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Article

Comparative Analysis of Heat Transfer Performance of Heat Sinks with Lattice Geometry

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Abstract: This paper presents a comparative study of heat transfer performance of lattice structured heat sinks. 20 different unit cells were chosen and heat sinks were modelled in nTop with constant unit cell size. Al 6061 alloy was chosen for analysis due to its good thermal conductivity, low weight, low cost, and high strength. Steady state thermal analysis was performed using ANSYS with constant input parameters for all samples. Heat flux and temperature distribution within the heat sinks were analysed. The study aims to provide a comprehensive understanding of the thermal performance of lattice heat sink designs.

Keywords: lattice structures, steady state thermal, nTop, ansys, heat sink

1. Introduction

Efficient heat transfer is crucial in various engineering applications, ranging from electronics cooling to HVAC systems, where enhancing heat dissipation capabilities can significantly improve system performance and reliability. Numerous studies have investigated the influence of fin geometry such as shape [1,2], size, arrangement [3] and spacing [4,5], on heat transfer performance. Advancements in manufacturing techniques have enabled the fabrication of intricate fin designs to further enhance heat transfer efficiency [6]. Lattice structures, drawing inspiration from the intricate patterns found in nature's cellular formations [7], have been designed to overcome inherent limitations in fin shape and structure. Lattice structures, characterized by their periodic arrangement of unit cells, possess distinct advantages such as high surface area-to-volume ratio, high strength to weight ratio [8] and low relative density. These attributes make lattice heat sinks promising candidates for applications requiring efficient heat dissipation. However, comprehensive analyses evaluating the thermal performance of lattice heat sink designs remain limited.

This paper presents a systematic investigation into the heat transfer characteristics of heat sinks with lattice structure using numerical analysis.

2. Lattice Structures

Lattice structures (also known as architected cellular materials) are a type of cellular structures [9] with repeating unit cells. Certain physical properties of lattice structures can be tailored by controlling their geometrical parameters [10]. Some lattice structures (lattice metamaterials) exhibit unique characteristics such as negative Poisson ratio [11], negative compressibility, negative thermal expansion, phononic band gap, etc., which make them useful for a wide range of applications which include light weighting, energy absorption, bioscaffolds, wave (noise/vibration) insulation and thermal management [12]. Lattice structures have been found to break the parasitic performance tradeoffs [13] seen in bulk materials such as strength vs. toughness [14,15], stiffness vs. energy dissipation, flexibility vs. fast response, etc... High surface area to volume ratio of lattice structures makes them an ideal choice for high performance heat exchanger applications. Powered by the rapid development of additive manufacturing techniques, compact lattice heat sinks may soon replace traditional heat sink types.

Based on the type and arrangement of unit cells, lattice structures are grouped into many classes [16–22] as shown in Figures 1 and 2.

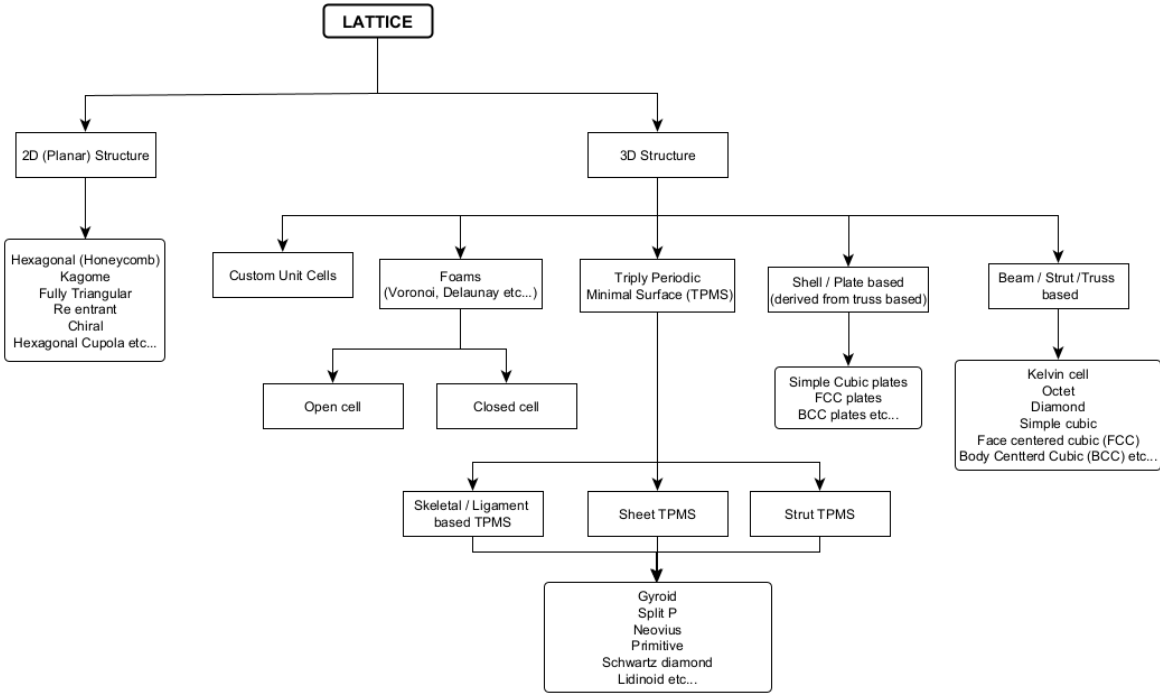


Figure 1. Classification of lattice structures (based on unit cell).

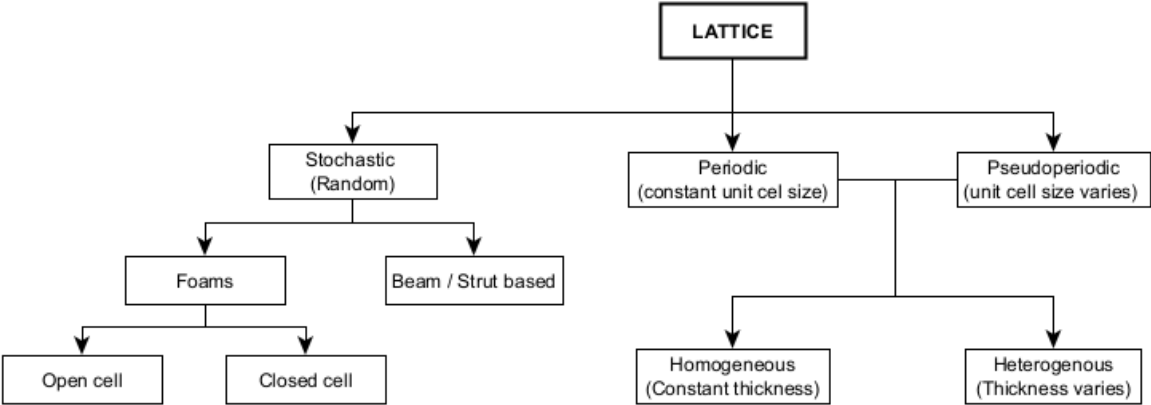


Figure 2. Classification of lattice structures (based on periodicity).

