EUROPEAN MECHANICAL SCIENCE

Research Article

e-ISSN: 2587-1110

Investigation of lattice geometry effects on the steady-state thermal performance of aluminum alloy CPU coolers via finite element analysis

Mustafa Guven Gok[1*]

[1]Gaziantep University, Metallurgical and Materials Eng. Dept., Gaziantep, Türkiye

Abstract: This study numerically investigates the effect of lattice geometry on the steady-state thermal performance of aluminum alloy CPU coolers using finite element analysis. Four heat sink (cooler) configurations with the same external dimensions and base thickness were considered. In addition to a reference heat sink with a conventional design, three lattice-based designs were developed as simple cubic (SC), body-centered cubic (BCC), and face-centered cubic (FCC) unit cell. All coolers were subjected to a constant temperature of 95 °C from the surface of base, while natural convection was modeled on the external surfaces in 28 °C ambient air. A film coefficient of 5.0×10^{-6} W/mm^2 °C was used for the reference and SC coolers, while a higher coefficient of 1.0×10^{-5} W/mm^2 °C was applied to the BCC and FCC coolers to represent improved convective cooling. The results show that all lattice geometries reduced both the minimum and volume-averaged temperatures compared to the solid reference heat sink. The volume average temperature decreased from 94.358 °C to 93.415 °C for the SC cooler, and to 91.804 °C and 91.446 °C for the FCC and BCC coolers, respectively. Line temperature analysis along the cooler height revealed that the BCC lattice produced the lowest path-averaged temperature, followed by FCC and SC designs. This suggests that in lattice-based coolers, the lattice design and heatsink topology can be as important as the total surface area.

Keywords: CPU cooler; lattice heat sink; finite element analysis; aluminum alloy

1. Introduction

Rapid advances in semiconductor technology and the proliferation of artificial intelligence (AI) applications demand that computer CPUs (Central Processing Unit) sustain rising computational loads. Therefore, the power consumed by processors has increased significantly in recent years [1–5]. Because this has the potential to affect the reliable and stable operation of CPUs in the future, thermal management is becoming even more important for modern computing systems. While solutions exist, particularly liquid-assisted cooling systems, these complex systems can have potential drawbacks in terms of reliability, maintenance costs, and energy efficiency. For example, a liquid leak in a liquid-cooled system, or an unexpected stoppage of the pump motor that circulates the liquid for any other reason, can cause significant damage to the CPU and/or the system. Regular maintenance and continuous monitoring of these complex systems are essential to prevent these problems. However, these prevention solutions require costs and the continuous operation of these systems may increases energy consumption.

On the other hand, conventional heat sinks used for heat removal in electronic systems are generally in the form of flat or finned aluminum blocks. However, in conventional finned or block type heat sinks, the effective surface area that can be obtained for a given volume is relatively limited, so the control of heat flow is also limited [6–8]. In recent years, thanks to three-dimensional (3D) additive manufacturing methods that allow for the very precise production of complex shaped parts, lattice structures and topology optimization-based heat sink geometries have begun to be intensively investigated due to their advantages of high surface area-volume ratio, controllable porosity and flow paths, and light weight properties. Beyond material selection, controlling geo-

*Corresponding author:
Email: mggok@gantep.edu.tr

Cite this article as:
Gok, M.G.. (2025). Investigation of lattice geometry effects on the steady-state thermal performance of aluminum alloy CPU coolers via finite element analysis. *European Mechanical Science*, 9(4): 328-334. https://doi.org/10.26701/ems.1837369

