ITherm Heat Sink Design Competition

Department of MECHANICAL ENGINEERING
THE UNIVERSITY OF UTAH

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Introduction:

Our senior project consists of a submission to the ITherm 2021 Heat Sink Design Competition. The ITherm Competition tasks student teams with designing creative and efficient passive heat sink designs to be manufactured using additive manufacturing (AM). A major motivation for the ITherm competition is creating an innovative heat sink design that fully utilizes AM processes.

The heat sinks were subject to natural convection conditions (no forced air flow) with a constant input heat rate of 25 W (comparable to a laptop CPU). Designs were required to be contained within the 3.5 in³ design volume shown in Figure 1.

Our submission to the ITherm 2021 competition consisted of a "white paper" writeup detailing our final heat sink design, a proof-of-concept heat sink design, and a corresponding analysis of heat sink performance. The heat sink performance analysis was calculated through a figure of merit (FOM), which considered a variety of different performance parameters of the design such as total material cost and base temperature. The heat sink was also qualitatively evaluated for its use of additive manufacturing.

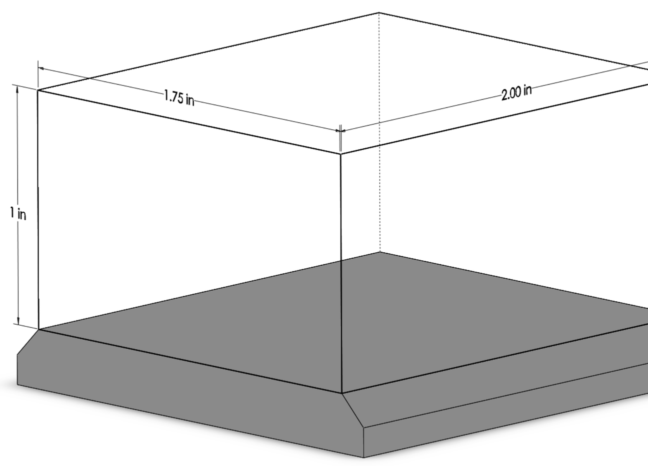

Figure 1. Heat sink design volume.

Design Principles:

The scoring of our heat sink was done using the cost-based figure of merit (FOM) equation given below. The FOM is inversely proportional to the temperature difference between the base of the heat sink and the surrounding air and the cost of the heat sink. The cost is entirely dependent on the heat sink volume. Therefore, our goal was to minimize the volume while maximizing the performance of the heatsink to succeed in the competition.

$$\mathrm{FOM} = \frac{1}{\$_{heatsink}(T_{base} - T_{amb})}$$

The temperature difference above is a factor of convective and conductive heat transfer. **Convective heat transfer** is governed by Newton's Law of Cooling (below). This means that we have three basic approaches to increase the convective heat transfer: increase the heat transfer coefficient, increase the surface area of the heat sink, or increase the temperature difference.

$$\underbrace{Q}_{\text{Rate of Heat Transfer }[W]} = \underbrace{h}_{\text{Heat Transfer Coefficient }\left[\frac{W}{m^2K}\right]} \cdot \underbrace{A}_{\text{Heat Sink Surface Area }[m^2]} \cdot \underbrace{\Delta T}_{\text{Temperature Difference Between Heat Sink and Atmosphere }[K]}$$

We found that, in general, a common heat sink design called a pin fin heat sink (Figure 2) has a high surface area with a low volume which allows for a high rate of heat transfer. We can also improve convective heat transfer by improving the **heat transfer coefficient (h)**. The heat transfer coefficient is dependent on the shape of the surface and the velocity of the flow of air over the surface. Flow occurs in two directions over the heat sink. The heating of the air induces a vertical buoyant flow. This is most pronounced at the center of the heat sink where the air is the hottest. This then causes an inward flow to the center of the heat sink that draws in cooler air. To improve the heat transfer coefficient (h) we chose to implement vertically oriented airfoils to streamline the buoyant flow (Figure 3). This also increases the surface area of the pins. It is also important to increase the **temperature difference (ΔT)** between the pins and the surrounding air. Because our original design had an inline pin layout (Figure 4), there were many stagnation points that caused the air to become very hot, which reduced the effectiveness of the heat sink. It is also important to consider **conductive heat transfer** in our pin design. Conductive heat transfer is dependent on the cross-sectional area of the pins. We found that the constriction at the bottom of the airfoil limited conductive heat transfer to the top of the pin, so we added a stem in our final design.

