

Abstract

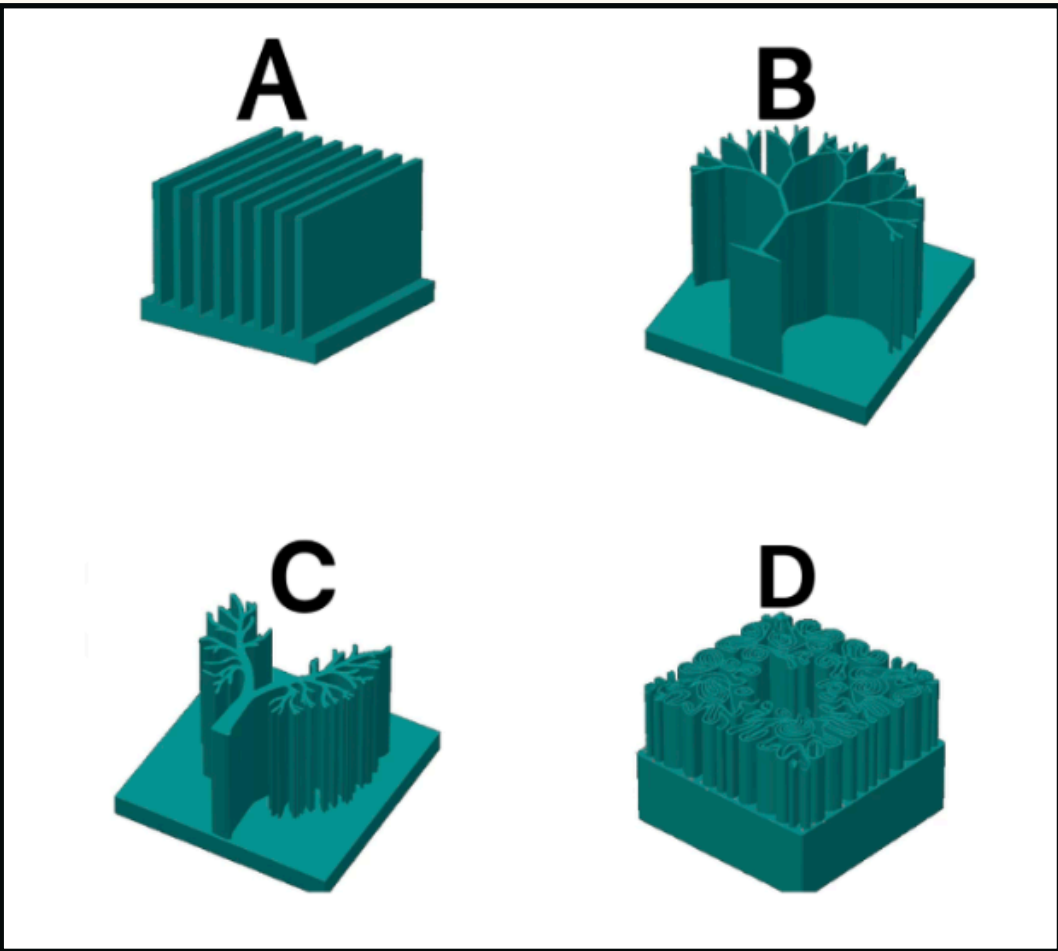
As edge computing devices become smaller and more powerful, passive thermal management must improve without adding excessive material. This study compares conventional, tree-inspired, lung-inspired, and AI-generated fractal heat sinks under controlled natural convection. AlSi10Mg heat sinks were tested at 20.6°C ambient with 7.5 W input and modeled using conjugate heat-transfer CFD. The AI-generated design had the lowest endpoint temperature (44.4°C) and thermal resistance (3.17°C/W), but its greater mass and 10 mm base limited attribution to geometry alone. The tree-inspired design used 51.1% less material than the control and achieved the highest mass-normalized thermal conductance. CFD predicted higher temperatures than experiments. These results show that biomimetic branching can improve material efficiency while maintaining competitive thermal performance.

Introduction

Conventional heat sinks often increase surface area to transfer heat, but geometry can limit airflow and material efficiency [1]. Biomimetic branching structures offer an alternative, yet relatively few studies directly compare complex designs through both physical testing and simulation [2]. This study compares conventional and biomimetic heat sinks under identical experimental and computational conditions, emphasizing both thermal performance and material efficiency.

Methods

Four geometries were designed within a 50 × 50 × 35 mm envelope, prototyped in PLA, and fabricated from AlSi10Mg by metal laser powder bed fusion. Each heat sink was tested under natural convection at 20.6°C with a constant 7.5 W heat input. Base and top temperatures were measured for 25 minutes, followed by 20 minutes of natural cooling; each design was tested twice. Performance was evaluated using endpoint temperature, thermal resistance, and mass-normalized thermal conductance. The same conditions were modeled in SimScale using conjugate heat-transfer CFD.

