The 6th International Electronic Conference on Applied Sciences

ASEC 2025 Conference

09–11 December 2025 | Online

Geometric Optimization and Advanced Material Integration for Enhanced Thermal Performance of Compact Cross-Flow Heat Exchangers in High-Temperature Applications

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INTRODUCTION & AIM

High-temperature energy systems, such as externally fired micro gas turbines (MGTs), demand heat exchangers that are compact, lightweight, and capable of operating with high thermal effectiveness. Traditional metallic exchangers (e.g., steel) have limited lifetime due to oxidation and mechanical instability, making Ceramic Matrix Composites (CMCs) necessary. This study focuses on Graphene Reinforced Ceramic Matrix Composites (G-CMC). G-CMC materials offer superior high-temperature stability, low density (providing ~50% weight reduction compared to steel), and significantly enhanced thermal conductivity (up to 200 W/m·K). The primary aim of this numerical study is to design and optimize a cross-flow block heat exchanger using G-CMC material. We systematically evaluate five different geometric configurations (including flow distributors, ribs, and turbulence promoters) to quantify their contribution to maximizing thermal effectiveness (ε).

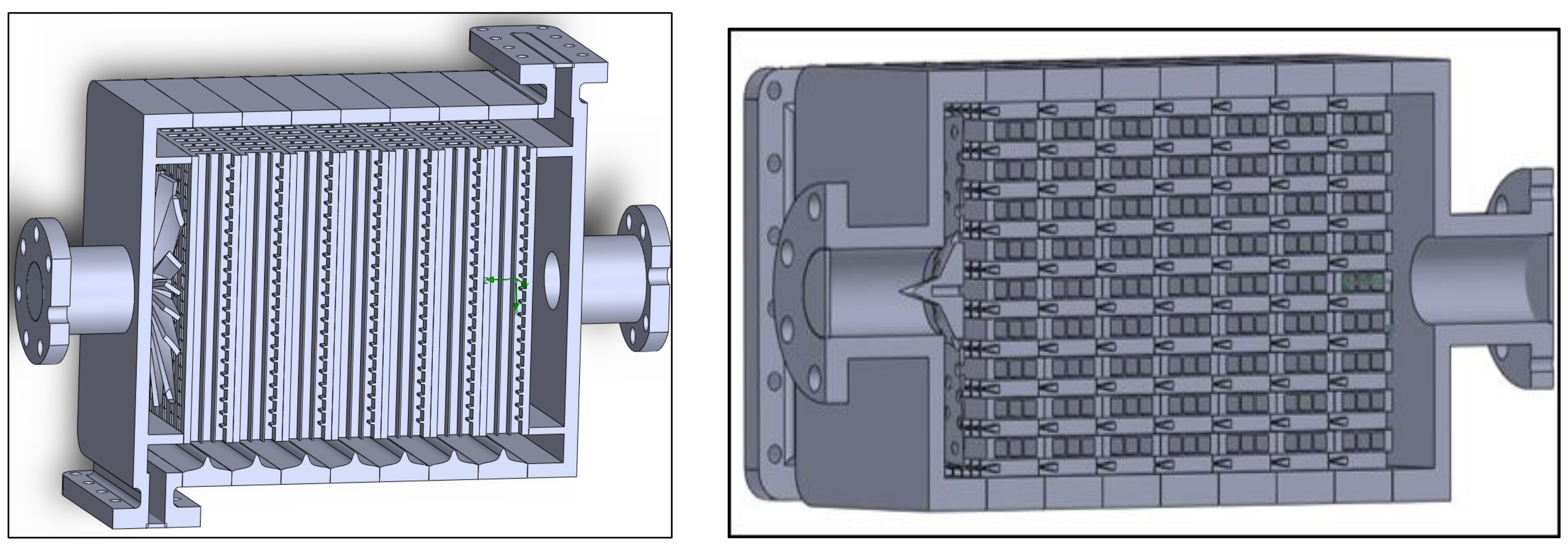

Figure 1. The compact heat exchanger model used in this study.

METHOD

- A compact cross-flow heat exchanger was modeled in SolidWorks and analyzed using the Flow Simulation module.
- Thermal and flow boundary conditions were kept constant, with inlet temperatures of 1223 K (hot) and 453 K (cold) at 0.01 kg/s.