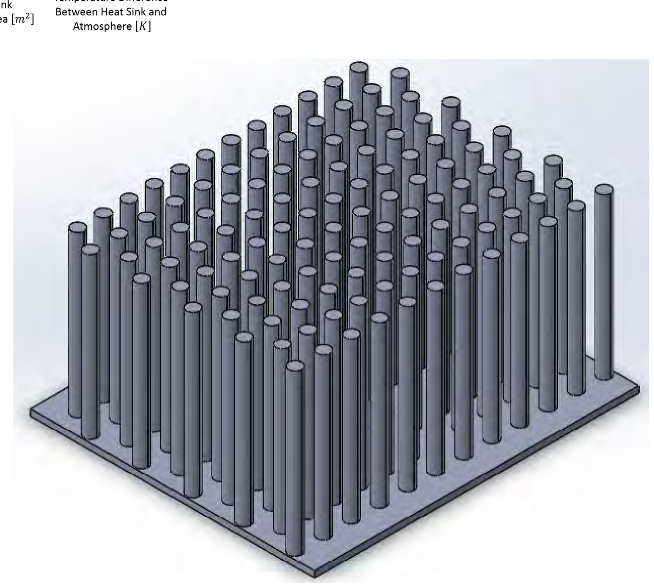
Figure 2. Generic pin fin heat sink.


Figure 3. Airfoil pin design.

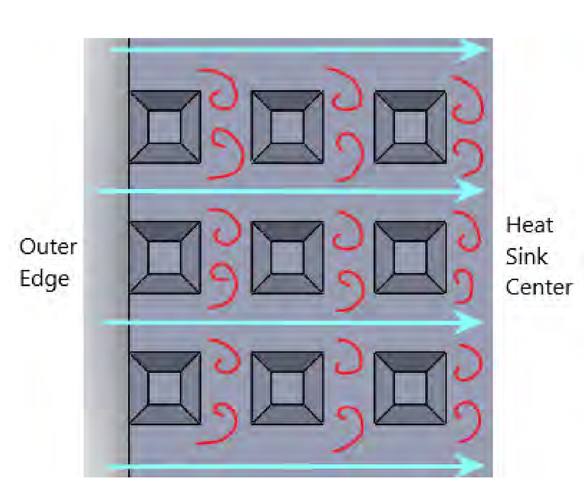

Figure 4. Air flow stagnation.

Design Principles (cont.):

In our simulations we discovered that the center pins were ineffective because the air in the center of the heat sink was very hot. We chose to remove pins along the diagonal and around the center pins to improve the flow of cool air to the hottest region of the heat sink. This improved the effectiveness of the center pins and reduced the total volume.
Our final design consideration is the **manufacturability** of the heat sink. The heat sink will be additively manufactured using aluminum A357 ("metal 3D printing"). Therefore, it must not have overhangs greater than 45 degrees or complex details smaller than 1 mm.

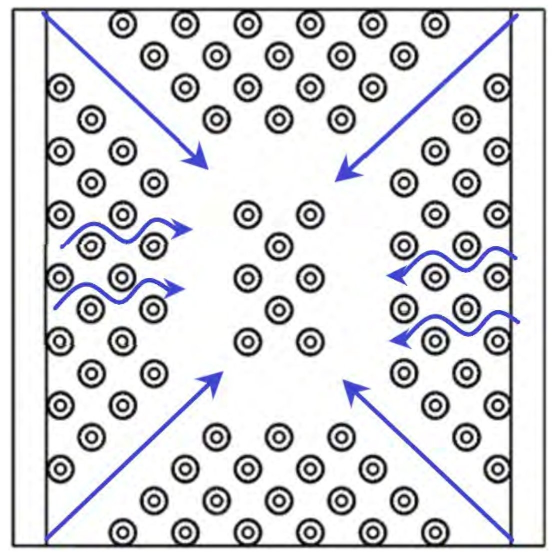
Figure 5. Pin Staggering and inflow channels

Design Solution:

There were several design solutions that improved performance:

- Round airfoil pins increase the overall surface area , while improving the heat transfer rate.
- A stem at the base of the pins improves heat transfer vertically in the pins.
- The staggered pin layout allows for continuous flow between the pins .
- Open channels where pins have been removed along the diagonal and around the center allow for more efficient cooling of the center pins.
- Removing the pins also reduced the overall volume, lowering the cost of the heat sink.

