

Optimization of Heat Exchanger Design with Zig-Zag Flow: Minimum Volume Design Satisfying Structural and Thermal Requirements

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1. Introduction

Compact heat exchangers with zig-zag channels are critical in small modular reactors (SMRs) and supercritical CO₂ (s-CO₂) Brayton cycles, where high thermal performance and structural integrity are required. Printed Circuit Heat Exchangers (PCHEs), manufactured by diffusion bonding of chemically etched or machined plates, are widely recognized for their compactness, high heat transfer coefficients, and excellent pressure resistance. Conventional photochemical etching, however, limits the channel depth to approximately 2.5 mm [1].

The present study explores larger channel diameters of 3–4 mm under s-CO₂ conditions, focusing on heat duty, pressure drop, and ASME BPVC compliance. Since these diameters exceed the proven etched-and-bonded range, they are referred to here as PCHE-like geometries rather than strict PCHEs. This distinction is important because PCHEs are defined by their diffusion-bonded plate construction, whereas microchannel plate-type heat exchangers employ sub-millimeter passages primarily for electronics cooling or compact thermal management. Additive manufacturing (AM) provides a separate fabrication route capable of realizing PCHE-like structures with enhanced design freedom, though it does not involve diffusion bonding and therefore falls outside the strict definition of PCHE.

Accordingly, this study evaluates the feasibility of scaling PCHE-like channels beyond etched limits, while maintaining the thermal–structural analysis framework typically applied to diffusion-bonded PCHEs.

2. Methodology

The optimization framework was established under fixed boundary conditions, with both primary and secondary fluids set as supercritical CO₂ under recuperator conditions. Prescribed mass flow rates, inlet/outlet temperatures, and pressures defined the constraints, and the objective was to identify geometries delivering the required heat duty while keeping pressure drops acceptable.

To assess channel size effects, hydraulic diameters beyond the conventional etched limit (1.8 mm) were extended to 3 and 4 mm. These larger cases are treated as

PCHE-like configurations; manufacturability was not modeled, though machining plus bonding or AM may offer future pathways.

Baseline values were taken from Li et al. (2025), who validated a one-dimensional s-CO₂ Brayton cycle model, ensuring operation within a confirmed envelope. Only candidates meeting feasibility checks were subjected to detailed thermal–structural evaluation. Both streams were modeled as supercritical CO₂ in a one-to-one channel arrangement following the KAIST HXD reference geometry. The applied boundary conditions are summarized in Table I.

Table I. Baseline operating conditions for PCHE design [2]

Parameter	Value
Hot-side inlet temperature	730 K
Cold-side inlet temperature	500 K
Hot side inlet pressure	9 MPa
Cold side inlet pressure	22.5 MPa
Working fluid	Supercritical-CO ₂
Hot side total mass flow rate	80 kg/s
Cold side total mass flow rate	100 kg/s

Each geometry was structurally evaluated according to ASME BPVC Section VIII Division 1, Appendix 13, with the effective width coefficient for SS316 conservatively taken as 5,800 psi (≈ 40 MPa) [3]. Although the actual channel cross-section is semicircular, all structural calculations were performed based on a rectangular cross section to ensure a conservative evaluation. Membrane and bending stresses of short-side, long-side, and stay plates were calculated following Appendix 13 procedures and compared with allowable stresses for SS316 from ASME Section II-D.

The overall geometry and dimensional parameters of the PCHE are summarized in Fig. 1 and Table II. The figure illustrates the geometric configuration, while the table lists the corresponding parameters used in the structural and thermal–hydraulic evaluation. In addition, Table III presents the adjusted dimensional parameters required to satisfy maximum allowable stresses, showing how wall thicknesses increase with larger channel diameters to maintain structural integrity.

