AERO Pro Max

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***Executive Summary* —The heat sink is a device used to conduct and release heat. A major motivation for the competition is to create an innovative heat sink design that fully utilizes the advantages of additive manufacturing (AM) in terms of complex geometries and high-strength materials. Our team, AERO Pro Max, designed a bionic heat sink that consists of conical pins with honeycomb holes and raised branches arranged in a honeycomb pattern, to enhance the overall aesthetic appeal of the heat sink. The airflow velocity and temperature distribution of the heat sink were simulated using ANSYS Fluent. The base average temperature of the designed heat sink under 1 m/s and 5 m/s cases were 307.917 K and 303.601 K, respectively. The mass of the design heat sink was 0.2823 Kg. The final figure of merit (FOM) was calculated to be 0.92264 W /(kg·K). The aspect-ratio, 60-degree rule and minimal feature size were strictly followed to make the designed heat sink suitable for fabrication by binder jet additive manufacturing.**

I. DESIGN DESCRIPTION

The most effective configuration was determined to be the utilization of circular truncated cones, specifically conical pins, with a total of 80 units. These cones were arranged in alternating rows, with odd rows consisting of 8 cones and even rows accommodating 7 cones. The diameter at the base of each circular truncated cone measured 5 mm, tapering down to 1mm at the top.

Subsequently, perforations were introduced onto these circular truncated cones based on the honeycomb bionics principle elucidated by Pie et al. [1]. The pattern efficiency was utilized, and six regular hexagons with appropriate side lengths were uniformly distributed on each cone. Considering the dimensional constraints of the feature size, a trapezoidal hole measuring 0.05mm and 0.96mm for the top and bottom lines, respectively, was introduced at the apex of the cone.

By integrating principles of cellular bionics and fractal design, the top view of the structure is depicted in Figure 1. It is worth noting that the wind velocity on the two sides of the heat sink was significantly higher compared to the mid-region. Motivated by this observation, a final bionic design inspired by tree branches was proposed, as shown in Figure 2 and Figure 3. According to the simulation results obtained from Fluent, this design demonstrated the highest level of optimality when comparing the FOM.

II. DESIGN ANALYSIS

In the realm of heat sink geometry design, the initial phase involved the uniform distribution of two conventional geometries, namely, pins and fins, across the base plane without incorporating any apertures. Additionally, considerations were made towards bionics design perspectives. Subsequently, in the conclusive section of the appendix, bionics design elements and apertures were introduced to enhance certain fundamental pin and fin structures. The selection of the optimal heat sink design from these conceptualizations was contingent upon the criteria of Figure of Merit (FOM) and Aspect Ratio.

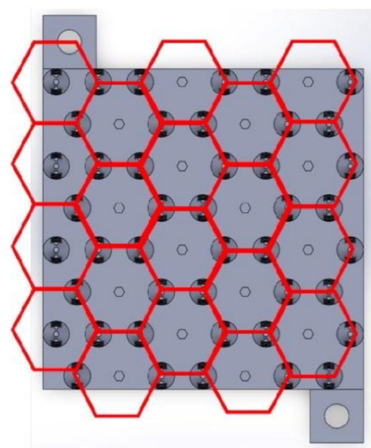

Fig.1 Honeycomb arrangement of conical pins

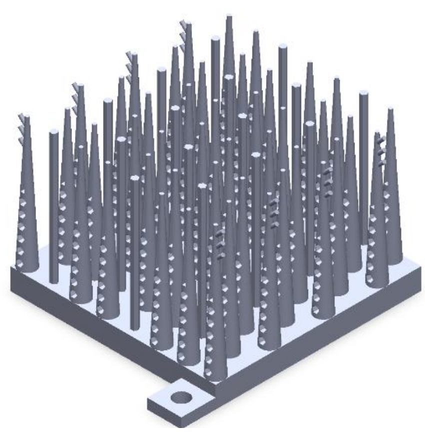

Fig.2 Structure of the bionic heat sink.