3. Modelling and Analysis

3.1. Geometric Modelling

The fins were modelled using nTop, an implicit modelling software. Unlike explicit modelling techniques which represent a body as a set of polygons or parametric patches [23], implicit modelling technique distinguishes between points inside and outside a body by representing them as a function or scalar field [24]. This allows for the creation of complex shapes and features which are otherwise impossible to model with explicit modelling softwares. Implicit modeling is also ideal for designing additively manufactured parts. However, implicit models require significantly high computational resources and is not the ideal method to represent 3d models for subtractive manufacturing as calculating the boundary of the slice is a complicated process [25]. All fins taken for analysis possess similar basic dimensions (Figure 3). The unit cells selected for analysis are depicted in Figures 4, 5 and 6. Constant unit cell size was used throughout the analysis.

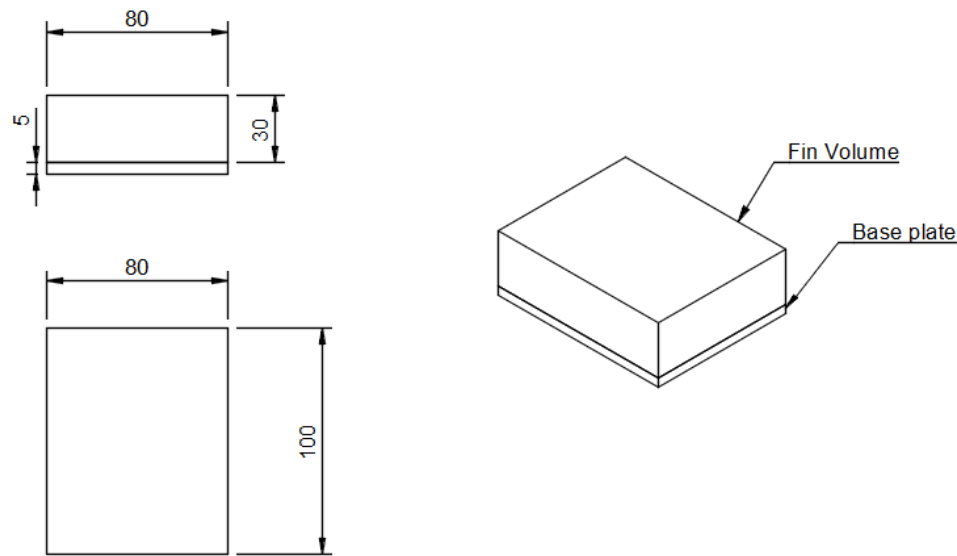


Figure 3. Basic heat sink dimensions.

The unit cells chosen for analysis are shown in Figures 4, 5 and 6. All unit cells are of the following dimensions: 15mm * 20mm * 20mm

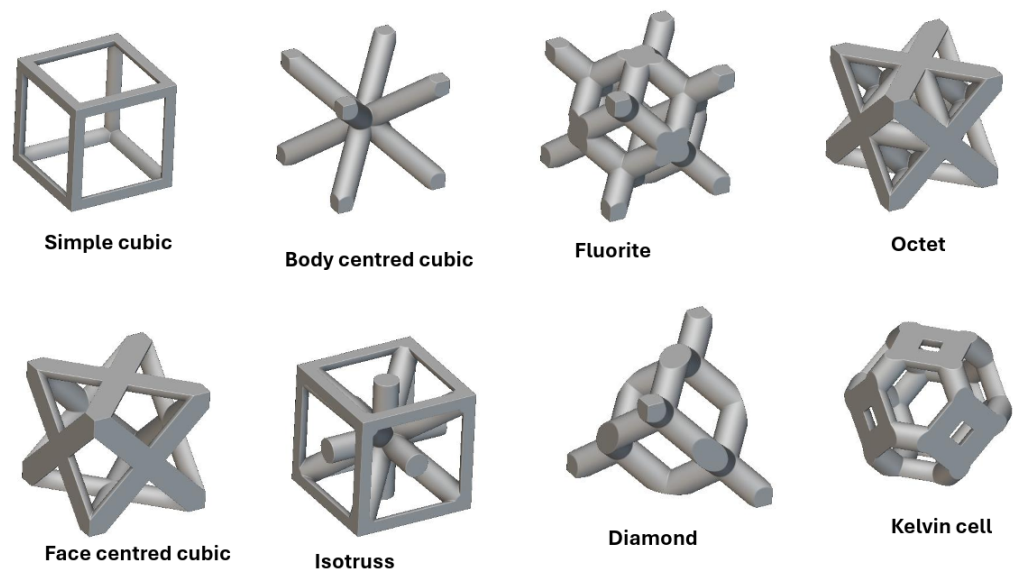


Figure 4. Beam/Truss based unit cells.

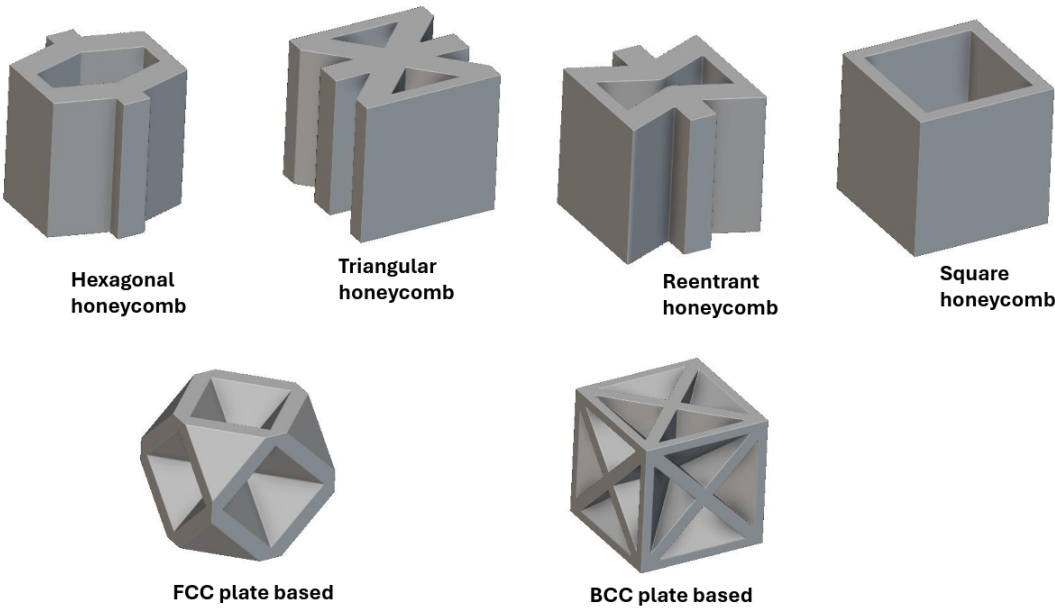


Figure 5. 2D and plate based unit cells.