History dates:
Received: 06.12.2025, ***Revision Request***: 16.12.2025, ***Last Revision Received***: 25.12.2025, ***Accepted***: 25.12.2025

metric features that alter exposed surface area, flow access, and boundary-layer behavior can often improve net heat extraction at steady state. Dixit et al. [9] numerically evaluated the thermal performance of different additively manufactured lattice architectures (e.g., cubic, kelvin, and octet) in heat sink applications using the finite element method and demonstrated that some topologies offer better thermal performance than certain microchannel and open-cell foam heat sinks. Similarly, Batikh et al. [10] reported that a BCCz (modified BCC lattice design with an extra strut in the z direction) based mesh heat sink additively fabricated with LPBF in a liquid-cooled application for rail power electronics provided significantly lower equivalent thermal resistance and lower baseplate temperatures compared to a conventional flat-fin heat sink. Ansari and Duwig [11] conducted a detailed thermohydraulic evaluation of a gyroid lattice based heat sink (HS) compared to a conventional pinfin heat sink under various porosities and flow rates, in terms of temperature nonuniformity, thermal resistance, and pumping power. The study shows that the gyroid lattice based heat sink provides superior thermal performance with lower thermal resistance and more uniform temperature distribution compared to the pinfin heat sink for all investigated porosities and flow rates, but at the expense of higher pressure drop/pumping power requirements. Furthermore, it can reduce hot spot temperature by approximately 30% and temperature variation by up to 17.3% under heterogeneous heating. Similarly, various studies [12–18] have proposed triple periodic minimal surface (TPMS)-based lattice structures as a new generation of heat exchangers and electronic heat sinks. For example, a recent review by Amara et al. [17] summarized the use of TPMS and lattice structures in heat exchangers, highlighting their high specific surface area, advantageous mechanical properties, and compatibility with metal additive manufacturing. Chouhan et al. [19] evaluated several L-PBF-fabricated TPMS lattice heat sinks (Gyroid, Diamond, Schwarz P, Lidinoid, and Split-P) of the same volume compared to a conventional pinfin heat sink. Their numerical and experimental results showed that TPMS designs provide up to 25–45% higher heat transfer and more uniform temperature distributions, primarily due to the increased surface area and the effect of unit cell size and periodicity.

While this topic is becoming increasingly important, studies generally focus on TPMS lattices with complex geometries or lattice heat sinks in the context of liquid cooling. Fewer studies have systematically compared "classical" cubic lattice topologies (simple cubic (SC), body-centered cubic (BCC), and face-centered cubic (FCC)) for air-cooled CPU heat sinks, particularly under realistic package sizes representative of desktop or embedded CPUs. Accordingly, this study systematically examines the thermal performance of aluminum-alloy CPU coolers incorporating three classical lattice topologies (SC, BCC, and FCC) designed to ensure good heat dissipation and minimize peak CPU temperature.

2. Materials and Methods

2.1. Geometric Modeling of CPU Coolers

In this study, four different metallic CPU cooler geometries were considered. These are (i) a conventional reference (ref) cooler with commercially available geometry, (ii) a simple cubic (SC) lattice cooler, (iii) a body-centered cubic (BCC) lattice cooler, and (iv) a face-centered cubic (FCC) lattice cooler. Three-dimensional solid models of these coolers are shown in Figure 1 (a-d).

To ensure a fair comparison under the same constraints, all models were designed to have the same general characteristics in terms of size, strut thickness (2.5 x 2.5 mm), etc. The external dimensions of the coolers, which could be manufactured using additive manufacturing techniques, were approximately 60 mm (X) x 60 mm (Y) x 40 mm (Z). The coolers consist of a flat base plate representing the CPU integrated heat sink contact surface and an upper heat dissipation zone (solid fins or lattice). The base plate thickness (5 mm) and the overall external dimensions (i.e., the outer envelope) were kept the same for all designs. However, the different lattice architectures within the same envelope volume naturally provide different total heat exchange surface