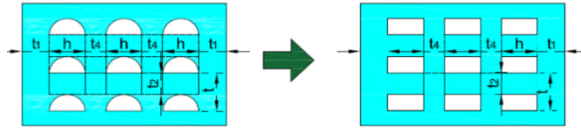


Fig. 1. PCHE Geometry and Dimensional Parameters

Table II. PCHE Dimensional Parameters

Parameter	Description	Parameter	Description
t_1	Side wall thickness	t_4	Channel-to-channel horizontal wall thickness
t_2	Channel-to-channel vertical wall thickness	h	Channel diameter
t	Overall plate thickness		

Table III. PCHE Dimensional Parameters Adjusted to Satisfy the Maximum Allowable

Channel diameter (mm)	t_1 (mm)	t_2 (mm)	t_4 (mm)	h (mm)	t (mm)
1.8	1.9	0.8	0.45	1.8	1.55
3.0	3.45	1.32	0.74	3.0	2.57
4.0	5.0	1.8	1.0	4.0	3.47

Thermal-hydraulic performance was verified using the KAIST HXD 1, 2D MATLAB code, which simulated two-dimensional heat transfer and pressure drop in zig-zag channels under the prescribed inlet/outlet conditions. As shown in Fig. 2, the baseline 1.8 mm channel geometry was used as the reference configuration for these simulations. The HXD code has been benchmarked against experimental PCHE data in previous KAIST studies, confirming its applicability to supercritical CO₂ conditions. Acceptance criteria required that the calculated heat duty match 20 MWth, the pressure drops on both sides remain within 200 kPa, and the calculated thermal conductance satisfy design requirements. Design failing to meet any of these criteria was excluded.

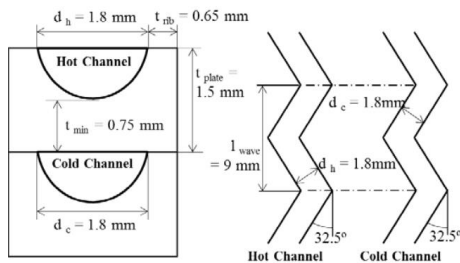


Fig. 2. Channel Geometry of 1.8mm diameter PCHE [4]

3. Results

The optimal partitions ($a \times b$), dimensions, and volumes are summarized in Table VI. The 1.8 mm case achieves the minimum volume; the 3.0 mm case delivers

the best thermal-hydraulic balance; the 4.0 mm case is structurally feasible but tends to be thermally unfavorable.

Table VI. Optimal partitions, dimensions, and performance indicators

Channel diameter (mm)	N _{channel}	L (m)	Optimal (a×b)	Width (m)	Thickness (m)	Volume (m ³)
1.8	92,000	0.60	125x736	0.230	1.254	0.173
3.0	33,000	1.08	132x250	0.406	0.694	0.304
4.0	18,400	1.52	115x160	0.750	0.407	0.465
Channel diameter (mm)	Inlet T (K) / P (MPa)	$\Delta P_{hot} / \Delta P_{cold}$ (kPa)	Heat duty (MW _{th})	Peak stress $\leq$ allow (MPa)		
1.8	730 / 9	199.32 / 109.12	20.06	σ_{stay} : 88.387 $\leq$ 89.997		
3.0	730 / 9	195.42 / 106.96	20.04	σ_{long} : 89.998 $\leq$ 89.998		
4.0	730 / 9	198.36 / 108.32	19.96	σ_{stay} : 88.247 $\leq$ 93.007		

The 1.8 mm channel design exhibited the smallest module volume, approximately 0.173 m³, which was the most compact configuration among the cases considered. This geometry fully utilized the width constraint while maintaining a relatively large thickness, thereby providing a significant advantage in terms of securing structural margin. Such structural robustness is particularly beneficial under high-pressure operating conditions, where mechanical reliability is a critical design factor. From a thermal perspective, this design is expected to achieve the required overall heat transfer conductance (UA). Nevertheless, the increased flow resistance associated with the narrow channels raises concerns about pressure drop, which must be carefully evaluated using the HXD analysis to confirm the feasibility of this configuration in practical operation.

In comparison, the 3.0 mm channel design yielded an intermediate module volume of about 0.304 m³, representing a moderate size that neither minimized nor maximized the system footprint. More importantly, this design offered the most balanced compromise between heat transfer performance and pressure drop. The surface-area density was sufficient to achieve effective thermal performance, while the larger hydraulic diameter alleviated the excessive pressure drop issues observed in the 1.8 mm case. This balance makes the 3.0 mm design a promising candidate for realistic applications, as it aligns both thermal and structural considerations in a relatively optimized manner. Consequently, it was regarded as the most practically viable solution in the present study.