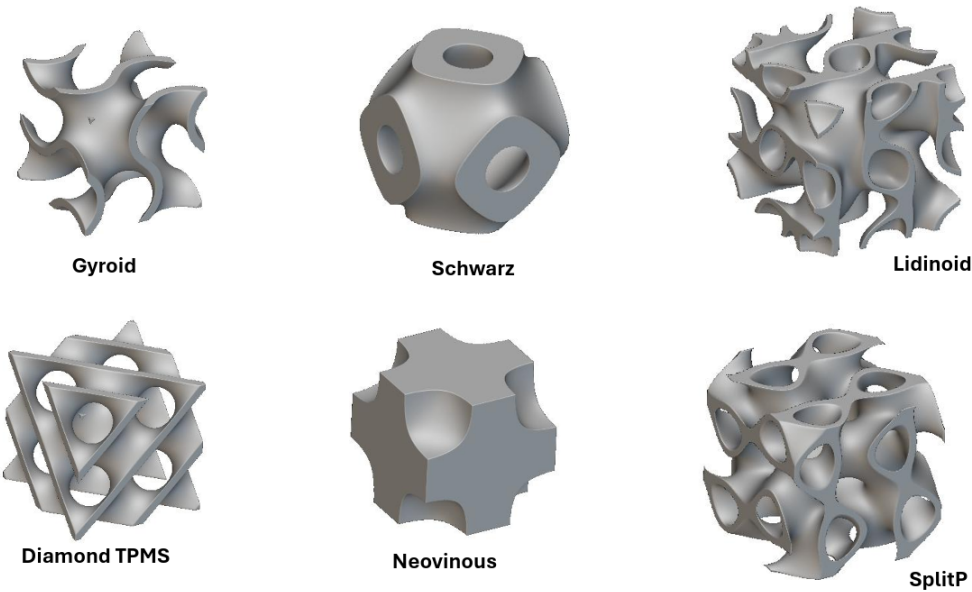


Figure 6. TPMS unit cells.

3.2. Analysis

Steady state thermal analysis was carried out using ANSYS. In steady state analysis, the object under study is assumed to be in equilibrium. Ambient conditions are also assumed to be constant. Same material properties and boundary conditions were defined for all heat sink types. The material is assumed to be isotropic and homogeneous with constant thermal conductivity.

3.2.1. Material Properties

Usually Aluminium alloys are the most preferred choice for heat sinks due to their good thermal conductivity, low weight, low cost and high strength. Al 6000 series alloys are widely used as they can

be extruded easily. Al 6061 alloy was taken for analysis. Some important properties of Al 6061 alloy are given below:

- Material: Al 6061 T6
- Density: 2713 kg/m^3
- Poisson's Ratio: 0.33
- Young's modulus: $6.904\text{E}+10\text{ Pa}$
- Bulk modulus: $6.7686\text{E}+10\text{ Pa}$
- Isotropic Thermal Conductivity: 155.3 W/mK
- Ultimate Tensile strength: $3.131\text{E}+8\text{ Pa}$
- Specific Heat(constant Pressure): 915.7 J/kgK
- Isotropic Secant Coefficient Of Thermal Expansion: $2.278\text{E}-5\text{ /K}$

Compositon of Al 6061 alloy is shown in Table 1.

Table 1. Material composition (Al 6061).

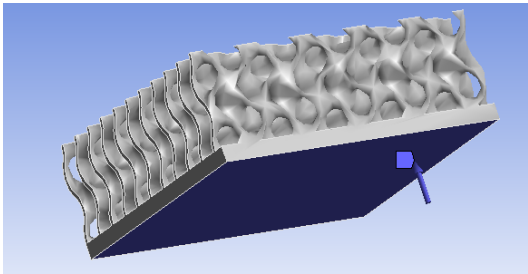
Element	Wt. %
Al	95.8- 98.6
Cr	0.04- 0.35
Cu	0.15- 0.4
Fe	Max 0.7
Mg	0.8- 1.2
Mn	Max 0.15
Si	0.4- 0.8
Ti	Max 0.15
Zn	Max 0.25

3.2.2. Boundary Conditions

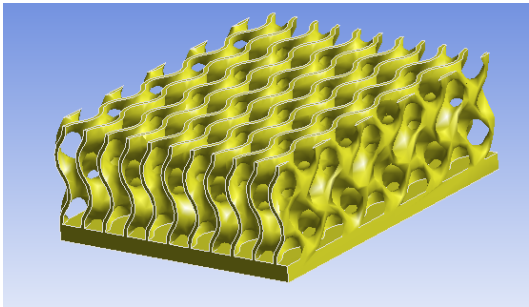
In this study, a constant film coefficient was assumed for simplicity. In actual practice, the film coefficient of a heat sink depends on various factors like surface roughness, geometrical parameters, fluid properties (viscosity, density), flow rate, heat flux, temperature gradient, etc... [26] Additionally, obtaining an accurate value of heat transfer coefficient is difficult as it changes locally and temporally [27–31]. Heat transfer due to radiation was neglected. A constant heat input of 100W was given in the bottom face of the base plate.

The following boundary conditions were defined:

1. Film coefficient: $25\text{ W/m}^2\text{ K}$
2. Heat flow(base): 100 W
3. Ambient temperature: 30^0 C



(a) Heat input boundary



(b) Convection boundary

Figure 7. Boundary regions.

Properties of the heat sinks used for analysis are tabulated below:

Table 2. Heat sink data.

Unit cell type	Thickness (mm)	Nodes	Elements	Mass(g)	Surface area (mm²)	Wt. %
Simple cubic	4	223143	138108	173.74	44571.33	22.87136012
Body centred cubic	3	279253	162839	191.86	55570.87	25.25670054
Face centred cubic	3	321148	187137	208.27	66091.82	27.41693434
Diamond	3	304447	181469	191.64	55724.85	25.22773946
Octet	3	526883	316205	291.18	98070.46	38.33131483
Kelvin cell	3	303670	177447	206.2	62850.66	27.14443684
Fluorite	3	438067	258296	260.78	82638.74	34.3294192
Isotruss	3	219156	136626	253.29	81405.53	33.34342583
Triangular honeycomb	3	343357	224716	494.2	96459.57	65.05713233
Hexagonal honeycomb	3	29284	122089	355	74245.7	46.73266284
Reentrant honeycomb	3	219977	135062	417.63	87043.11	54.9773577
Square honeycomb	3	123582	74924	289.2	60256.69	38.07066505
FCC plate	1	428251	253213	326.36	155390.4	42.9624559
BCC plate	1	477545	296874	370.86	180576.59	48.82049392
Gyroid	2	197347	103200	247.82	102846.45	32.6233479
Schwarz	2	207814	121741	350.62	79234.29	46.15607393
Diamond TPMS	2	226259	116393	275.64	120721.57	36.28560897
Lidinoid	2	281184	166176	360.86	157632.11	47.50408088
SplitP	2	609100	325740	295.65	152601.96	38.91975146
Neovinous	1	866475	597273	422.76	74812.35	55.65267758