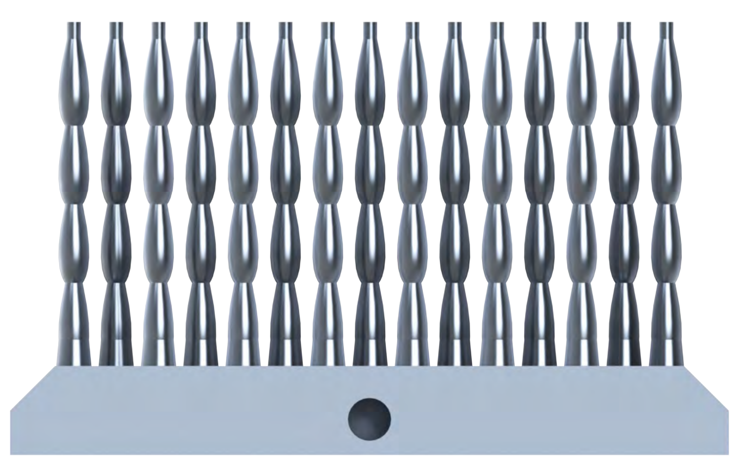
Figure 6. Side view of final heat sink design.

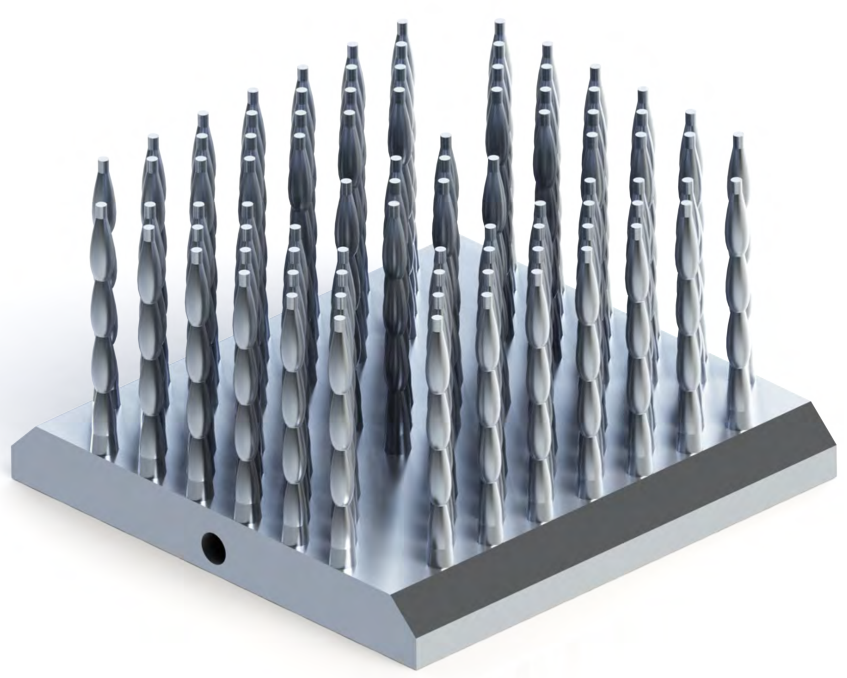
Figure 7. Isometric view of final heat sink design.

Analysis:

In order to analyze candidate heat sink designs, computational fluid dynamics (CFD) was employed to model the coupled fluid flow and heat transfer physics involved in the competition scenario. We conducted CFD analysis on numerous iterations of heat sink geometries. The results of our CFD analysis guided our selection of the features implemented in the geometry in our designs in SolidWorks. We iterated many times before producing our final heat sink design. A spreadsheet was used to calculate the FOM for each of our design iterations. The heat sink with the highest FOM based on the CFD simulations was selected to be our final design.

The CFD program works to numerically solve the Navier-Stokes and energy equations which govern the fluid and heat transfer physics, respectively. The heat sink and air around the heat sink are split up into many smaller three-dimensional triangle blocks and the governing equations are solved on each individual block (called a tetrahedral) to make the calculations simpler. As the problem is split up, the computation time to solve the problem increases, but the solution becomes more accurate. For our simulation we used roughly 2.2 million elements to analyze our final heat sink design and acquire a good result. Ansys Fluent CFD simulations were performed on the final heat sink design that we selected as a team to submit to the competition. The simulation results were checked against known results to ensure that the model was relatively accurate.