By contrast, the 4.0 mm channel design produced the largest module volume, approximately 0.465 m³, which substantially increased the overall footprint of the heat exchanger module. As the channel diameter increases, the total flow cross-sectional area becomes larger, and the length of the channel must also grow to meet the thermal

duty, inevitably enlarging the module size. On the other hand, the increased length allows the thickness of the module to be reduced, which introduces some degree of flexibility when adapting the design to spatial constraints in a plant layout. Despite this benefit, the 4.0 mm design suffers from significantly reduced surface-area density, which limits the heat transfer capability per unit volume. This thermal disadvantage makes it unlikely to achieve the required UA, indicating that this configuration is less favorable from a performance standpoint and would require substantial compensation measures if adopted.

4. Discussion

The study demonstrated that minimizing exchanger volume requires balancing geometry, structure, and thermal performance. Increasing channel length improves heat transfer area and effectiveness but linearly increases pressure drop according to the Darcy–Weisbach relation. Excessive ΔP can reduce outlet pressure below the CO₂ critical pressure (7.38 MPa), potentially causing the fluid to leave the supercritical regime mid-channel. This risk highlights the necessity of imposing ΔP limits in design.

Structurally, external pressure buckling was often the governing factor for wide plates. Thermally, smaller etched channels enhanced heat transfer but raised concerns about fouling and manufacturability. Although smaller diameters improve performance, manufacturability constraints such as minimum etching width and bonding limits restrict the feasible range; in practice, conventionally etched-and-bonded SS316L PCHEs achieve wall thicknesses of about 0.75 mm at 20 MPa [4]. While smaller diameters tend to maximize heat transfer, manufacturing constraints and cost considerations may limit the minimum feasible channel size, which must be addressed in practical applications. The use of SS316 was justified by its corrosion resistance and high-temperature applicability, though its allowable stress decreases at elevated temperatures, requiring conservative safety margins. The KAIST HXD 1, 2D MATLAB code was essential in resolving these trade-offs, as it could capture zig-zag flow effects beyond simplified correlations. In this context, the 3–4 mm designs analyzed here are regarded as PCHE-like geometries, extending beyond the established etched range but useful for exploring thermal–structural feasibility. Additional sensitivity checks further indicated that stricter pressure drop limits shift the optimum toward larger diameters, while relaxed limits allow smaller channels with higher UA density, confirming the importance of selecting realistic ΔP criteria.

5. Conclusion

A design procedure for zig-zag channel compact heat exchangers was developed to minimize volume while ensuring structural and thermal–hydraulic performance. The overall workflow is summarized in Fig. 3, providing

a stepwise method for screening feasible designs. Among the cases, the 1.8 mm design minimized volume, the 3.0 mm design offered the best balance, and the 4.0 mm case was structurally feasible but thermally insufficient. While etched PCHEs are limited to ~ 2.5 mm, PCHE-like 3–4 mm channels provide useful insight into design trade-offs under s-CO₂ conditions.

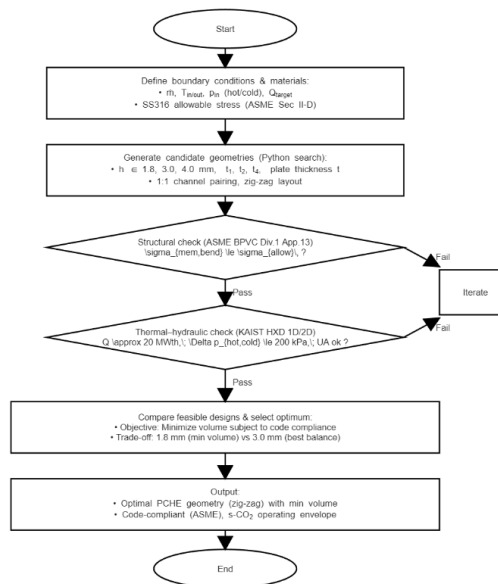


Fig. 3. PCHE Zig-Zag Design Procedure (Minimum Volume under Structural and Thermal Constraints)

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