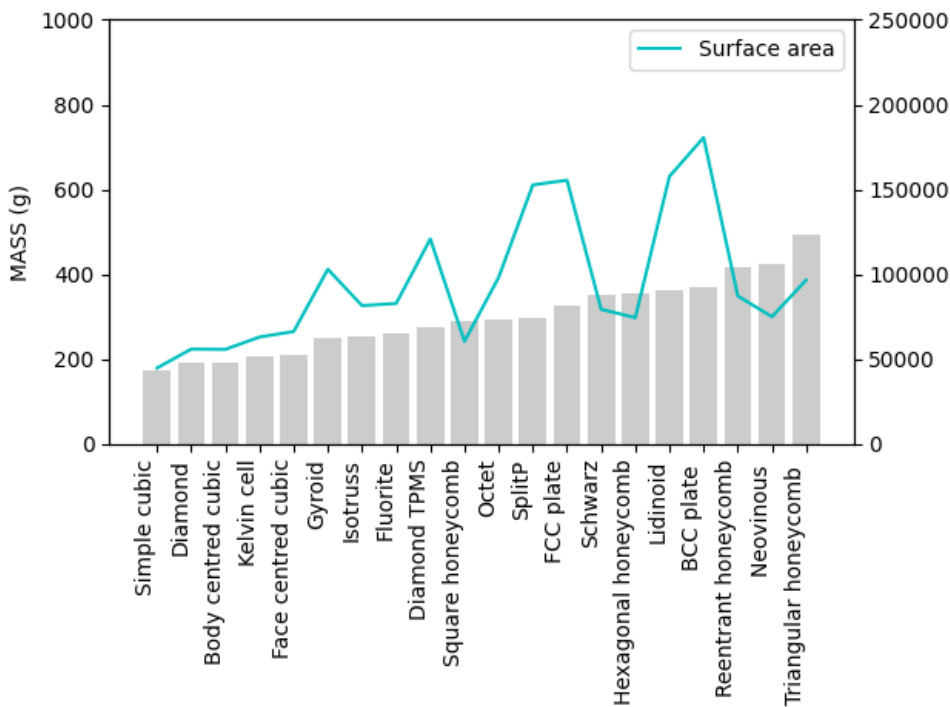


Figure 8. Mass vs Surface area plot

4. Results and Discussion

From Table 3, it is evident that the temperature difference is the highest within the simple cubic heat sink. But, the maximum temperature produced in the simple cubic heat sink is the highest among all types taken for analysis. Maximum temperature reached in plate based heat sinks is lower when compared to

other types. In most of the cases, the temperature difference increases with decreasing mass of the heat sink (with same film coefficient). Temperature distribution in the 2D lattice structured heat sinks is not uniform along the vertical axis and changes based on the unit cell orientation. A more uniform heat flux distribution is seen in 2D, honeycomb and TPMS lattices as compared to beam/truss based structures. The results are highly subject to the design parameters of unit cells and the heat transfer coefficient. It can be seen that for a given value of film coefficient, beam/truss based heat sinks outperform other types in terms of mass and temperature difference produced. Future works may study the heat transfer properties of heat sinks with film coefficient obtained using CFD analysis results.

The results of the analysis are tabulated below:

Table 3. Analysis results.

Unit cell type	Min. temp.	Max. temp.	Temperature difference	Min. heat flux	Max. heat flux
Simple cubic	104.16	176.89	72.73	365.95	5.61E+05
Body centred cubic	89.87	144.43	54.56	99.05	4.82E+05
Face centred cubic	75.89	128.43	52.54	171.42	2.43E+05
Diamond	86.84	144.33	57.49	41.645	4.31E+05
Octet	64.18	90.85	26.67	41.633	1.34E+05
Kelvin cell	83.23	129.14	45.91	175.63	4.17E+05
Fluorite	71.93	101.24	29.31	56.76	3.00E+05
Isotruss	69.61	104.44	34.83	135.36	2.29E+05
Triangular honeycomb	72.54	80.04	7.5	572.32	50991
Hexagonal honeycomb	85.58	95.22	9.64	246.49	1.29E+05
Reentrant honeycomb	76.86	86.59	9.73	195.95	99972
Square honeycomb	104.63	109.75	5.12	654.98	69641
FCC plate	52.44	66.94	14.5	143.12	99131
BCC plate	49.34	61.32	11.98	53.9	1.00E+05
Gyroid	64.4	84.07	19.67	149.76	1.23E+05
Schwarz	80.96	93.69	12.73	219.91	1.44E+05
Diamond TPMS	58.67	74.94	16.27	107.53	1.57E+05
Lidinoid	66.23	76.42	10.19	135.47	64755
SplitP	51.46	66.83	15.37	67.57	1.82E+05
Neovinous	86.51	95.77	9.26	129.53	72583

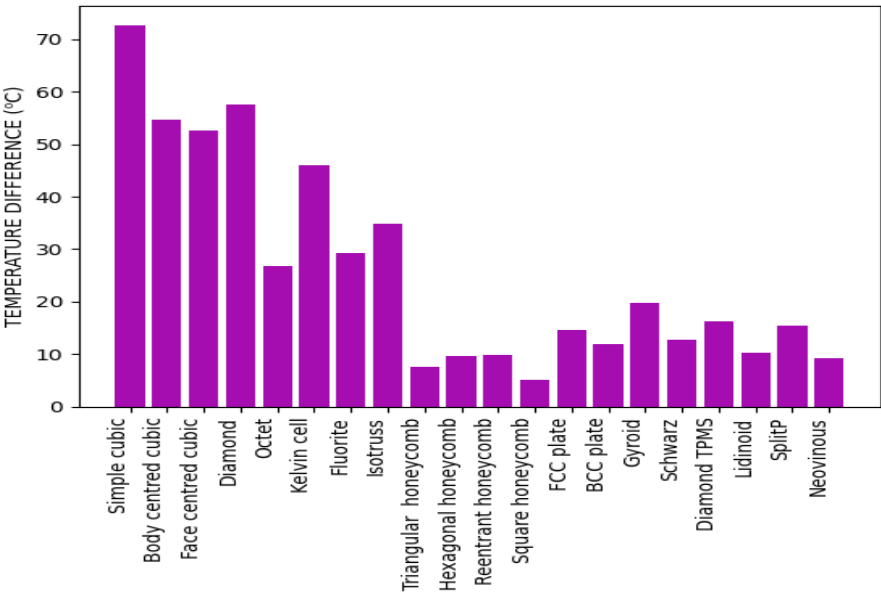


Figure 9. Temperature difference

The following figures show the temperature distribution within the heat sinks.