Fig.3 Detailed structure of the feature elements

The performance of the designed heat sink is evaluated by the criterion called Figure of Merit (FOM), which is calculated as below:

$$FOM = \frac{1}{(R_1 + R_5)m_{hs}} \quad (1)$$

$$R_j = \frac{T_{meas} - T_{amb}}{Q_{meas}} \quad (2)$$

where m_{hs} is the weight of the heat sink, R_1 and R_5 represent the measured heat resistance at $1m/s$ and $5m/s$ respectively. T_{meas} is the average temperature of the heat sink base, T_{amb} is the ambient temperature, and Q_{meas} is the measured thermal power input. Eqn. (2) indicates that the thermal resistance of the heat sink is inversely proportional to the heat dissipation ability of the heat sink, which could be represented according to Newton's Law of Cooling:

$$Q = h \cdot A \cdot \Delta T \quad (3)$$

where Q is dissipated heat from the heat sink, h is the heat convection coefficient between the heat sink and the air, A is the interface area between the heat sink and the air, and ΔT is the temperature difference between the heat sink and air. Therefore, the design of the heat sink aims to increase the dissipated heat while reducing its weight. The main goal of our design is to increase the interface surface area of the heat sink. Additionally, the heat convection coefficient is positively related to the airflow speed through the heat sink. The temperature difference could also be increased by keeping cooled air continuously supplied.

To ensure an accurate design proposal, it is imperative to establish the feature size of the heat sink based on pertinent references. According to Mostafaei et al. [2], the minimum feature size of this particular heat sink, which will be made by a binder jet, is 1.0 mm.

To predict the heat transfer (conduction and convection) performance of the designed heat sink, the simulation was performed using the ANSYS Fluent solver. A velocity-inlet boundary condition was applied at the inlet to simulate the airflow. The bottom surface of the heat sink was assumed to be a uniform heat source. An equivalent heat flux $\phi = \frac{P}{A} = 796.14\ W/m^2$ was calculated based on the given P=3 W power input and applied on the surface. A pressure-outlet boundary condition (gauge pressure of 0) was applied at the outlet. Non-slip wall conditions were set for the heat sink and air domain walls. During the meshing process, the global element size was specified as 10mm, while the size of the heat sink was set to 0.5mm. As a result, the entire geometry consisted of 685,536 nodes and 3,987,978 elements.

The result of temperature and streamlines distribution of final geometry is shown as following Figure 4.

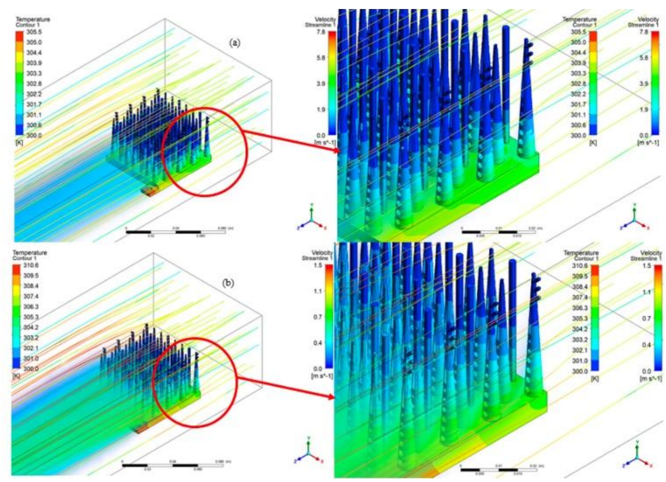

Fig. 4. The CFD simulation results of the final design. (a) Contour of temperature distribution on the surface of the heat sink at the incoming flow velocity of 5 m/s, volume rendering of the temperature at wake region of heat sink and streamline map around the heat sink.(b) Result at the incoming flow velocity of 1 m/s.