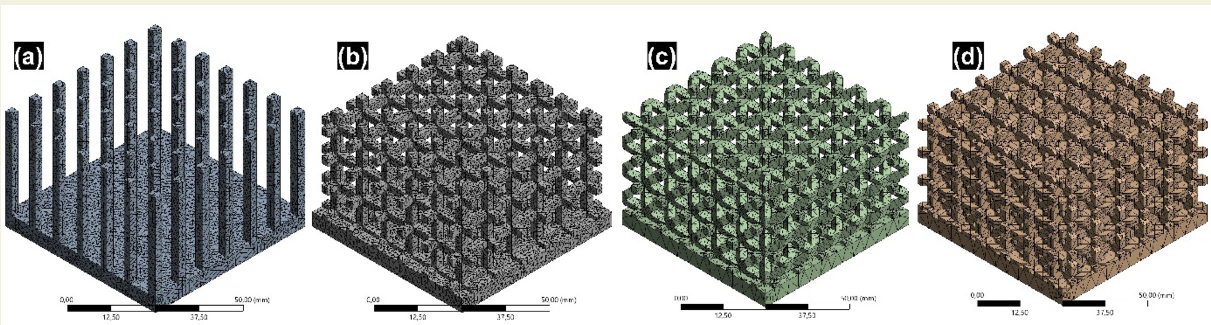

Figure 1. Three-dimensional solid models of CPU coolers (finite element meshes generated). (a) ref., (b) SC, (c) BCC and (d) FCC

areas. Therefore, only the internal geometry above the base was changed. The reference cooler uses traditional compact finblock geometry, while the lattice coolers replace this volume with periodically repeating unit cells with SC, BCC, or FCC topologies. The CAD geometries for all coolers were created in SolidWorks software and exported as IGES (*.igs) files. These IGES models were imported into ANSYS Workbench using the "Geometry Import" module with solids enabled and the 3D analysis type.

2.2. Material properties

All CPU cooler geometries are assumed to be manufactured from aluminum alloy, consistent with common practice in air-cooled electronics coolers. The Aluminum alloy material in ANSYS Mechanical is assigned to the solid area for all models. The density, specific heat capacity, and coefficient of thermal expansion values of the imported aluminum material were 2.77×10^{-6} kg/mm^3, 8.75×10^5 mJ/(kg K), and 2.3×10^{-5} K^{-1}, respectively. According to the material definition, the thermal conductivity of the aluminum alloy is temperature-dependent and varies between 0.114 W/(mm K) at 173.15 K and 0.175 W/(mm K) at 473.15 K. Since the focus of this study is on steady-state thermal behavior under a specific thermal load, the mechanical and fatigue material data found in the ANSYS material chart were not used in the solution.

2.3. Finite element model and meshing

All simulations were performed using the Steady-State Thermal module in ANSYS Workbench. For each heatsink geometry, the imported CAD body was meshed using unstructured tetrahedral elements using the Patch Independent algorithm. The physics preference was "Mechanical" and a program-controlled element order (second-order tetrahedra) was used. Adaptive sizing was enabled with a default resolution of 2, mesh gradient was enabled, and a maximum tetrahedron element size of 4 mm was implemented, along with curvature and proximity-based refinement, with a minimum size limit of 1.25 mm. Thus, the resulting meshes contained approximately 175,000 nodes and 95,000 elements for each cooler (see Fig. 1).

2.4. Boundary conditions and loading

All simulations were performed as purely conductive–convective steady-state thermal analyses. To focus on the effect of lattice geometry on convective heat removal, which is the dominant mechanism under the conditions studied, radiative heat transfer between colder surfaces and the surroundings are neglected. The initial temperature was set at a constant 28 °C in all cases. This value was also used as the ambient air temperature for convection. As seen in Fig. 2 (a-d), a constant temperature boundary condition of 95°C was applied to the bottom surface of the base plate, which will be in contact with the CPU's integrated heat spreader.

All remaining external surfaces of the cooler (fins and exposed base surfaces) were assigned a convective boundary condition with constant film coefficients (5.0×10^{-6} W/mm^2 °C for ref. and SC, 1.0×10^{-5} W/mm^2 °C for BCC and FCC) and an ambient temperature of 28 °C.

2.5. Solution settings

The nonlinear controls for temperature and temperature approximation were kept at their default program-controlled values. The resulting values were taken from the ANSYS solution for temperature (volume distribution within the cooler), total heat flux (magnitude of the heat flux vector, W/mm^2), and the temperature distribution on a defined path along the cooler's height. The path representing the temperature distribution along the height was defined in the solid model as a straight line starting from the base of the cooler and extending toward the top of the cooler (from Z = 0 mm to Z = 40 mm) at fixed X = 5 mm and Y = 5 mm in the global coordinate system, with 47 equidistant sampling points.