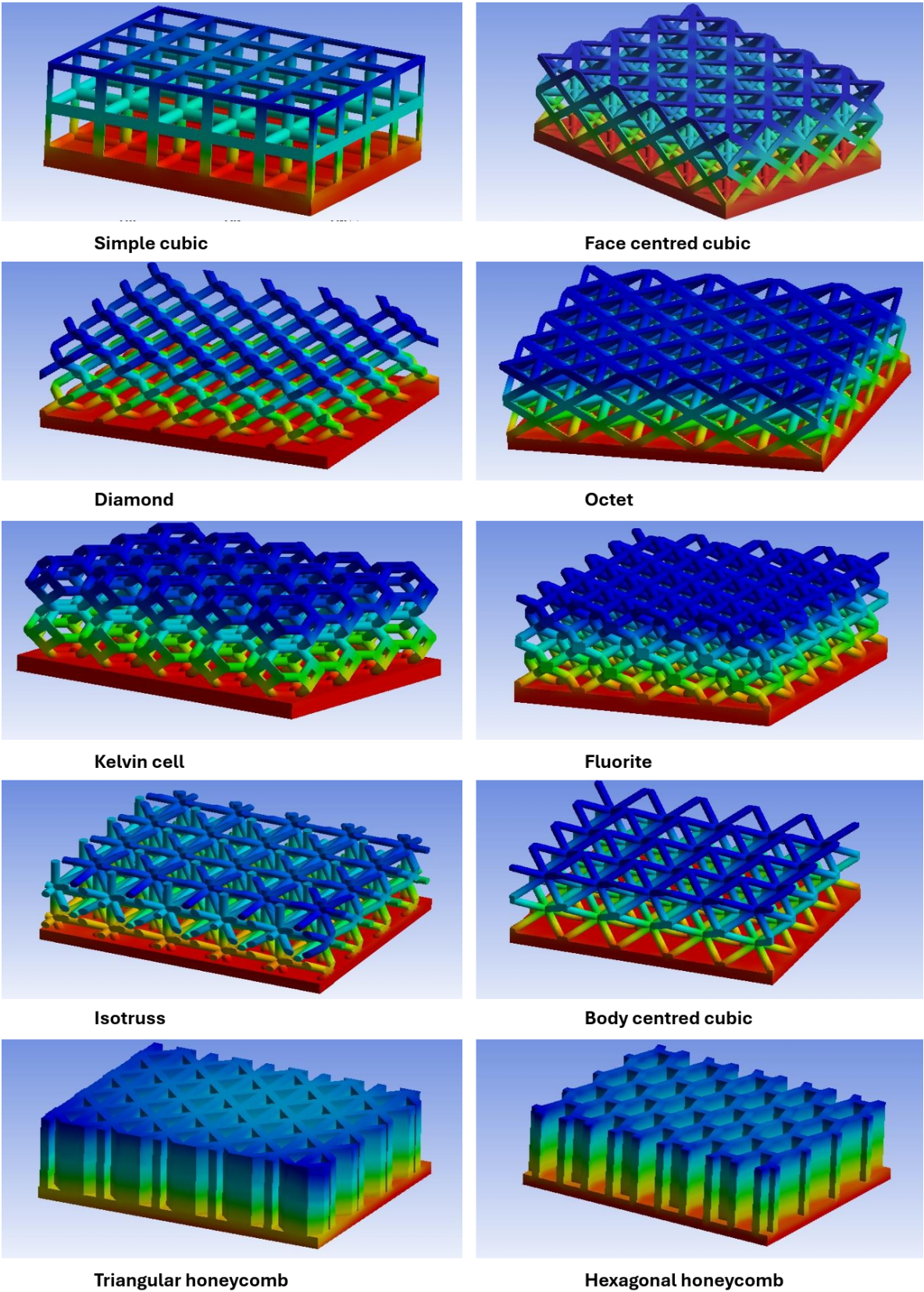


Figure 10. Temperature distribution results (contd...)

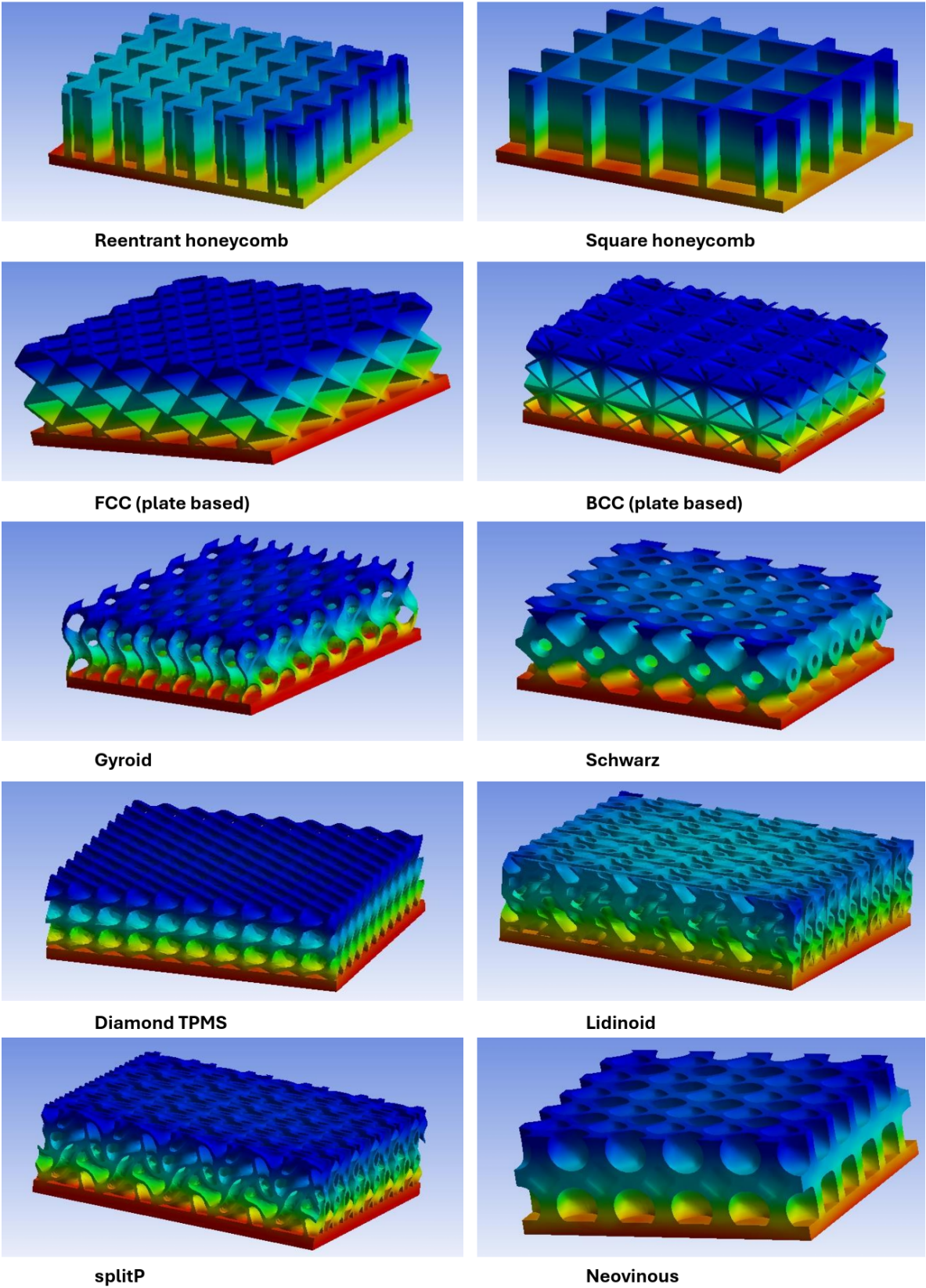


Figure 11. Temperature distribution results (contd...)

The following figures show the heat flux distribution within the heat sinks.

