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

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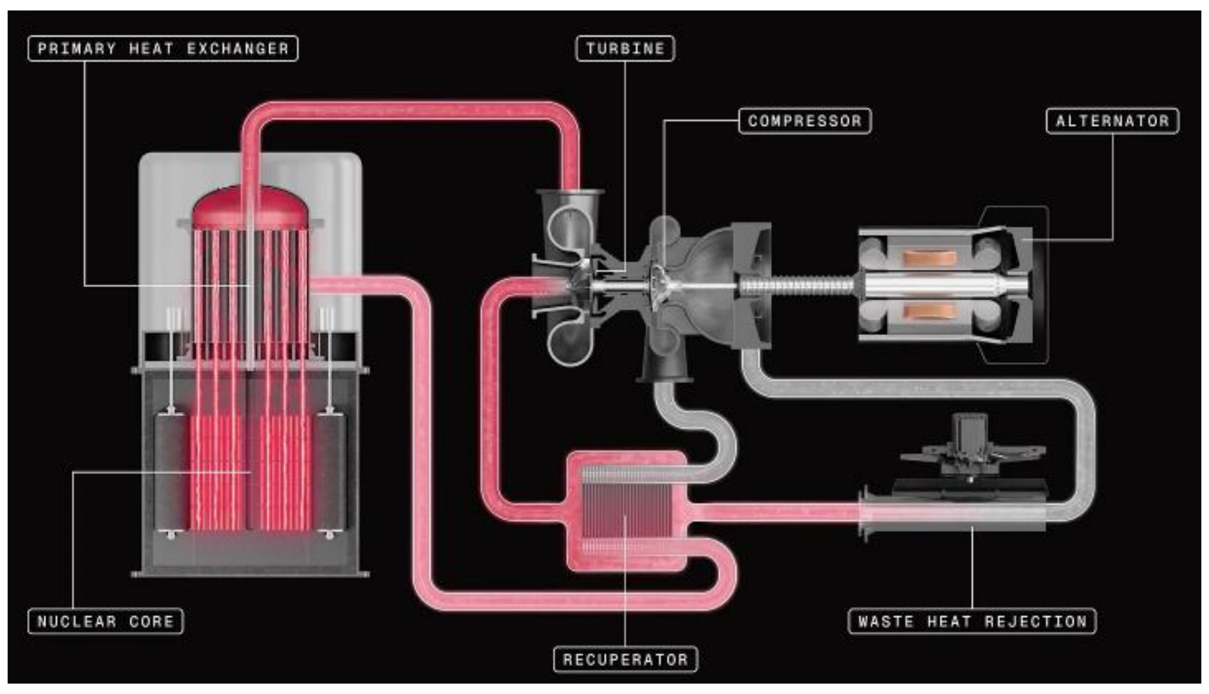
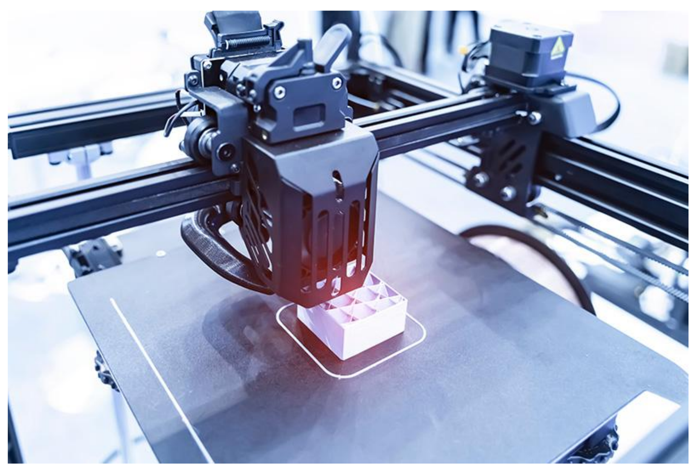
Introduction

- Zig-zag channels are key for SMRs and supercritical CO_2 (s-CO_2) Brayton cycles, enabling high heat transfer in compact, high-pressure hardware.
- Printed Circuit Heat Exchangers (PCHEs) which are made by diffusion-bonding etched plates offer high heat-transfer coefficients, exceptional pressure tolerance, and compactness, suiting nuclear and power-cycle service.
- Conventional photochemical etching caps channel diameters at ~2.5 mm; this work evaluates 3–4 mm s-CO_2 channels for heat-transfer efficiency, pressure drop, and structural integrity.
- Additive manufacturing, while outside the strict PCHE definition, is explored as a route to PCHE-like geometries with greater design freedom.