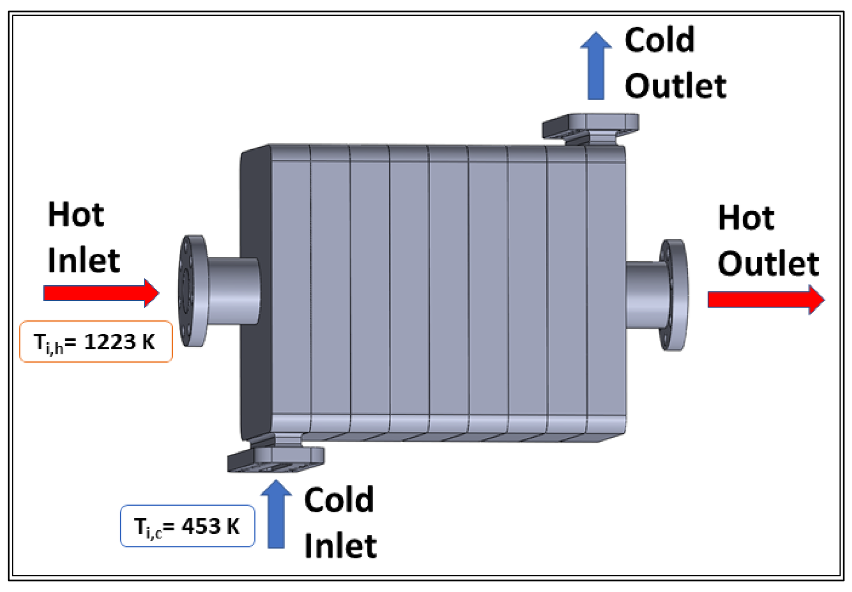

Figure 2. Boundary conditions of numerical analysis.

Table 1. Material properties of stainless steel and graphene/Al_2O_3 ceramic composite.

Property	AISI 304 Stainless Steel	G-CMC
Density (kg/m³)	7850	3800
Thermal conductivity (W/m·K)	16	200
Specific heat (J/kg·K)	500	900
coefficient of thermal expansion (1/K)	17.3×10^{-6}	4.5×10^{-6}