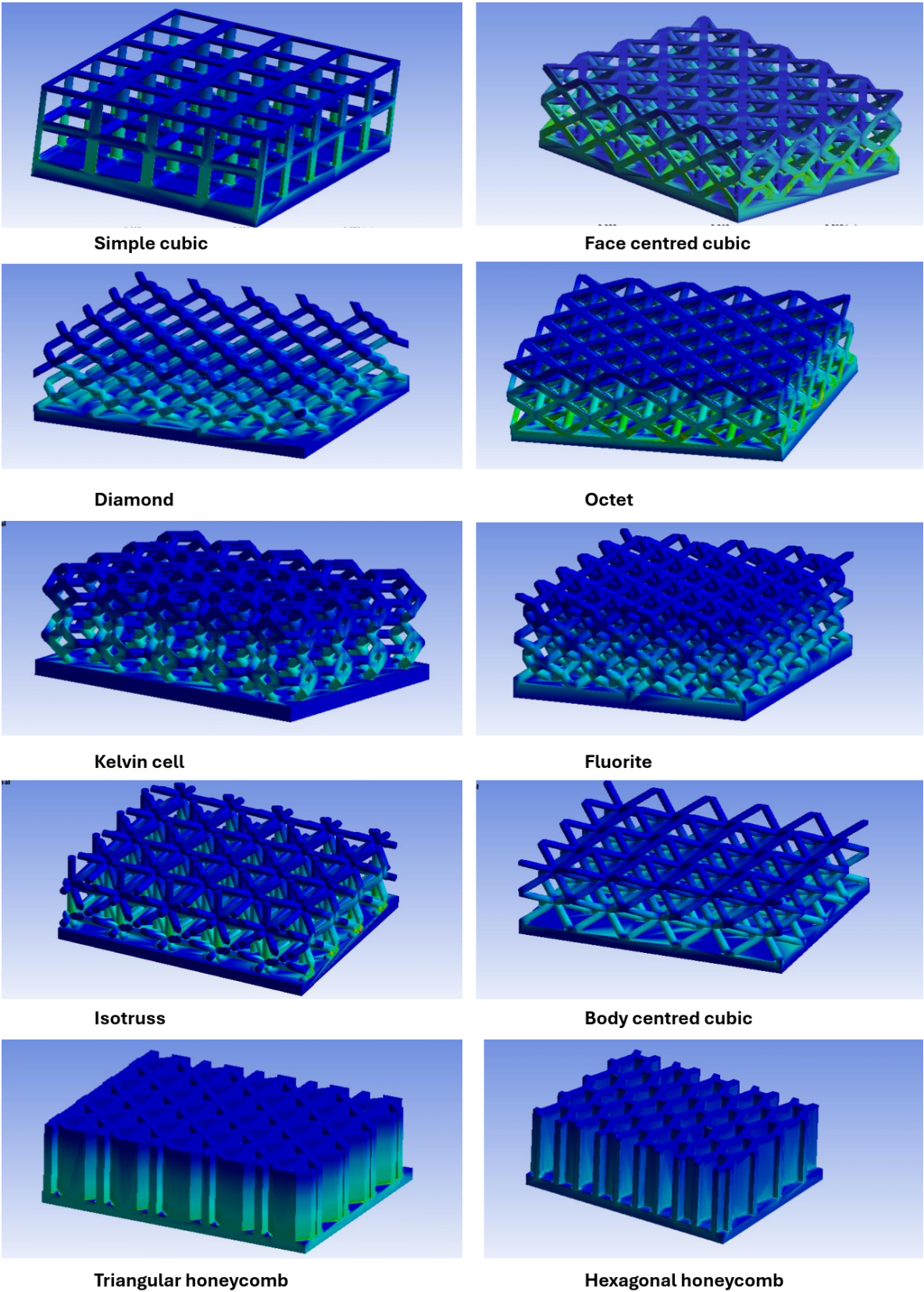


Figure 12. Heat flux distribution (contd...)

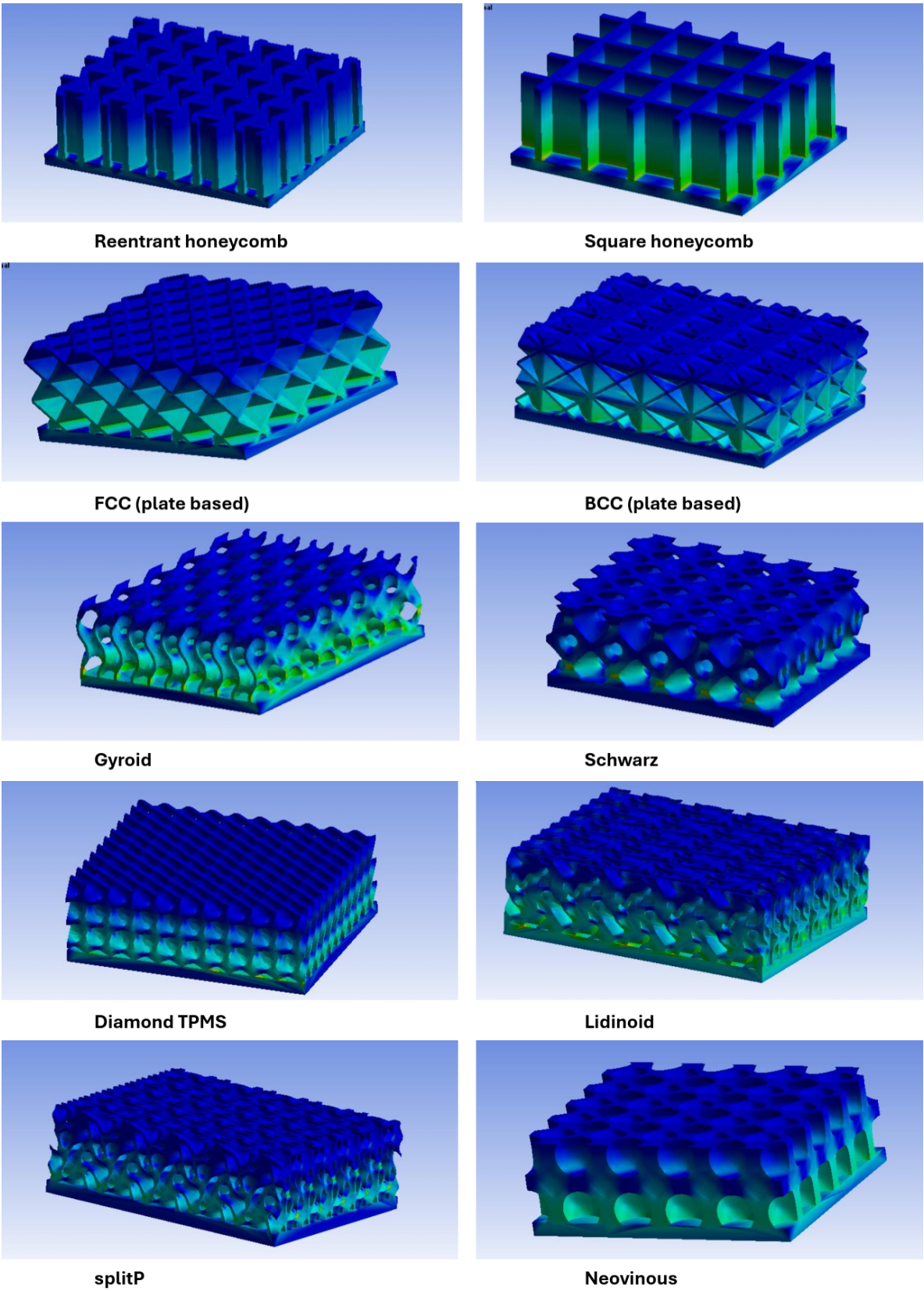


Figure 13. Heat flux distribution (contd...)

