

Multi-Objective Topology Optimization of Additively Manufactured Heat Exchangers

Basil J. Paudel¹, Mohammad Masoomi², Scott M. Thompson^{3,*}

¹Department of Mechanical Engineering, Auburn University, Auburn, AL 36849

²ANSYS Inc., Canonsburg, PA, 15317

³Dept. of Mechanical & Nuclear Engineering, Kansas State University, Manhattan, KS 66506

*Corresponding author: smthompson@ksu.edu

Abstract

The higher design flexibility offered by additive manufacturing (AM) allows for radical improvements in the design and functionality of legacy parts. In this study, a flat-plate heat exchanger is designed and optimized using the ANSYS topology optimization module. Unlike conventional numerical optimization tools, the current optimization approach employs multiple objective functions, including mass reduction and maximization of heat transfer efficiency. Two unique, initial designs were used for ‘seeding’ the multi-objective topology optimization (TO) routines and the results are compared and discussed. Topology design and operating (boundary condition) variables were varied to elucidate major design sensitivities. The predicted heat transfer within the topology-optimized parts was validated using separate numerical methods. Constraints related to flow pressure drops and additive manufacturability were enforced. In both cases, the optimal design performed significantly better than the conventional heat exchanger in terms of thermal efficiency per unit mass.

KEYWORDS: Laser-Powder Bed Fusion, Optimization, Heat Sink, Topology, Fin Design

Introduction

With the ongoing rapid advancements in electronics and technology, an increasing number of devices require unique heat dissipating solutions with enhanced capability while constrained to a smaller footprint. Conventional manufacturing methods narrow down the design imagination by either limiting the design shape and topology or by introducing unwanted thermal resistances resulting from any part with needed assembly (thermal contact resistance). Additive manufacturing, however, removes those limitations and provides the ability to adopt from an infinite possibility of innovative designs. This allows for a unique opportunity in the thermal sciences/management field of electronics cooling. Thermal solutions such as heat sinks and heat exchangers need not be constrained to simple geometries and arrays. AM provides more flexibility in the design spectrum enabling engineers to instead shift their efforts towards the maximization of heat dissipation while meeting the system requirements.

Recently, several new AM-enabled/design case studies within the thermal management field have been published. Arie et al. [1] designed and tested a Ti-6Al-4V air-water heat exchanger manufactured via laser-powder bed fusion (L-PBF) and observed that significant pressure losses

can exist due to low fidelity in printing thin films. However, for similar pressure losses, a thermal performance enhancement of 15-50% was observed relative to wavy-fin surfaces. Thompson et al. [2] utilized L-PBF to fabricate a flat-plate oscillating heat pipe with closed-loop, multi-layered circular mini channels in Ti-6Al-4V material. The heat pipe operated successfully for heat loads on-the-order- of 100 W and demonstrated performance enhancement in excess of 400% as compared to solid Ti-6Al-4V. The authors highlighted similar manufacturing difficulties. Paudel et al. [3] designed an AM-only heat sink with airfoil-based, progressively-tapered wavy pin fins. The heat sink was designed with consideration of both pressure and thermal resistance and embodied pressure loss reduction features such as airfoil shape. The device was fabricated using L-PBF technology and performed well against other fin arrays and manifold based additively manufactured heat sinks in experimental trials. Saltzman et al. [4] designed a compact aircraft heat exchanger for manufacturing (AlSi10Mg powder was used for fabrication) while considering common AM constraints, and included features such as vortex generators within the fin section to enhance thermal performance.

In the past, least mass optimization schemes have often been used by researchers to enhance performance while keeping material costs low. Iyengar and Bar-Cohen [5] used analytical methods to optimize plate fin heat sinks for maximum thermal performance and reduced mass. In general, numerical approaches such as topology optimization (TO) have been limited to design cases where the structural integrity of the product is paramount [6–8]. Despite the advancements in AM technology, few studies in the past have used TO to design thermal devices. Dede et al. [9] performed TO to design and fabricate an air-cooled heat sink for low fluid velocity. Experimental results were found to indicate a higher coefficient of performance compared to conventional plate and pin-fin heat sink geometries.