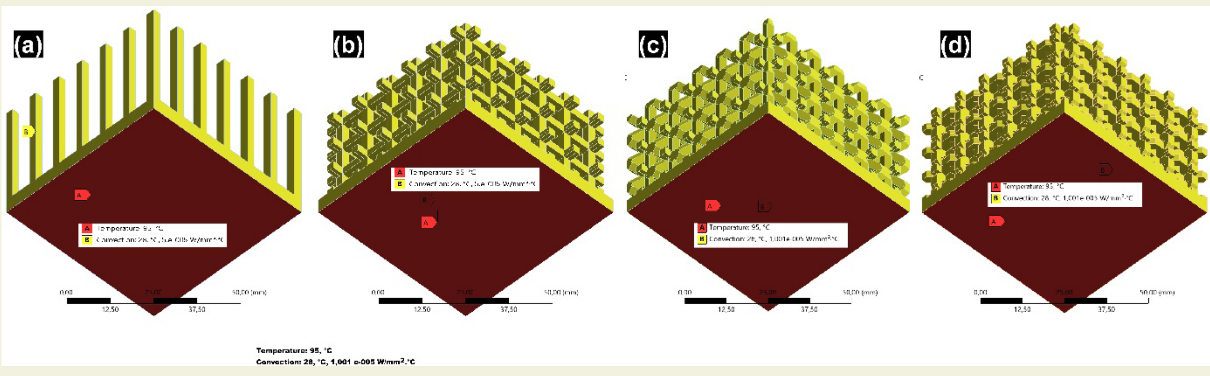

Figure 2. Boundary conditions used in finite element analyses of CPU coolers having lattice geometries (a) ref., (b) SC, (c) BCC, and (d) FCC.

3. Results and discussions

3.1. Temperature distribution

Figure 3 (a–d) shows the total surface temperatures obtained under a base temperature of 95 °C and an ambient temperature of 28 °C for the ref., SC, BCC, and FCC coolers, respectively. In all configurations, as it is expected, the highest temperature is found in the base region in contact with the CPU (set at 95 °C), and the temperature gradually decreases along the heat sink region toward the free end of the cooler. A quantitative comparison of global temperature statistics cab be summarized as follows. The minimum, maximum, and volume-averaged temperatures for the ref. cooler are 92.756 °C, 95 °C, and 94.358 °C, respectively (Figure 3 (a)). The small internal temperature gradient implies limited use of the available heat sink volume for heat rejection especially resulting from the limited surface area. As seen Figure 3 (b), the SC lattice cooler design reduces these values to 90.975 °C (minimum) and 93.415°C (average), while the maximum remains fixed at the prescribed 95 °C at the base. The SC lattice design resulted in a moderate improvement attributed to increased external surface area and additional conduction pathways within the lattice. It should also be noted that the convection coefficients are the same as in the reference lattice. The BCC lattice yields the lowest temperatures of all designs, with a minimum temperature of 89.602°C and an average temperature of 91.446°C (see Figure 3 (c)). Because in this design, interconnected body-centered supports increased both lateral heat dissipation and vertical conduction, creating a more efficient heat transfer network. The FCC lattice design given in Figure 3 (d) performs similarly to the BCC with minimum and average temperatures of 90.143 °C and 91.804 °C, respectively. These results clearly demonstrate that lattice based heat sinks reduce both average and minimum temperatures. However, it should be noted that the convective boundary condition for BCC and FCC is defined by a higher film coefficient. This value is approximately twice that used for the ref. and SC coolers. Consequently, the lower temperatures observed for BCC and FCC reflect the combined effects of (i) more favorable lattice geometries and (ii) stronger convection.