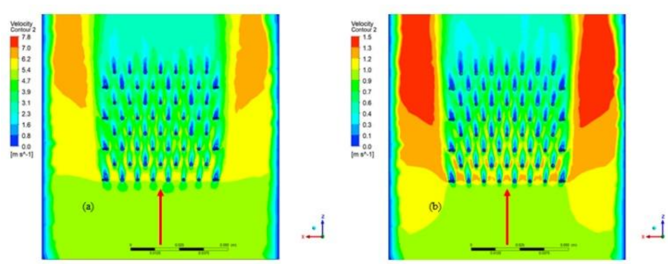

Fig. 5. Flow velocity contour on the plane parallel to the plane with a height of 31 mm. (a) Results at the incoming flow velocity of 5 m/s. (b) Results at the incoming flow velocity of 1 m/s.

Figure 5. shows the distribution of velocity at the section plane, It is obvious that the tree branches resist some of the boundary fluid for forced heat convection.

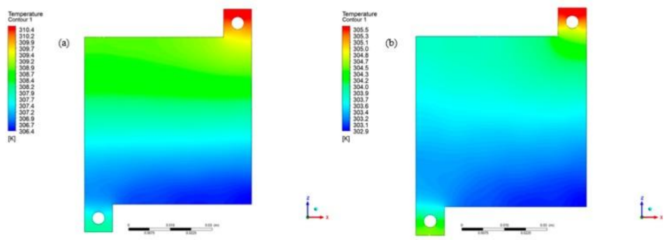

Fig. 6. Temperature contour of the bottom surface of the heat sink (a) Results at the incoming flow velocity of 5 m/s. (b) Results at the incoming flow velocity of 1 m/s.

Based on Figure 6, the average temperature of the heat source can be determined as 307.917K and 303.601K, respectively.

PREDICTED FIGURE OF MERIT

The mass of the heat sink can be acquired as 0.2823 kg using SOLIDWORKS software. The final figure of merit (FOM) for this structure can be calculated as 0.92264, as shown in Table 1.

TABLE 1 Predicted FOM of the design heat sink

Heat Sink		
Parameter	**Value**	
Heater Power, *P* [W]	3	
Ambient Temperature, T_{amb} [◦C]	26.85	
Heat Sink Mass, m_{hs} [kg]	0.2823	
Velocity *V* [m/s]	1 m/s	5 m/s
Measure heat resistance *R*	2.639	1.200
Figure of Merit[FOM] [W/(kg K)]	0.92264	

III. ADDITIVE MANUFACTURING

The heat sink consisting of conical pins with honeycomb holes and raised branches arranged in a honeycomb pattern is designed. In the designed model, the truncated cones and hexagonal prisms are arranged very densely, and each truncated cone is punched with holes of different shapes to increase the heat transfer surface area and reduce weight. Additionally, the branch-shaped structure will also bring difficulties to conventional manufacturing. Additionally, the minimum feature size of the designed structure is 1.0mm, which means big costs to produce models with this level of precision through conventional manufacturing. Those characteristics make conventional manufacturing of the designed heat sink virtually impossible. However, those difficulties could be solved through additive manufacturing (AM).

The heat sink consisting of conical pins with honeycomb holes and raised branches arranged in a honeycomb pattern is designed. The intricate holes on each and the small gaps between them make the designed heat sink very difficult and time-consuming to fabricate by conventional machining or material forming. binder jet, as one of the metal Additive Manufacturing (AM) techniques, is a proficient way to produce such kind of metal parts with free surfaces and complex internal channels. To ensure the successful printing of the designed heat sink, the heat sink is further revised and the final geometry is shown in Figure 7. The modifications towards binder jet additive manufacturing are as below:

(1) To make the aspect ratio smaller than 6.7, the top diameters and basal diameters of the conical pins are increased and the height of the hexagonal prisms are decreased.

(2) Mostafaei et al. [2] indicated that the allowed minimum feature size of the binder jet technique is approximately 1.0 mm. The heat sink is thus designed with a reasonable minimal feature size of 1.0mm.

(3) The raised branches at the top of the conical pins are designed with an angle larger than 60 degrees to the horizontal plane.

(4) The corners at acute angles are chamfered. And chamfer radii are made greater than 0.5mm.

(5) The original hexagonal holes at the bottom of the conical pins are replaced with an ellipse, which is convenient to clean while increasing the value of FOM.