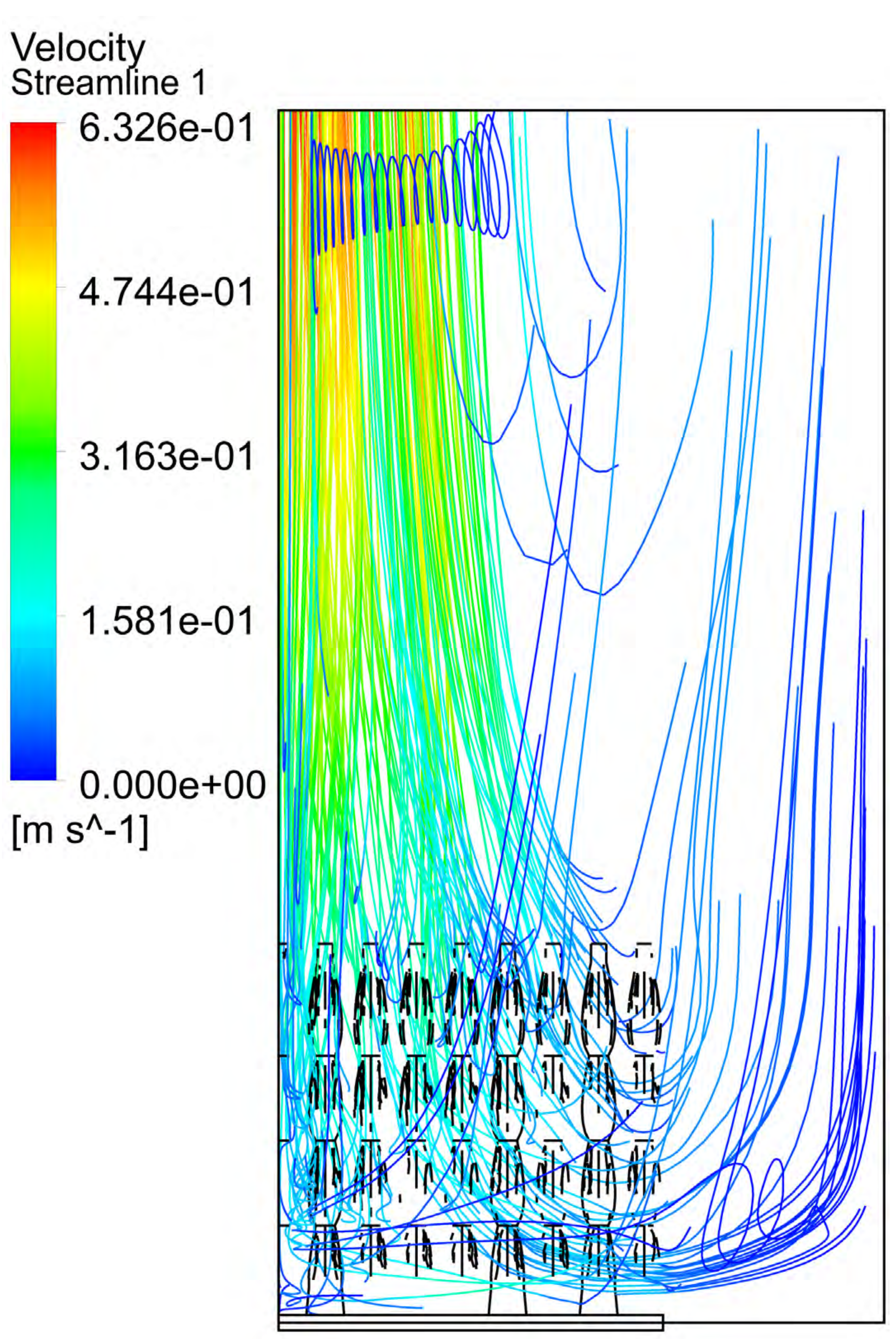

Figure 8. Velocity streamlines of air flow through the heat sink due to natural convection.