3.2. Total heat flux

The total heat flux magnitude across the heat sink surfaces provides additional information about the heat removal capacity of each geometry. The contours showing the total heat flux states in the samples are given in Figure 4 (a-d). The average heat flux of the reference heat sink is 5.2421x10^{-3} W/mm^2, with a maximum value of 2.3373x10^{-2} W/mm^2. In the SC lattice design, the average total heat flux increases to 6.3724x10^{-3} W/mm^2, which corresponds to an increase of approximately 22% compared to the reference geometry. This improvement is consistent with the reduction in average temperature and is primarily attributable to the greater effective surface area and improved exposure of interior surfaces to ambient The heat flux increased even more in the BCC and FCC lattice designed coolers, which have higher convective film coefficients. The minimum, maximum, and average total heat fluxes for the BCC cooler are 3.5096x10^{-5} W/mm^2, 7.0444x10^{-2} W/mm^2, and 1.6649x10^{-2} W/mm^2, respectively; while for the FCC cooler, these values are 1.9604x10^{-5} W/mm^2, 5.1167x10^{-2} W/mm^2, and 1.3742x10^{-2} W/mm^2. These significant gains in BCC and FCC demonstrate the beneficial effect of increased surface area and convection coefficient. However, since BCC and FCC share the same film coefficient, the relative performance difference between them can be interpreted as a purely geometric and topological effects. Specifically, the higher

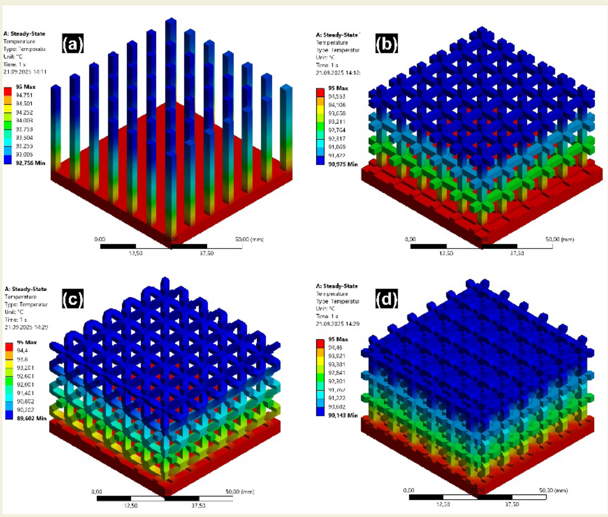

Figure 3. Steady-state temperature distributions for the (a) ref., (b) SC, (c) BCC, and (d) FCC lattice geometries.

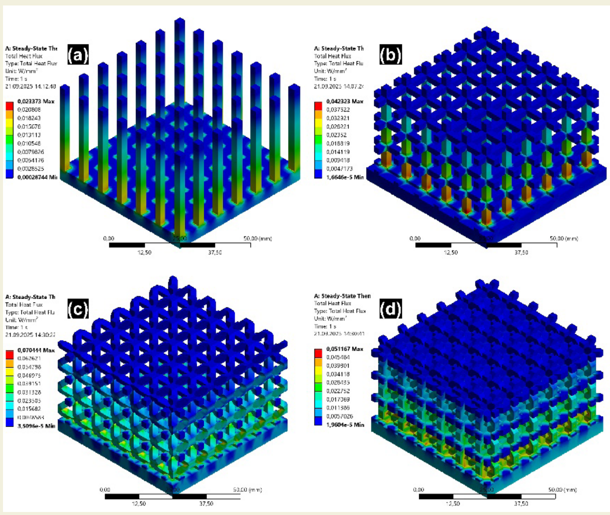

Figure 4. Distribution of total heat flux magnitude on the surfaces for all cooler geometries. (a) ref., (b) SC, (c) BCC, and (d) FCC

 https://doi.org/10.26701/ems.1837369

average and peak heat flux in BCC compared to FCC suggests that, despite the slightly larger solid volume and nominally greater surface area of FCC, the BCC unit cell connection creates a more efficient conduction network between the hot base and the cooled outer surfaces. From a design perspective, this indicates that maximizing surface area alone is not sufficient. The arrangement and orientation of the struts, and thus the effective conduction paths from the base to the upper surface, play a decisive role in determining thermal performance of cooler.