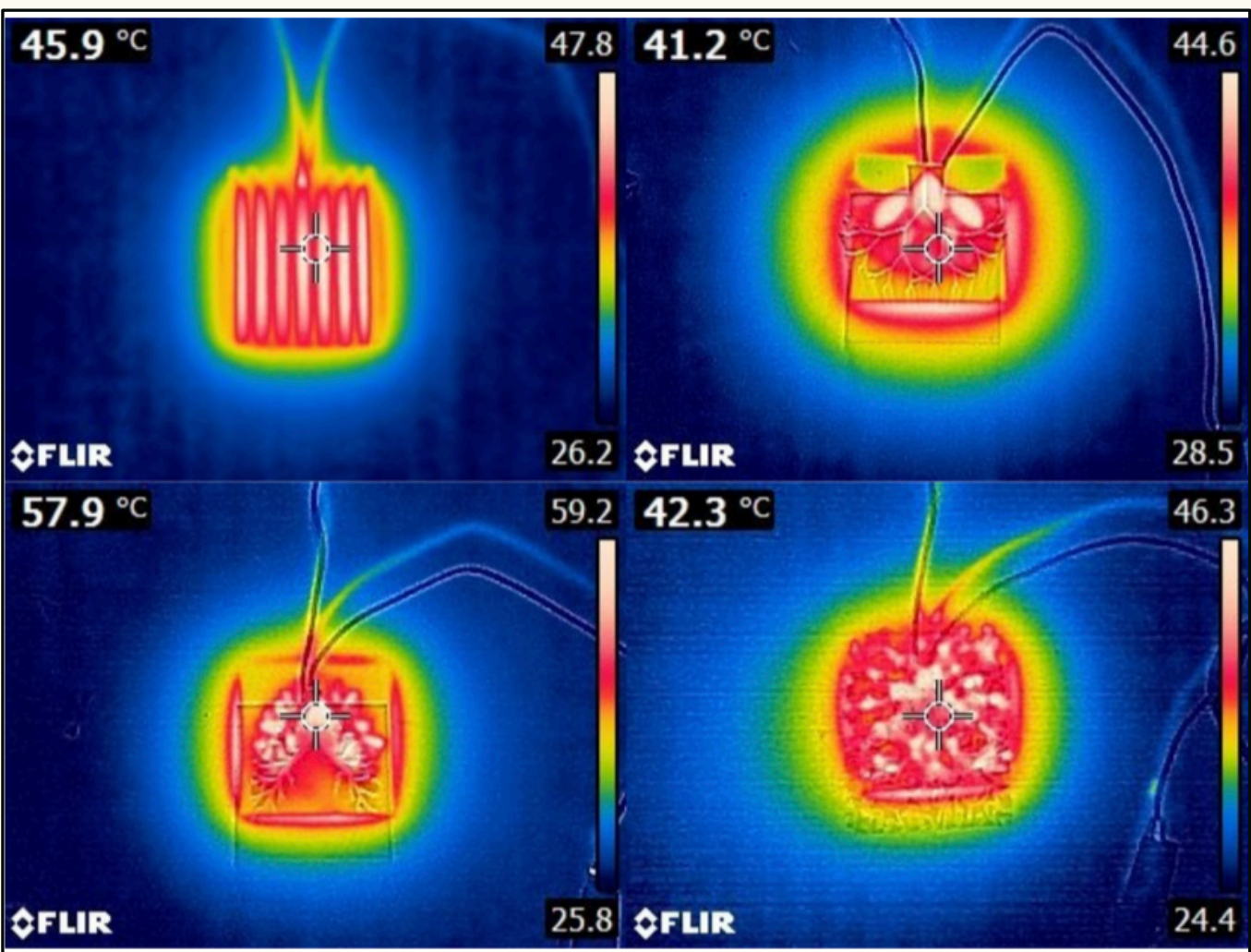


Geometric Characteristics				
	Control	Tree	Lung	AI
Volume (cm³)	36.50	17.87	21.31	62.73
Surface Area (cm²)	309.60	215.23	213.57	444.67
Mass (g)	97.46	47.70	56.90	167.49
SA / Mass (cm²/g)	3.18	4.51	3.75	2.65

Results

The AI-generated design reached the lowest endpoint temperature (44.4°C) and thermal resistance (3.17°C/W), compared with 46.5°C for the control, 51.2°C for tree, and 52.8°C for lung. However, the tree-inspired design used 51.1% less mass than the control and achieved 71.5% greater mass-normalized thermal conductance. The AI-generated design had the lowest mass-normalized performance. CFD predicted higher temperatures than experiments for all designs.

Heat Sink	Mass (kg)	$G_{\theta,25}$ (W/K)	$G_{\theta,25}/m$ (W/K/kg)
Conventional Control	0.0975	0.290	3.00
Tree-Inspired	0.0477	0.246	5.15
Lung-Inspired	0.0569	0.233	4.09
AI-Generated	0.1675	0.316	1.89



Discussion

The results show that greater surface area alone does not determine heat-sink efficiency. Although the AI-generated design had the largest surface area, its greater mass and thicker base reduced material efficiency. The tree-inspired design achieved the strongest balance between thermal performance and material use, partially supporting the hypothesis that biomimetic fractal structures can improve efficiency. Differences between CFD and experimental temperatures also demonstrate the importance of validating simulations with physical testing.

Conclusion

The tree-inspired fractal provided the best overall balance between thermal performance and material efficiency, using substantially less material while achieving the highest thermal conductance per unit mass. Although the AI-generated design produced the lowest endpoint temperature and thermal resistance, its greater mass and thicker base reduced its material efficiency and made it difficult to isolate the effect of its geometry alone. Overall, the findings support biomimetic branching as a promising approach for lightweight passive cooling and demonstrate that maximizing surface area does not necessarily produce the most efficient design. Future work should explore additional fractal geometries, improve manufacturing consistency, and optimize geometry, material distribution, and manufacturability together to develop more efficient passive cooling systems.

References

[1] P. Wang, J. Sun, and K. Nawaz, “Revolutionizing thermal management in next-generation ai data centers: Challenges and breakthrough innovations,” Applied Energy, vol. 421, p. 128180, 2026. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0306261926008329>

[2] C. Ma, Y. Sun, Y. Wu, Q. Zhang, Y. Wang, and G. Ding, “A bio-inspired fractal microchannel heat sink with secondary modified structure and sub-total-sub fluid transmission mode for high heat flux and energy-saving heat dissipation,” International Journal of Heat and Mass Transfer, vol. 202, p. 123717, 2023. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0017931022011851>