▲ *Schematic of Nuclear reactor design [1]*

▲ *PCHE [2]*



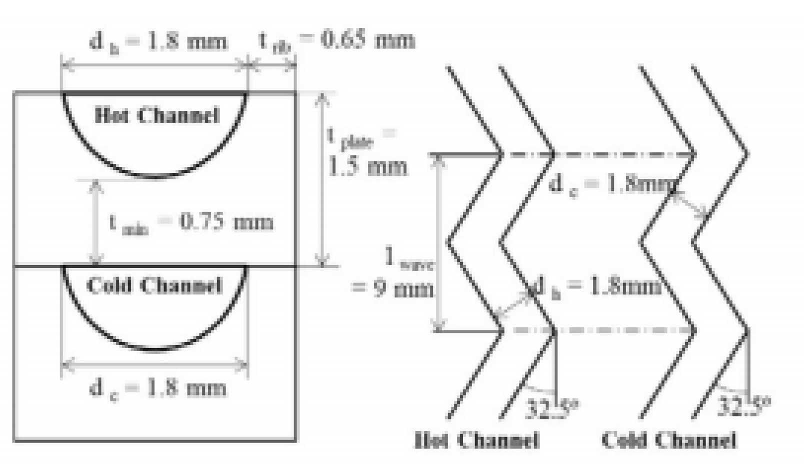
▲ *Additive Manufacturing [3]*

Methodology

- The optimization assumed a recuperator with fixed boundaries, using s-CO_2 on both hot and cold sides and prescribing mass flow rates, inlet/outlet temperatures, and pressures

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	S-CO_2
Hot side total mass flow rate	80 kg/s
Cold side total mass flow rate	100 kg/s

▲ *Baseline Operating Conditions for PCHE design*



▲ *Channel Geometry of 1.8mm diameter PCHE [4]*

- Channel diameters were scaled from the ~1.8 mm etched baseline to 3–4 mm as PCHE-like geometries to test thermal performance and compliance with specifications, including pressure-drop limits.
- Structural feasibility was checked against ASME BPVC Section VIII, Division1, Appendix13. Thermal-hydraulic behavior in zig-zag channels was simulated with the KAIST HXD MATLAB code to predict s-CO_2 heat transfer and pressure loss.

Results

- The 1.8 mm design is the most compact but suffers from high pressure drops, the 3.0 mm design offers the best balance of thermal performance and pressure drop, while the 4.0 mm design, though structurally feasible, results in a larger volume and reduced thermal performance.

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

▲ *PCHE Geometry and Dimensional Parameters*

Channel diameter (mm)	N_ Channel	L (m)	Optimal (a*b)	width (m)	Thickness (m)	Volume (m^3)	Inlet T (K) / P (MPa)	ΔP_hot / ΔP_cold (kPa)	Heat duty (MW_{th})	Peak stress ≤ allow (MPa)
1.8	92,000	0.60	125*736	0.230	1.254	0.173	730 / 9	199.32 / 109.12	20.06	σstay : 88.387 ≤ 89.997
3.0	33,000	1.08	132*250	0.406	0.694	0.304	730 / 9	195.42 / 106.96	20.04	σlong : 89.99 ≤ 89.998
4.0	18,400	1.52	115*160	0.750	0.407	0.465	730 / 9	198.36 / 108.32	19.96	σstay : 88.247 ≤ 93.007