3.3. Temperature distribution along the line

To examine the thermal behavior along the main heat flow direction, a sampling line (path way) containing 47 equally spaced sampling points was defined from the bottom of the cooler to the top of the fin or lattice region (Z=0-40 mm) at fixed coordinates of X=5 mm and Y=5 mm, as shown in Figure 5 (a-d). Additionally, the temperature changes in all coolers along these path ways are graphically presented as temperature versus distance in Figure 6. According to these results, for the reference cooler, the temperature decreases monotonically from 95 °C at Z=0 mm to about 92.9 °C near the top surface, and the path-averaged temperature is 93.72 °C. For the FCC lattice design, the path way temperature profile is lower than that of the reference cooler. Temperatures decrease from 95 °C at the base to approximately 90.24 °C near the top. Representative values are 93.445 °C at Z = 10 mm, 91.675 °C at Z = 20 mm, and 90.614 °C at Z = 30 mm. The path way mean temperature is 92.092 °C. For the BCC cooler, the line-averaged temperature is 91.777°C. This lattice was found to reduce the temperature along the height by a relatively significant amount compared to the reference. The graph in Figure 6 also shows that the BCC lattice design achieves the lowest line-averaged temperature among all designs. Consequently, along the chosen path, the local transmission network surrounding the line is more favorable in the BCC topology, providing shorter and more numerous heat paths to the convectively cooled regions. This results in slightly lower temperatures along the line in the lattice design of BCC compared to the FCC, even with the same convection coefficient. Overall, the comparative results of the analyses reported in Table 1 provide a general basis for evaluating the thermal response of reference and lattice-based cooler designs under the specified effective convection conditions.

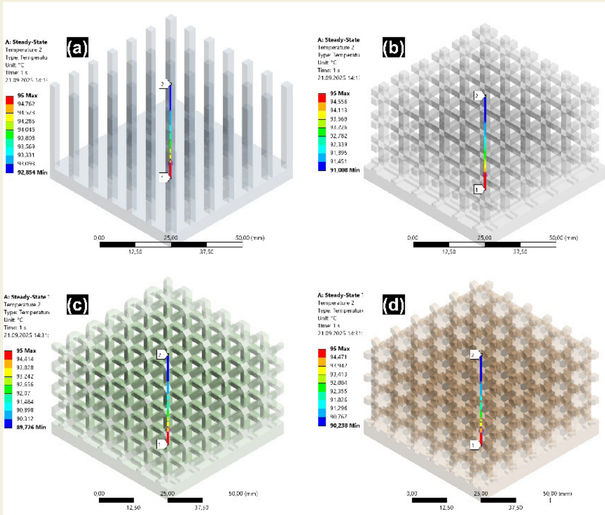

Figure 5. Comparison of temperature distributions along a line. (a) ref., (b) SC, (c) BCC, and (d) FCC

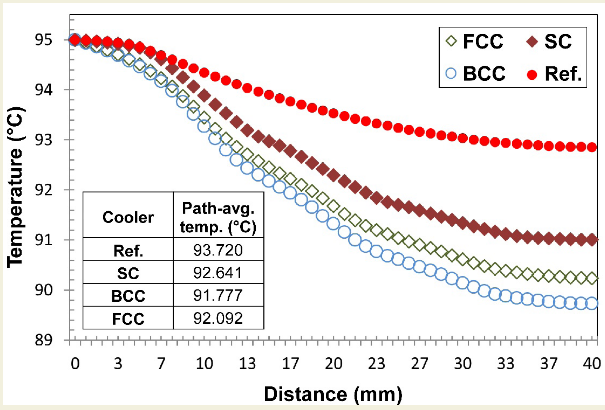

Figure 6. Temperature-distance graph showing temperature distributions along a line.

4. Conclusions

In this study, the steady-state thermal performance of aluminum alloy CPU coolers with different lattice geometries was investigated through finite element analysis. Based on the numerical results, the following con-

Table 1. Summary of cooler configurations and some of the numerical results.