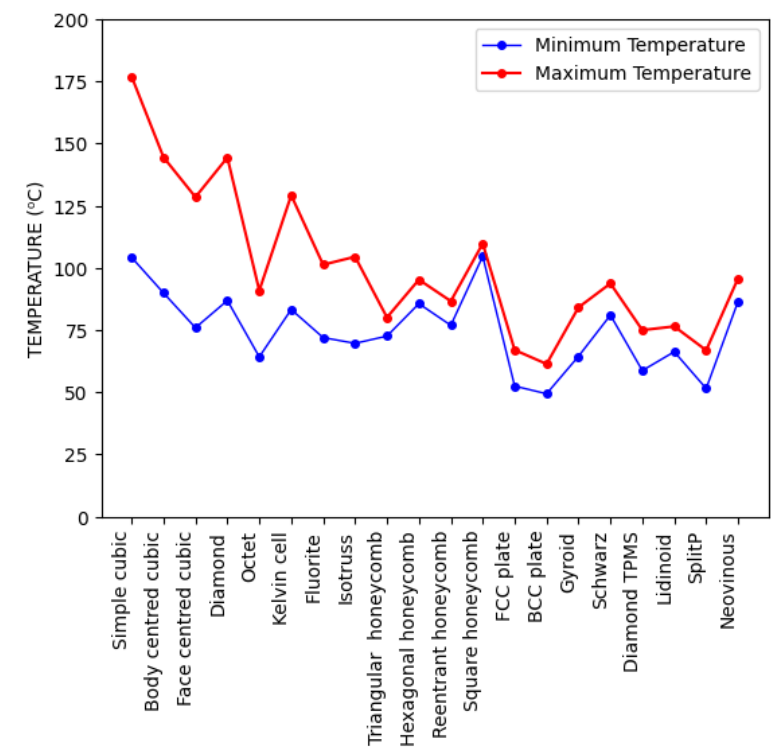


Figure 14. Maximum and minimum temperatures plot

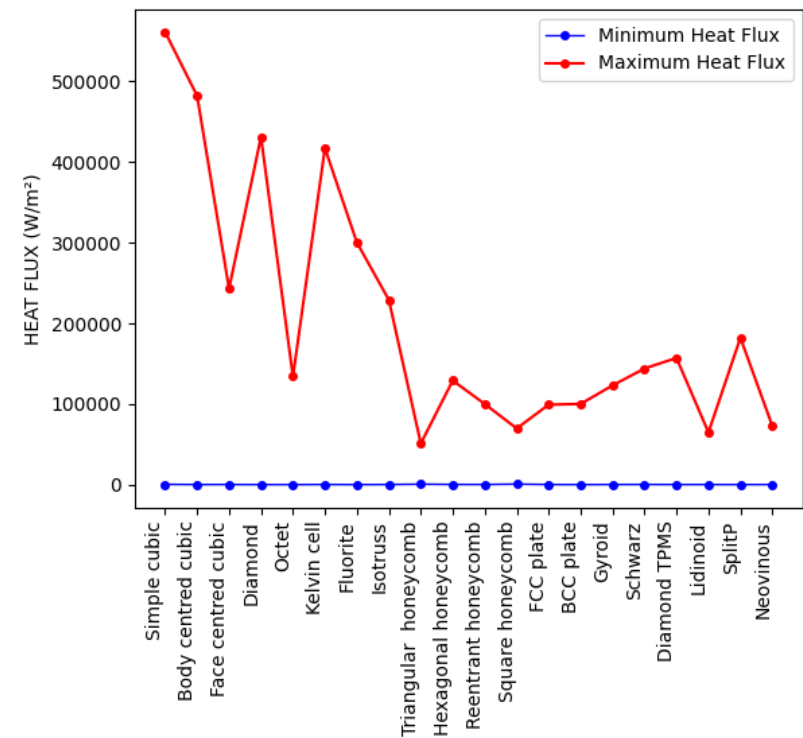


Figure 15. Minimum and maximum heat flux plot

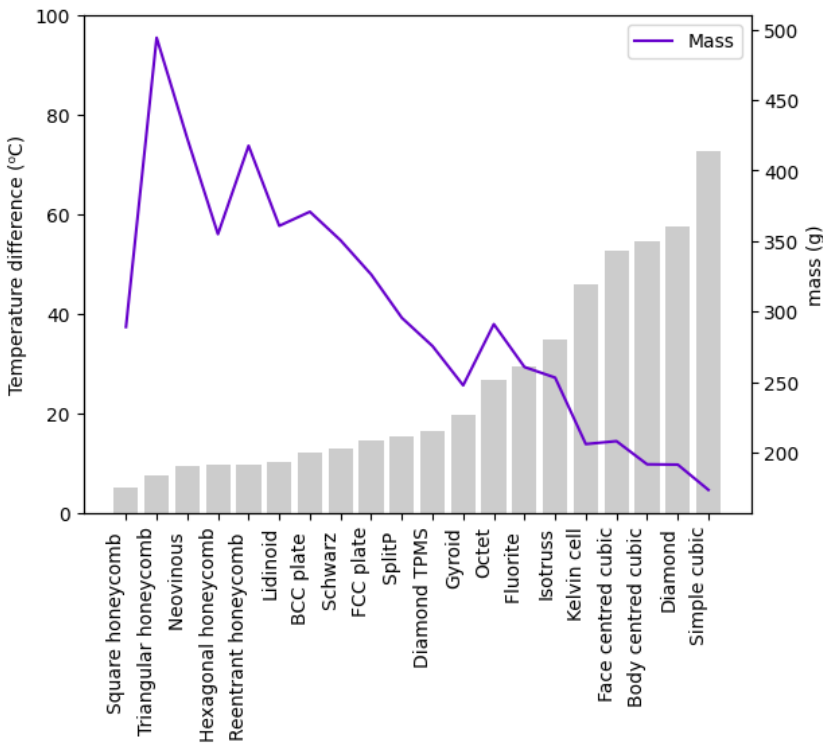


Figure 16. Mass vs Temperature difference plot

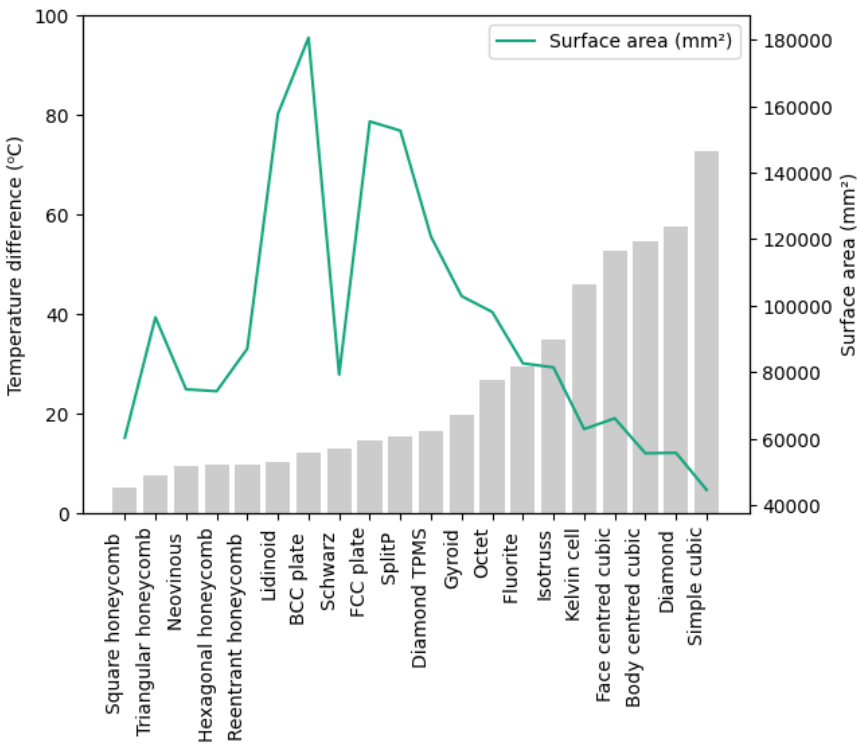


Figure 17. Temperature difference vs surface area plot

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Conflicts of Interest: The author hereby declares that he has no competing interests.