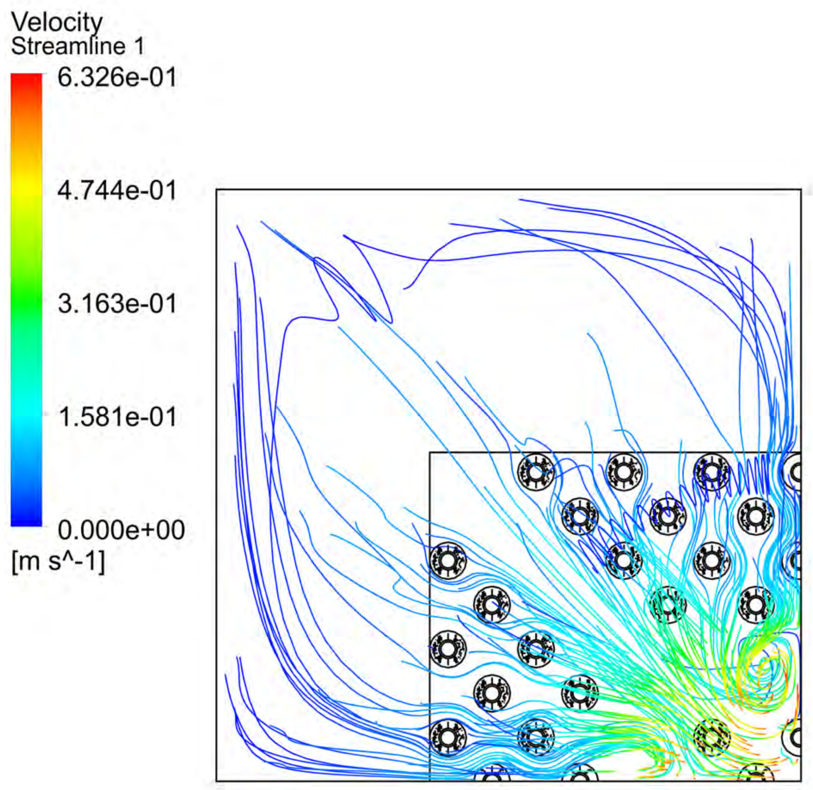

Figure 9. Velocity streamlines of airflow through the heat sink due to natural convection.

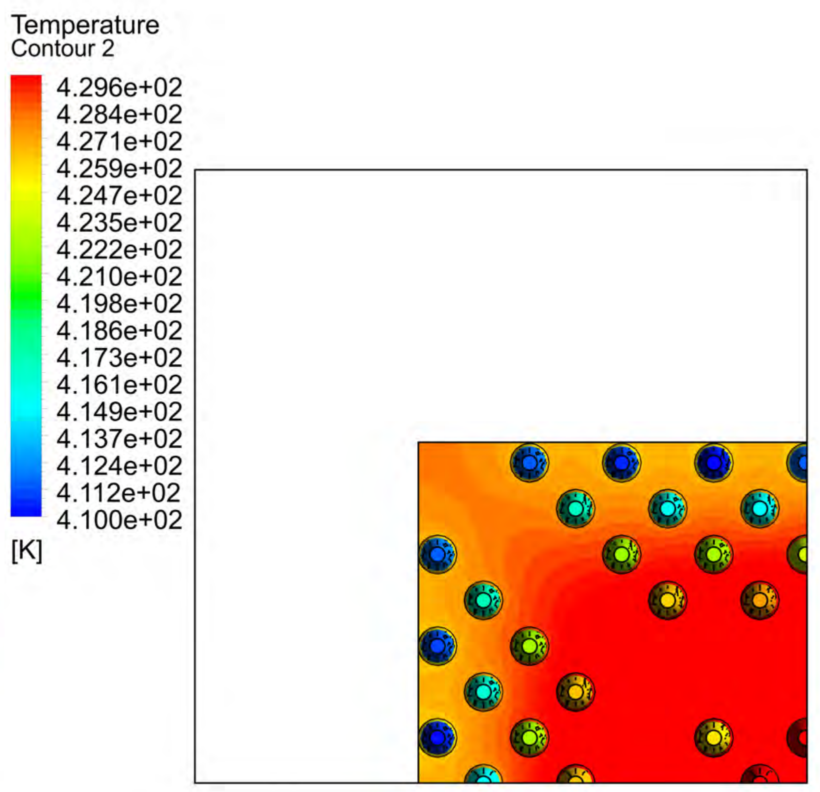

Figure 10. Temperature contour plot of the heat sink surface. The uncolored region is part of the air domain.

Additive Manufacturing:

Several design features make conventional manufacturing of the final heat sink design impossible. The use of AM allows for more intricate and nonuniform shapes that would be impossible to create using traditional manufacturing methods. The extremely complex and irregular geometry of the pin fins make the heat sink only manufacturable through AM processes. Additionally, each pin has an extremely small cross-section which makes subtractive manufacturing very difficult regardless of the irregular cross-section. A potential downside to the design is that the large pins could potentially collapse during the AM process due to residual stresses and layer recoating. Even with this potential downside considered, our design satisfies a multitude of other AM design considerations while still minimizing both heat sink volume and base temperature.