Cooler Design	Film Coef. (W/mm^2·°C)	Vol. (cm^3)	Temp. (°C)		Heat Flux (W/mm^2)			The path way avg. temp. (°C)
			Min.	Avg.	Min.	Avg.	Max.	
Ref.	5.0x10^{-6}	29.34	92.76	94.36	2.87x10^{-4}	5.24x10^{-3}	2.34x10^{-2}	93.72
SC		37.69	90.97	93.41	1.66x10^{-5}	6.37x10^{-3}	4.23x10^{-2}	92.64
BCC	1.0x10^{-5}	71.29	89.60	91.45	3.51x10^{-5}	1.66x10^{-2}	7.04x10^{-2}	91.78
FCC		75.99	90.10	91.80	1.96x10^{-5}	1.37x10^{-2}	5.12x10^{-2}	92.09

clusions can be drawn:

1. For the given boundary conditions, all lattice-based coolers provide lower minimum and volume-averaged temperatures than the reference cooler. For the SC lattice, this improvement arises solely from the modified geometry under the same convection coefficient as the reference, whereas for the BCC and FCC coolers it reflects the combined effect of lattice topology and a higher convective film coefficient.

2. The use of lattices also leads to a significant increase in average total heat flux due to the increased effective surface area and better exposure of the internal surfaces to ambient air.

3. A line-based analysis of temperature distributions along the cooler height shows that the BCC lattice yields the lowest path-averaged temperature (91.777°C), followed by the FCC (92.092°C) and SC (92.641°C) designs, while the reference cooler exhibits the highest path-averaged temperature (93.72°C). This demonstrates that lattice topologies can utilize the available heat sink volume more effectively than a compact fin block geometry.

4. The BCC lattice consistently exhibits slightly lower average temperatures and higher average heat flux compared to the FCC lattice, even though both coolers share the same (higher) convective film coefficient. This behavior demonstrates that the lattice connection and heat path topology are as important as the total surface area and solid volume in determining thermal performance. In the current configuration, the body-centered supports in the BCC unit cell create a more efficient three-dimensional conduction network between the hot base and the convectively cooled external surfaces.

Research ethics

Not applicable

Author contributions

The author solely conducted all stages of this research.

Competing interests

The author states no conflict of interest.

Data availability

The raw data can be obtained on request from the corresponding author

Research funding

None declared

Peer review

Externally peer-reviewed

Orcid

Mustafa Guven Gok https://orcid.org/0000-0002-5959-0549

References

[1] Ghadim, H.B., Godin, A., Veillere, A., Duquesne, M., Haillot, D., (2025). Review of thermal management of electronics and phase change materials. Renewable and Sustainable Energy Reviews. 208: 115039. doi: https://doi.org/10.1016/j.rser.2024.115039.

[2] Hunter, L.Y., (2025). Artificial Intelligence, Data Centers, Energy Capabilities, and International Security: An Exploratory Analysis. Armed Forces & Society. 0(0): 0095327X241308839. doi: 10.1177/0095327X241308839.

[3] Samal, S.K., Chang, H.-C., Fulpagare, Y., Wang, C.-C., (2025). Thermal management of data centers: Chip-scale cooling using novel distributed inlet–outlet jet impingement liquid cold plate. Applied Thermal Engineering. 271: 126360. doi: https://doi.org/10.1016/j.applthermaleng.2025.126360.

[4] Li, Z., Luo, H., Jiang, Y., Liu, H., Xu, L., Cao, K., et al., (2024). Comprehensive review and future prospects on chip-scale thermal management: Core of data center's thermal management. Applied Thermal Engineering. 251: 123612. doi: https://doi.org/10.1016/j.applthermaleng.2024.123612.

[5] Ramakrishnan, B., Turner, C., Alissa, H., Trieu, D., Rivera, F., Melton, L., et al., (2025). Understanding the Impact of Data Center Liquid Cooling on Energy and Performance of Machine Learning and Artificial Intelligence Workloads. Journal of Electronic Packaging. 147(2). doi: 10.1115/1.4067136.