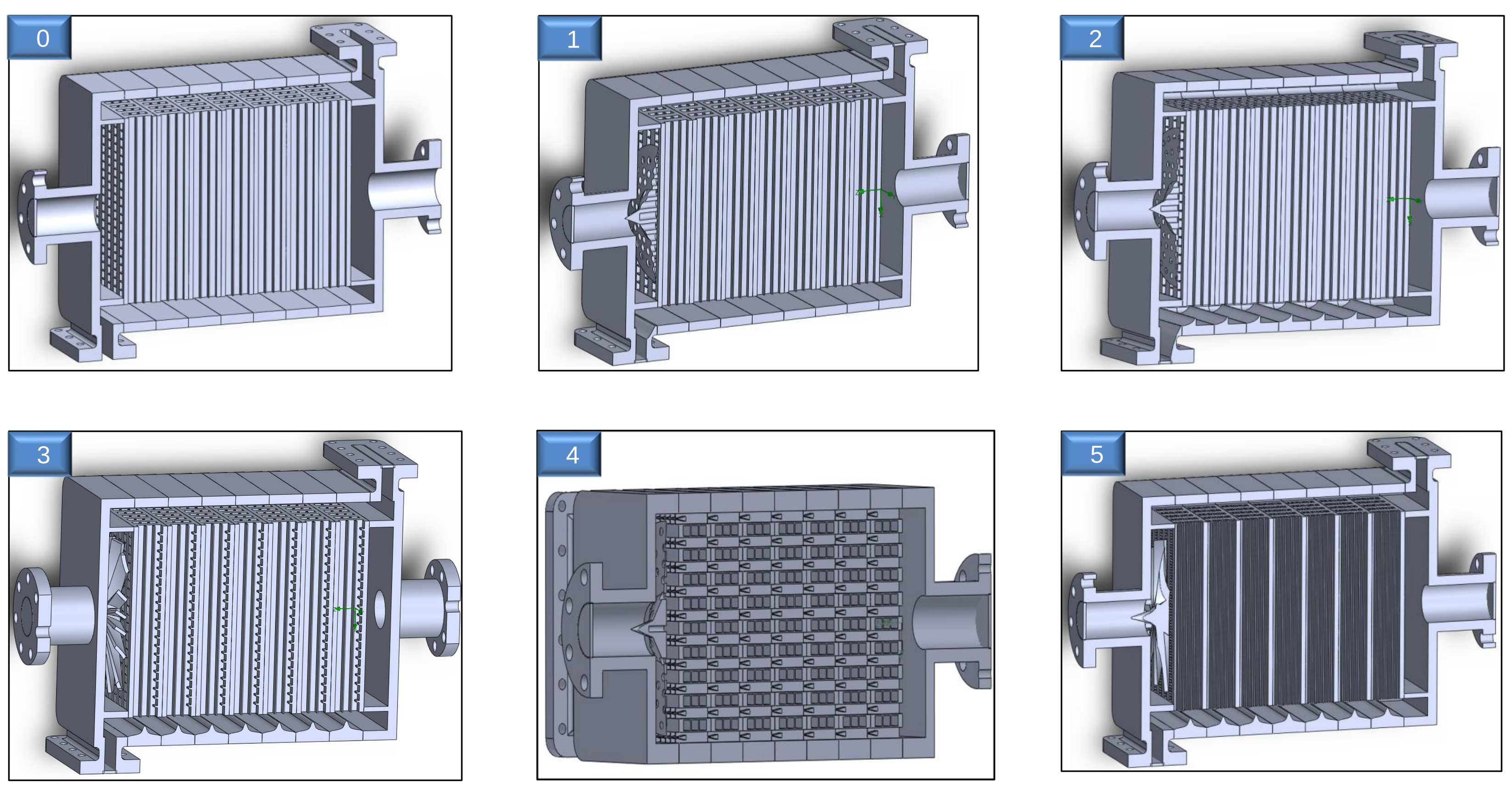

Figure 3. Design variants of heat exchanger model analyzed in this study.

RESULTS & DISCUSSION

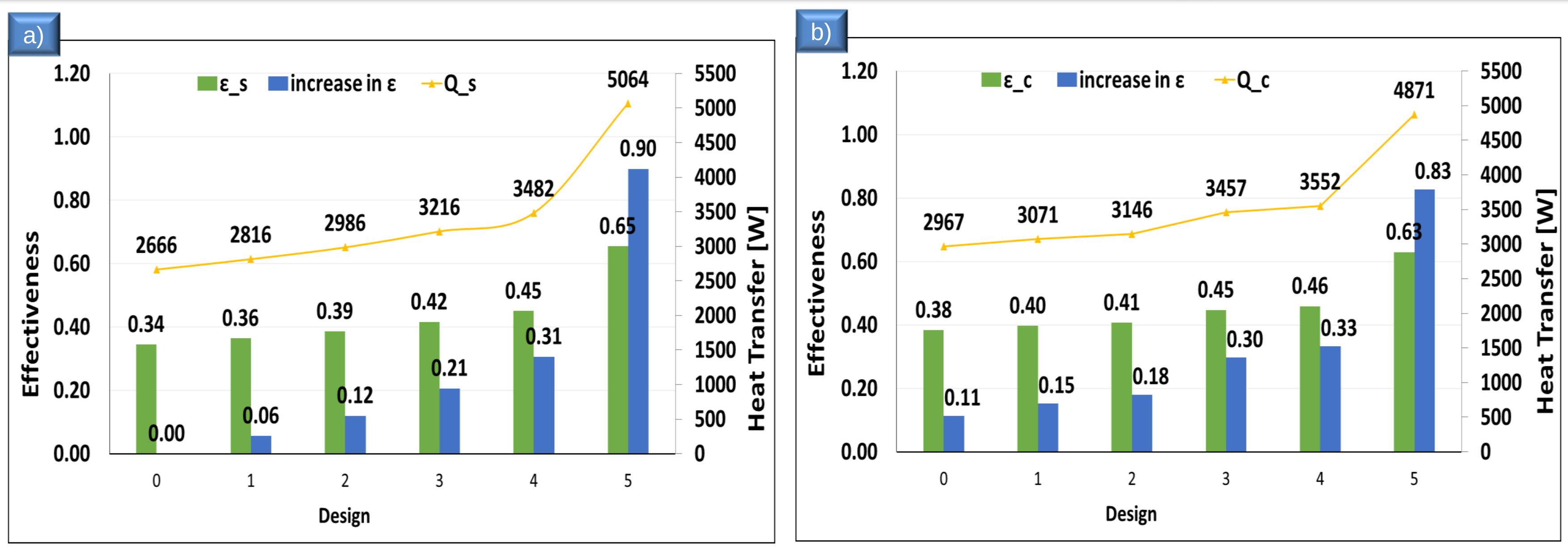

Figure 4. Results comparison of a) steel and b) G-CMC heat exchangers.