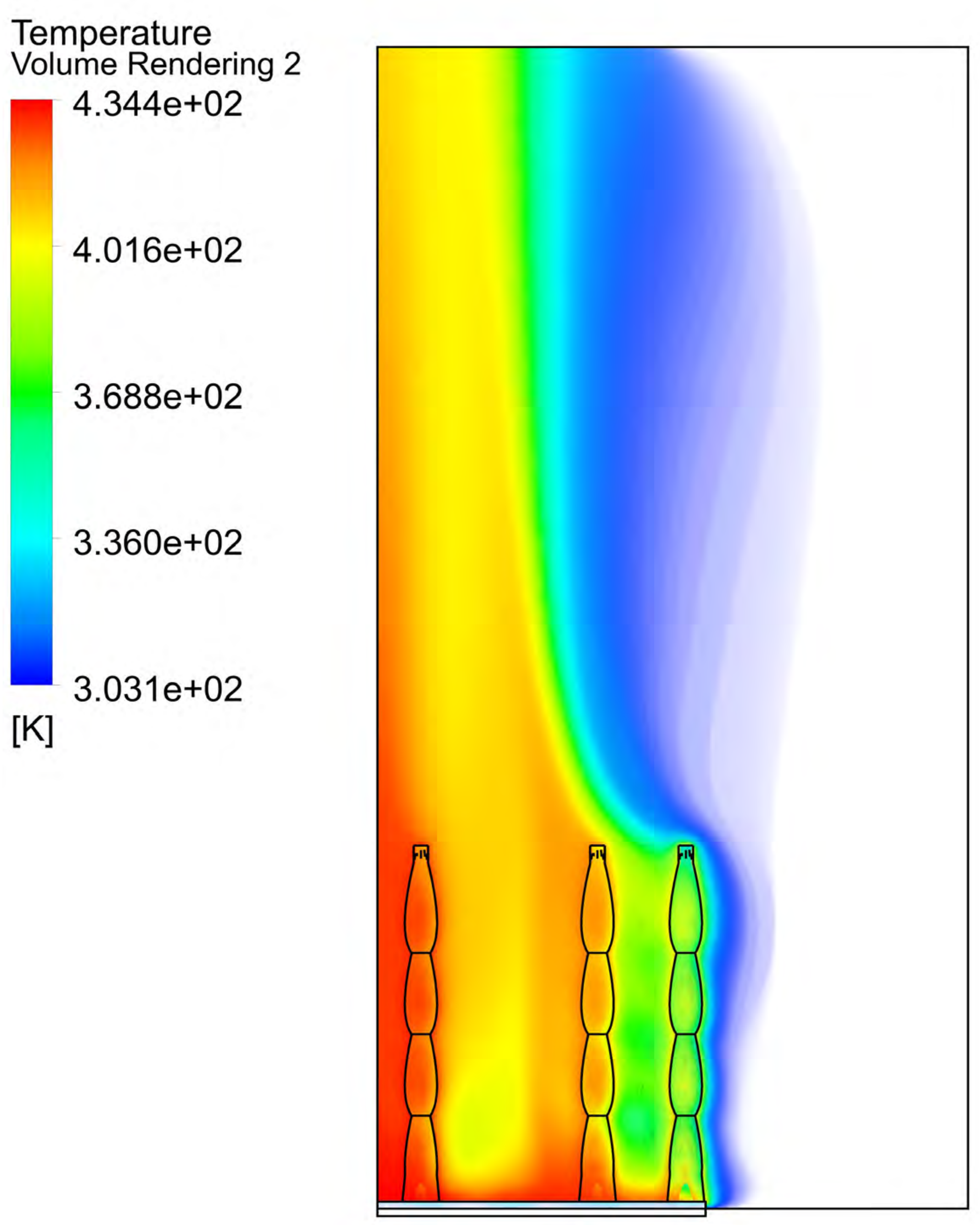

Figure 11. Temperature plot of the air surrounding the heat sink.

Conclusions:

The submitted heat sink design met all the necessary requirements outlined in the ITherm 2021 competition. The performance of the pin-fin design paired with the removal of pins on the diagonal and surrounding the center pins was found to be the highest performing heat sink. Additionally, each pin was designed with a repeating airfoil structure to improve the flow characteristics of the air. From the final Ansys Fluent model, the average base temperature of the final heat sink design was 429.8 °K, and correspondingly, the FOM was 0.002268 $\$^{-1}\,°K^{-1}$. Our heat sink was selected as a semi-finalist in the ITherm 2021 competition because of our white paper submission, FOM, creative design, and its manufacturability.

Acknowledgments:

ITherm heat sink design competition organized by:

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