[6] Rasangika, A.H.D.K., Nasif, M.S., Al-Waked, R., (2023). Comparison of Forced Convective Heat-Transfer Enhancement of Conventional and Thin Plate-Fin Heat Sinks under Sinusoidal Vibration. Applied Sciences. 13(21). doi: 10.3390/app132111909.

[7] Ozbalci, O., Dogan, A., Asilturk, M., (2022). Heat Transfer Performance of Plate Fin and Pin Fin Heat Sinks Using Al2O3/H2O Nanofluid in Electronic Cooling. Processes. 10(8). doi: 10.3390/pr10081644.

[8] Bayrak, F.T., Toprak, B.İ., Solmaz, İ., Bayer, Ö., (2025). The influence of slotted solid cylindrical fin with aluminum foam insert on the thermal and hydraulic characteristics of air-cooled pin-fin heat sink. International Communications in Heat and Mass Transfer. 162: 108595. doi: https://doi.org/10.1016/j.icheatmasstransfer.2025.108595.

[9] Dixit, T., Nithiarasu, P., Kumar, S., (2021). Numerical evaluation of additively manufactured lattice architectures for heat sink applications. International Journal of Thermal Sciences. 159: 106607. doi: https://doi.org/10.1016/j.ijthermalsci.2020.106607.

[10] Batikh, A., Fradin, J.-P., Castro Moreno, A., (2025). Computational and Experimental Investigation of Additively Manufactured Lattice Heat Sinks for Liquid-Cooling Railway Power Electronics. Energies. 18(14). doi: 10.3390/en18143753.

[11] Ansari, D., Duwig, C., (2024). A gyroid TPMS heat sink for electronic cooling. Energy Conversion and Management. 319: 118918. doi: https://doi.org/10.1016/j.enconman.2024.118918.

[12] Chen, M., Shi, Y., Yang, L., Yan, C., Song, B., Liu, Y., et al., (2024). Thermal performances of Gyroid-fin heat sink for power chips. Case Studies in Thermal Engineering. 61: 105095. doi: https://doi.org/10.1016/j.csite.2024.105095.

[13] Saghir, M.Z., Yahya, M., Ortiz, P.D., Impellizzeri, S., Al-Ketan, O., (2025). Heat Enhancement of Ethylene Glycol/Water Mixture in the

Presence of Gyroid TPMS Structure: Experimental and Numerical Comparison. Processes. 13(1). doi: 10.3390/pr13010228.

[14] Shen, J., Zhang, Q., Wang, Z., (2024). Conjugate study on heat transfer enhancement of a TPMS-based hybrid heat sink design. Applied Thermal Engineering. 257: 124350. doi: https://doi.org/10.1016/j.applthermaleng.2024.124350.

[15] Chen, M., Shi, Y., Yang, L., Yan, C., Su, B., Fu, H., et al., (2025). Performance evaluation for additively manufactured heat sinks based on Gyroid-TPMS. Thermal Science and Engineering Progress. 60: 103499. doi: https://doi.org/10.1016/j.tsep.2025.103499.

[16] Al-Ketan, O., Abu Al-Rub, R.K., (2021). MSLattice: A free software for generating uniform and graded lattices based on triply periodic minimal surfaces. Material Design & Processing Communications. 3(6): e205. doi: https://doi.org/10.1002/mdp2.205.

[17] Amara, K., Saghir, M.Z., Abdeljabar, R., (2025). Review of Triply Periodic Minimal Surface (TPMS) Structures for Cooling Heat Sinks. Energies. 18(18). doi: 10.3390/en18184920.

[18] Gado, M.G., (2025). Thermal management and heat transfer enhancement of electronic devices using integrative phase change material (PCM) and triply periodic minimal surface (TPMS) heat sinks. Applied Thermal Engineering. 258: 124504. doi: https://doi.org/10.1016/j.applthermaleng.2024.124504.

[19] Chouhan, G., Namdeo, A.K., Guner, A., Essa, K., Bidare, P., (2025). Heat transfer performance of compact TPMS lattice heat sinks via metal additive manufacturing. Progress in Additive Manufacturing. doi: 10.1007/s40964-025-01366-0.