- Enhanced Flow Dynamics: The optimized geometry (Design 5) eliminated dead zones and ensured uniform flow distribution in both hot and cold channels.
- Increased Surface Area: The integration of ribs and turbulence promoters resulted in a 2.5-fold increase in the effective heat-transfer surface area.
- Temperature Distribution: Numerical results showed a significant improvement in temperature uniformity and heat transfer rates for the optimized configurations.

Table 2. Numerical performance outputs and comparative thermal effectiveness improvements for steel and ceramic heat exchanger design variants.

No	Steel Hot Outlet	Steel Cold Outlet	Ceramic Hot Outlet	Ceramic Cold Outlet	ε_s	ε_c	Increase rate of ε_s	Increase rate of ε_c
0	957.7	759.5	927.8	764.2	0.34	0.38	0.00	0.11
1	942.8	758	917.4	784	0.36	0.40	0.06	0.15
2	925.9	782	910	804	0.39	0.41	0.12	0.18
3	903	812.8	879	799.6	0.42	0.45	0.21	0.30
4	876.5	831.5	869.6	811.7	0.45	0.46	0.31	0.33
5	719.1	955.5	738.3	940.3	0.65	0.63	0.90	0.83

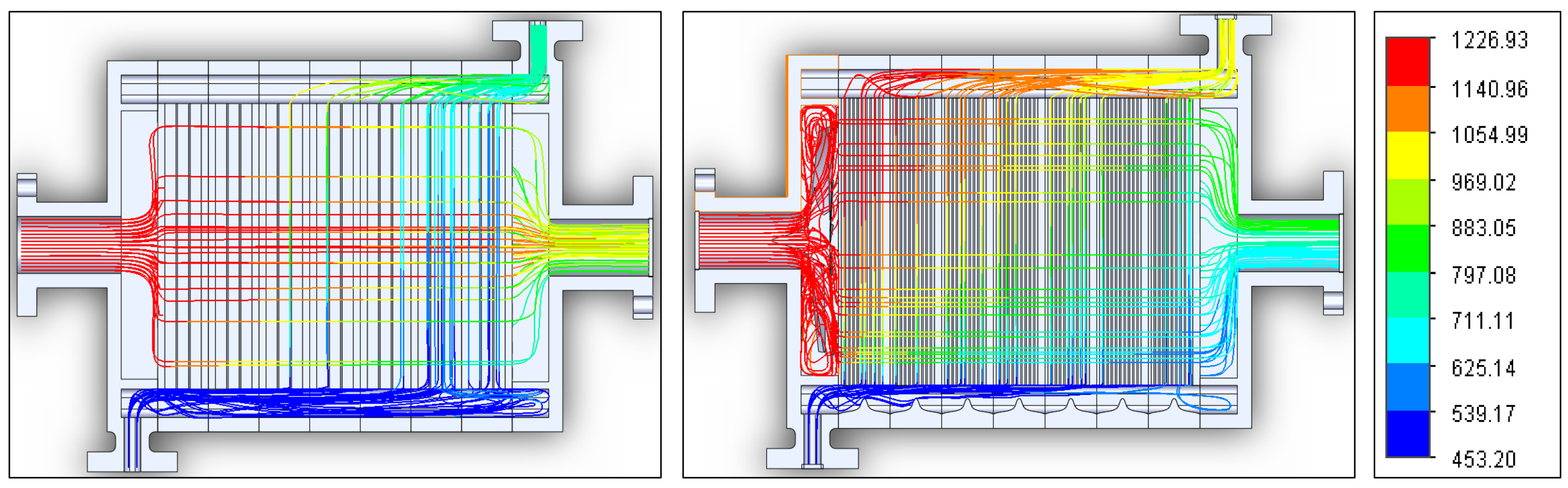

Figure 5. Thermal performance comparison between the steel base model and the G-CMC optimized design.

CONCLUSION

- Steel heat exchanger effectiveness: 0.65 (90% increase over base model).
- G-CMC heat exchanger effectiveness: 0.63 (83% increase) with ~50% weight reduction.
- The proposed design successfully maximized heat transfer through improved flow uniformity and temperature distribution.
- This study confirms that optimized G-CMC heat exchangers are a highly efficient, lightweight solution for high-temperature energy systems.

ACKNOWLEDGEMENT

The present work was carried out within the framework of the SpreeTec neXt project, funded by the Federal Ministry for Research, Technology and Space (BMFTR), and is managed under the funding number 02P21Z000.