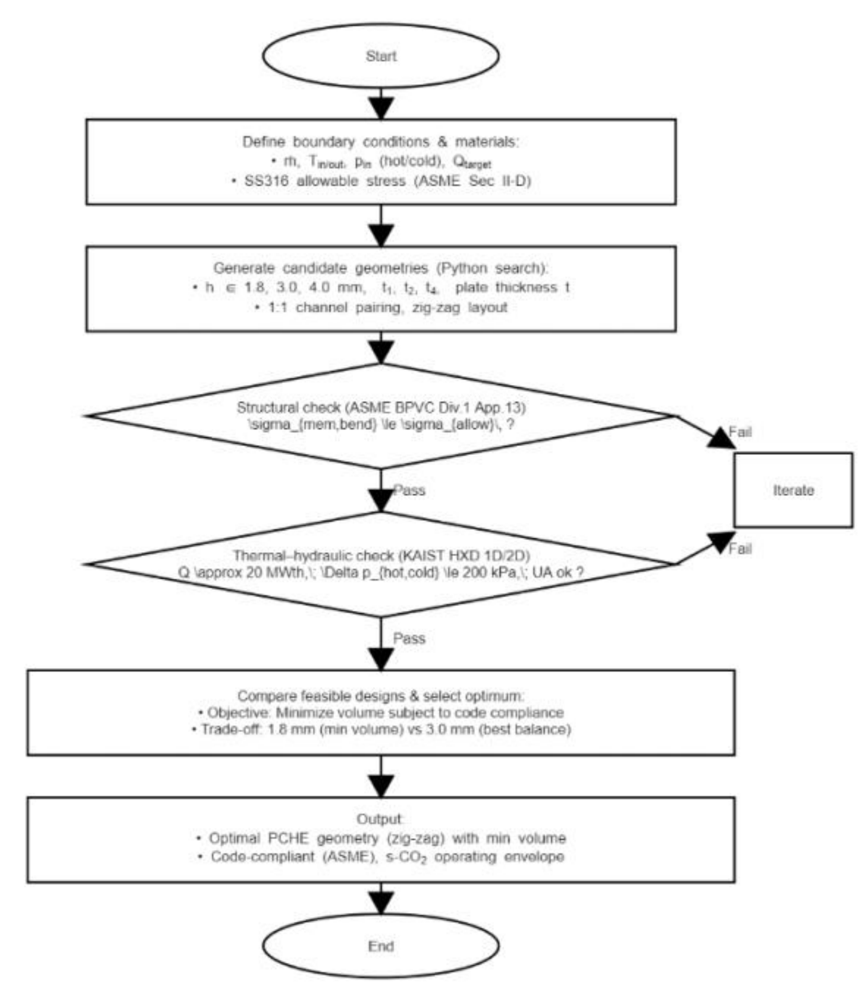
▲ *Optimal partitions, dimensions and performance indicators*

Discussion

- Minimizing volume is a trade-off: longer channels add area but raise Δp (Darcy–Weisbach), and too much Δp can push CO_2 out of the supercritical regime—so strict pressure-drop limits are required.
- Structural limits are set mainly by external-pressure buckling of wide plates; smaller diameters help heat transfer but risk fouling and face etching/bonding limits. SS316 is corrosion-resistant at high T, yet allowable stress falls with temperature, so conservative margins are needed.
- KAIST HXD 1D/2D modeling captures zig-zag effects beyond simple correlations, enabling a balanced feasibility check of 3–4 mm channels for both thermal-hydraulic performance and structural integrity.

Conclusion

- A zig-zag PCHE design workflow was established to minimize volume while satisfying thermal-hydraulic and structural requirements, including geometry selection and integrity checks.



▲ *PCHE Zig-Zag Design Procedure (Minimum Volume under Structural and Thermal Constraints)*

- The 1.8 mm channel is most compact but incurs excessive pressure drop; the 3.0 mm channel offers the best performance–Δp trade-off and is most practical; the 4.0 mm channel is structurally acceptable but thermally inefficient and larger.
- Extending beyond ~2.5 mm to 3–4 mm channels clarifies key sCO_2 trade-offs and informs future heat-exchanger development.

[1] Antares Industries.Official website.
[2] SHENSHI EC. PCHE (Printed Circuit Heat Exchanger)
[3] Manufacturing Digital. Next-level 3D printing developed by the University of Tokyo
[4] Baik, S., Kim, S. G., Son, S., Kim, H. T., & Lee, J. I. (2015). Printed circuit heat exchanger design, analysis and experiment. In NURETH-16, Chicago, IL: ANS