal enhancement can come with considerable changes in pressure loss. The collective message is that heat duty, compactness, fluid pumping work and manufacturability must be assessed jointly.

5. Numerical Investigation Framework for Future Studies

A reproducible study should begin with a fixed heat-duty requirement, prescribed hot- and cold-side inlet states, material selection and manufacturable volume envelope. Competing cores—standard gyroid, stretched/graded gyroid, diamond and a conventional exchanger—should be generated at matched outer dimensions, available exchange volume or thermal duty. Key design variables include unit-cell pitch, iso-value, wall thickness, porosity, anisotropic stretch, flow orientation and manifold geometry. Optimization based on area density alone is insufficient because the local cross-sectional area and path tortuosity also determine velocity and friction.

Three-dimensional steady conjugate heat transfer provides a useful baseline, solving conservation of mass, momentum and energy in both fluid passages and conduction in the solid separating wall. The working-fluid properties should vary with temperature when relevant, especially for supercritical fluids and wide temperature spans. Laminar, transitional or turbulent treatment must follow the local Reynolds regime and be supported by sensitivity tests where flow transition is uncertain. Numerical heat balance and mesh independence should be reported before deriving correlations. At least three refinement levels, near-wall resolution checks and local pressure-loss scrutiny are advisable [6–8,12].

For a two-stream exchanger, hot-side and cold-side heat rates are $Q_h = \dot{m}_h c_{ph} (T_{hi} - T_{ho})$ and $Q_c = \dot{m}_c c_{pc} (T_{co} - T_{ci})$. Their relative mismatch, $|Q_h - Q_c| / [(Q_h + Q_c)/2]$, is a basic energy-closure check. Overall conductance may be estimated from $UA = Q/\Delta T_{lm}$ when the assumptions for the log-mean temperature difference hold. A fluid-side Reynolds number is $Re = \rho u D_h/\mu$, and the Nusselt number is $Nu = hD_h/k$. Pumping power should be computed as $W_{pump} \approx \Sigma(\Delta p\, \dot{V})/\eta_{pump}$. In corrugated or TPMS passages, the definition of hydraulic diameter must be explicit and consistent with the chosen wetted area [8,23].

Recommended outputs include Q, UA, exchanger effectiveness ε, total Δp, pumping power, specific duty Q/V, Q/mass, temperature uniformity, entropy generation and uncertainty bands. A Pareto front of duty or effectiveness versus pumping work, mass and fabrication cost is more informative than selecting the highest Nusselt number. When performing sensitivity analysis, material thermal conductivity, wall thickness, roughness, as-built dimensional deviation and

header pressure loss should be perturbed independently. Experimental validation should document test-fluid properties, instrument calibration, thermal leakage and measurement uncertainty.

6. Discussion and Comparative Analysis

Table 1 separates the direct observations of representative studies from the implications for numerical model design. Reported comparisons are retained against their actual baseline and should not be read as a single ranking.

Study	Approach / comparator	Reported observation	Interpretation / limitation
Yan et al. [6], 2023	Conjugate CFD; TPMS vs PCHE	~90–110% overall coefficient improvement for selected structures at Re 200–500	Numerical; baseline-specific
Yan et al. [7], 2024	316L SLM gyroid; water tests + CFD	At 500 kg/h, measured U +9.70%, cold-side Δp +69.82% vs theoretical	As-built effects critical
Renon & Jeanningros [8], 2025	Gyroid vs Diamond channels; CFD	Similar thermal behavior; Diamond less Δp in studied cases	No universal gyroid superiority
Yu et al. [12], 2025	Optimized Haynes 282; sCO_2 test	51.8 kW; Q +26.4%; Δp at least 16% lower vs straight pipe	High-temperature validation; baseline-specific
Kim et al. [19], 2026	Printed gyroid vs brazed plate exchanger	U up to +4.4%; f up to −30.5%; flow direction mattered	Real benchmark; depends on setup
Coe et al. [17], 2025	Stretched TPMS; periodic CFD	Strong heat-transfer/pumping trade-off benefits in selected criteria	Cell stretch changes comparator geometry

Table 2 provides an engineering evaluation matrix rather than a literature-derived numerical score. It explicitly distinguishes opportunities from constraints.