References

1. Arefin, A.M.E. Thermal analysis of modified pin fin heat sink for natural convection. 2016 5th International Conference on Informatics, Electronics and Vision (ICIEV). IEEE, 2016, pp. 1–5.
2. Kushwaha, A.S.; Kirar, R. Comparative study of rectangular, trapezoidal and parabolic shaped finned heat sink. *IOSR J. Mech. Civ. Eng* **2013**, *5*, 1–7.
3. Shah, S.I. Effect of Geometry and Arrangement of Pin Fin in Heat Exchanger: A Review **2016**.
4. Yardi, A.; Karguppikar, A.; Tanksale, G.; Sharma, K. Optimization of Fin spacing by analyzing the heat transfer through rectangular fin array configurations (Natural convection). *International Research Journal of Engineering and Technology (IRJET)* **2017**, *4*.
5. Dewan, A.; Patro, P.; Khan, I.; Mahanta, P. The effect of fin spacing and material on the performance of a heat sink with circular pin fins. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy* **2010**, *224*, 35–46.
6. Catchpole-Smith, S.; Sélo, R.; Davis, A.; Ashcroft, I.; Tuck, C.; Clare, A. Thermal conductivity of TPMS lattice structures manufactured via laser powder bed fusion. *Additive Manufacturing* **2019**, *30*, 100846.
7. Nazir, A.; Abate, K.M.; Kumar, A.; Jeng, J.Y. A state-of-the-art review on types, design, optimization, and additive manufacturing of cellular structures. *The International Journal of Advanced Manufacturing Technology* **2019**, *104*, 3489–3510.
8. Perween, S.; Fahad, M.; Khan, M.A. Systematic experimental evaluation of function based cellular lattice structure manufactured by 3d printing. *Applied Sciences* **2021**, *11*, 10489.
9. Dong, G.; Tang, Y.; Zhao, Y.F. A survey of modeling of lattice structures fabricated by additive manufacturing. *Journal of Mechanical Design* **2017**, *139*, 100906.
10. Schaedler, T.A.; Carter, W.B. Architected cellular materials. *Annual Review of Materials Research* **2016**, *46*, 187–210.
11. Ashby, M.F.; Gibson, L.J. Cellular solids: structure and properties. *Press Syndicate of the University of Cambridge, Cambridge, UK* **1997**, pp. 175–231.
12. Jia, Z.; Liu, F.; Jiang, X.; Wang, L. Engineering lattice metamaterials for extreme property, programmability, and multifunctionality. *Journal of Applied Physics* **2020**, *127*.
13. Jia, Z.; Yu, Y.; Wang, L. Learning from nature: Use material architecture to break the performance tradeoffs. *Materials & Design* **2019**, *168*, 107650.
14. Ritchie, R.O. The conflicts between strength and toughness. *Nature materials* **2011**, *10*, 817–822.
15. Bouville, F.; Maire, E.; Meille, S.; Van de Moortèle, B.; Stevenson, A.J.; Deville, S. Strong, tough and stiff bioinspired ceramics from brittle constituents. *Nature materials* **2014**, *13*, 508–514.
16. Benedetti, M.; Du Plessis, A.; Ritchie, R.; Dallago, M.; Razavi, N.; Berto, F. Architected cellular materials: A review on their mechanical properties towards fatigue-tolerant design and fabrication. *Materials Science and Engineering: R: Reports* **2021**, *144*, 100606.
17. Pei, E.; Kabir, I.; Breški, T.; Godec, D.; Nordin, A. A review of geometric dimensioning and tolerancing (GD&T) of additive manufacturing and powder bed fusion lattices. *Progress in additive manufacturing* **2022**, *7*, 1297–1305.
18. Abou-Ali, A.M.; Lee, D.W.; Abu Al-Rub, R.K. On the Effect of Lattice Topology on Mechanical Properties of SLS Additively Manufactured Sheet-, Ligament-, and Strut-Based Polymeric Metamaterials. *Polymers* **2022**, *14*, 4583.
19. Guo, X.; Zheng, X.; Yang, Y.; Yang, X.; Yi, Y. Mechanical behavior of TPMS-based scaffolds: a comparison between minimal surfaces and their lattice structures. *SN Applied Sciences* **2019**, *1*, 1145.
20. Tancogne-Dejean, T.; Diamantopoulou, M.; Gorji, M.B.; Bonatti, C.; Mohr, D. 3D plate-lattices: an emerging class of low-density metamaterial exhibiting optimal isotropic stiffness. *Advanced Materials* **2018**, *30*, 1803334.
21. Andrew, J.J.; Alhashmi, H.; Schiffer, A.; Kumar, S.; Deshpande, V.S. Energy absorption and self-sensing performance of 3D printed CF/PEEK cellular composites. *Materials & Design* **2021**, *208*, 109863.
22. Pronk, T.; Ayas, C.; Teköglu, C. A quest for 2D lattice materials for actuation. *Journal of the Mechanics and Physics of Solids* **2017**, *105*, 199–216.
23. Opalach, A.; Maddock, S. An overview of implicit surfaces. *Introduction to modelling and animation using implicit surfaces* **1995**, pp. 1–1.

24. Fayolle, P.A.; Fryazinov, O.; Pasko, A. Rounding, filleting and smoothing of implicit surfaces. *Computer-Aided Design and Applications* **2018**, *15*, 399–408.
25. Li, Q.; Hong, Q.; Qi, Q.; Ma, X.; Han, X.; Tian, J. Towards additive manufacturing oriented geometric modeling using implicit functions. *Visual Computing for Industry, Biomedicine, and Art* **2018**, *1*, 1–16.
26. Moreira, T.A.; Colmanetti, A.R.A.; Tibirica, C.B. Heat transfer coefficient: a review of measurement techniques. *Journal of the Brazilian Society of Mechanical Sciences and Engineering* **2019**, *41*, 1–25.
27. Gradziel, S.; Majewski, K.; Majdak, M. Experimental determination of the heat transfer coefficient in internally rifled tubes. *Thermal Science* **2019**, *23*, 1163–1174.
28. Bury, T.; Drapała, M.H. Evaluation of selected methods of the heat transfer coefficient determination in fin-and-tube cross-flow heat exchangers. *MATEC Web of Conferences*. EDP Sciences, 2018, Vol. 240, p. 02004.
29. Erdoğan, F. A review on simultaneous determination of thermal diffusivity and heat transfer coefficient. *Journal of Food Engineering* **2008**, *86*, 453–459.
30. Abramkina, D.; Abramyan, A.; Shevchenko-Enns, E. Experimental Determination of Convective Heat Transfer Coefficients in Thermal Buoyancy Ventilation System. *Herald of Dagestan State Technical University Technical Sciences* **2019**, *45*, 133–141.
31. Korprasertsak, N.; Leephakpreeda, T. Real-time determination of convective heat transfer coefficient via thermoelectric modules. *Journal of Heat Transfer* **2017**, *139*, 101701.

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