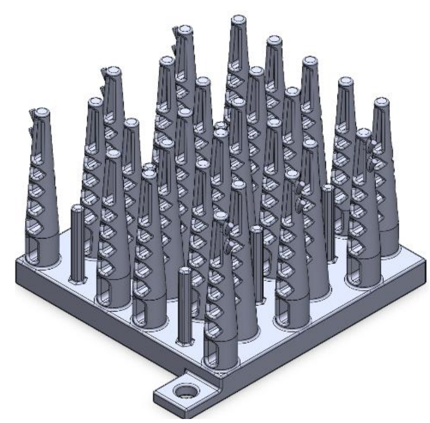

Fig.7 Final structure of the biomic heat sink.

ACKNOWLEDGEMENTS

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[2] Mostafaei, A., Elliott, A. M., Barnes, J. E., Li, F., Tan, W., Cramer, C. L., ... & Chmielus, M. (2021). Binder jet 3D printing—Process parameters, materials, properties, modeling, and challenges. Progress in Materials Science, 119, 100707.

APPENDIX A: ADDITIONAL SUPPORTING MATERIALS

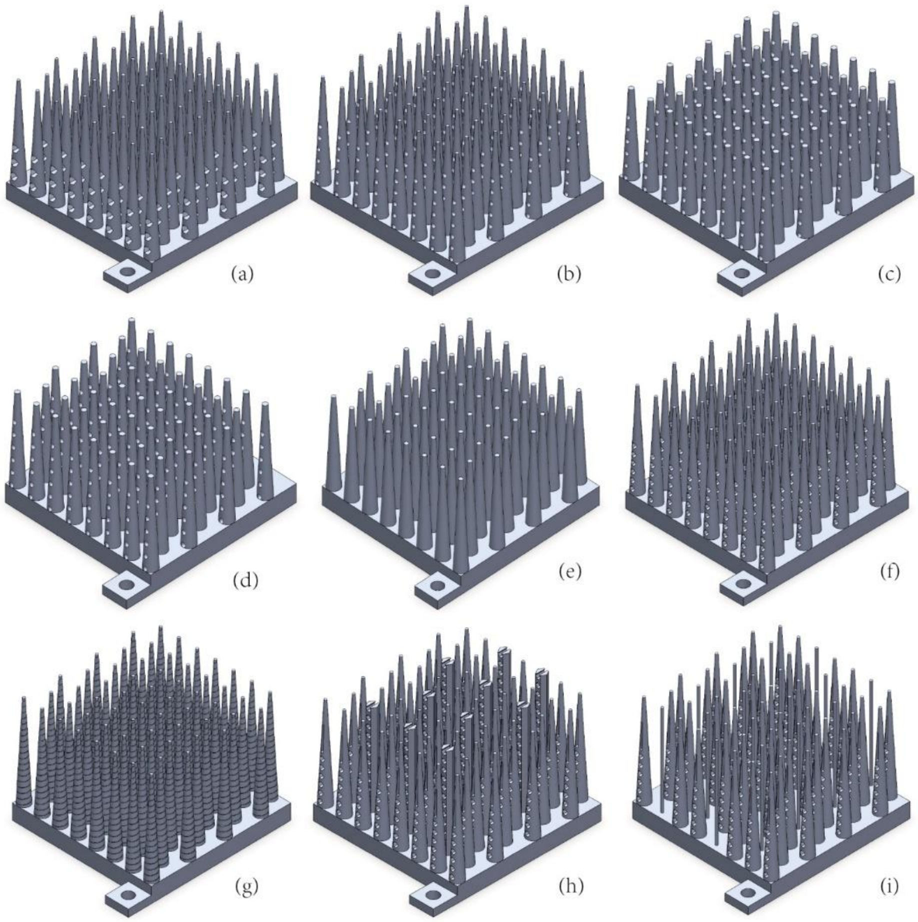

Fig.8. Different designed models

TABLE.2. FOM VALUE OF DIFFERENT STRUCTURE

Structure number	FOM
a	0.604
b	0.836
c	0.878
d	0.827
e	0.823
f	0.854
g	0.853
h	0.814
i	0.901
final design	0.923