Criterion	Potential gyroid advantage	Main engineering risk	Recommended verification
Heat transfer	Large area and mixing	Uneven allocation / bypass	Matched Q and UA with local fields
Pumping power	Tunable flow network	High tortuosity / header loss	Measure total Δp and Wpump
Compactness	High area density	Wall-thickness and strength limits	Duty per volume and pressure proof
Manufacturing	Monolithic integrated core	Roughness, pores, residual powder	CT/roughness inspection and leak test
Reliability	Fewer assembly joints	Fouling and internal cleaning difficulty	Long-duration / cyclic testing
Sustainability	Possible mass and duty savings	Build energy, powder wastage and cost	Life-cycle and cost sensitivity

The apparent tension between studies reporting major improvements and those finding hydraulic disadvantages is not contradictory. Different investigators vary Re, fluid properties, periodic-cell length, topology (sheet versus solid), baseline exchanger, definition of friction factor and the inclusion of manifolds. A gyroid can be thermally superior but still unattractive where pumping-power availability is limited. Conversely, pressure-drop optimization through stretching or conformal transitions may improve whole-device performance even if local Nu decreases. It is therefore preferable to report both equal-flow-rate and equal-pumping-power comparisons, and to distinguish a core-only model from a complete exchanger [8,12,17,19,21].

A second theme is the difference between mathematical and as-built geometry. LPBF creates stair-stepped surfaces, partially fused particles, roughness and potential occlusions. These can increase the effective wetted area while raising viscous drag and uncertainty. Any CFD model that reports excellent thermal predictions but large hydraulic discrepancies needs targeted calibration rather than unqualified acceptance. Contemporary studies of high-temperature prototypes, copper/aluminum/ceramic materials and phase-change heat exchangers extend the application domain, but they also add material dependence and transient processes that complicate simple correlations [7,12,18,24,25].

7. Outcomes, Research Gaps and Future Direction

The review yields four principal outcomes. First, gyroid-based exchangers are credible alternatives for high-area compact thermal devices, but improvements are conditional on geometry and comparator. Second, fluid-path curvature and repeated mixing contribute to thermal enhancement, while friction and manifold design determine whether these gains are useful. Third, manufacturing-induced roughness and dimensional deviations are first-order modeling inputs, not optional afterthoughts. Fourth, a high-quality numerical paper should demonstrate both energy-balance closure and an optimization objective that accounts for pressure drop. These outcomes are drawn from the reviewed literature; no new performance measurements are presented.

The most defensible future numerical investigation would compare standard, stretched, graded and anisotropic gyroids against diamond and conventional cores under identical fluid conditions, heat-duty targets and pumping-power constraints. A coupled geometry–CFD–experimental workflow should quantify mesh sensitivity, roughness correction, uncertainty and additive-manufacturing tolerance. Further gaps include time-dependent fouling, thermal cycling, fatigue, pressure containment, powder evacuation, channel cleaning and

generalizable Nu/f correlations across fluids and material systems. Carefully designed benchmark datasets could also support physics-guided surrogates without obscuring thermodynamic constraints [12,17,22,26–28].

8. CONCLUSIONS

Gyroid-based compact heat exchangers exemplify the design freedom created by metal additive manufacturing. The reviewed work supports their potential for high surface density and intensified heat transfer, but it does not establish that a gyroid is universally optimal. Diamond and modified TPMS forms can outperform it under certain hydraulic criteria. Experimental studies demonstrate that surface roughness, manifolds and flow direction can materially alter CFD–hardware agreement. Consequently, numerical claims of enhancement should be grounded in matched boundary conditions, validated conjugate models, complete pressure-loss accounting and multi-objective performance indicators. Future progress is most likely to come from fabrication-aware geometry optimization and independent experimental replication, rather than from additional idealized flow-field comparisons alone.

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