Air cooling is perhaps the most cost-effective design concept for heat dissipation via thermal devices. Air cooling concepts are often accompanied by a fan for establishing forced air convection through an array of extended surfaces, i.e. fins. While conventionally, simple shapes and geometries such as plates, pin and cylinders, spines are used, the demand for reducing the size, weight and power (SWaP) has pushed cooling technology to go beyond the use of traditional and primitive shapes. For example, take the gyroid – which consists of triply periodic minimal surfaces (TPMSs). The implicit function that can generate a gyroid surface is defined by Eq. (1).

$$f_g(x, y, z, t) = \sin(x) \cos(y) + \sin(y) \cos(z) + \sin(z) \cos(x) - t \quad \text{Eq. 1}$$

where t is a measure of lattice structure's cross section. Given that the gyroid embeds an intertwining network of channels with minimal surface area, it provides an opportunity for serving as a heat exchanger. The TPMS-based designs, such as gyroids among others, provide a higher surface area to volume ratio resulting in higher heat transfer rates, which makes them a good fit for heat sink/exchanger applications [10].

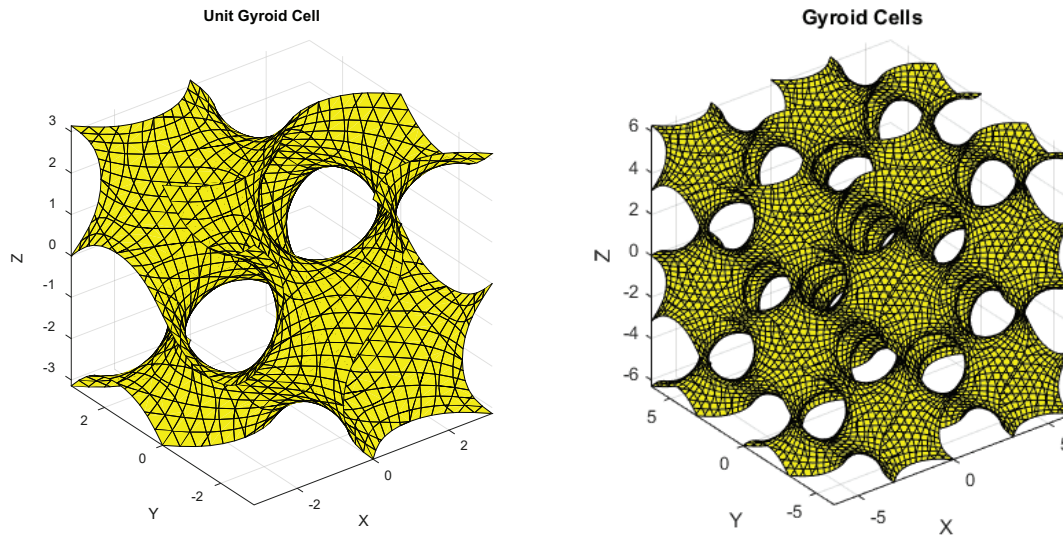


Figure 1: Gyroid surface representation within a cubic unit cell (left) and eight cells (right) with parameter $t = 0$, length scale shown is in ‘mm’

In the current study, the TO module from ANSYS® is used to generate a unique heat exchanger design. Numerical 3D optimization of heat exchangers is a new and emerging field and the AM/optimization-coupled tools provided by ANSYS have only recently been introduced commercially. This study will utilize these new software tools and compare the thermal performance of optimized designs (software output) with analytical results. Optimized designs will also be validated for performance with the use of proven numerical finite element analysis (FEA) codes. It is important to note that the current study only demonstrates the ability of ANSYS topology optimization module in conceptualizing thermal solutions.

Method

Initially, a plate fin heat sink was selected for TO against various air velocity conditions. However, due to the lack of conjugate models for TO within the module, the goal to connect ANSYS Fluent was not successful. Thermally-optimized, thin plate fin designs [5] were adopted for proceeding with the TO via the ANSYS module. Since the employed code only assigned one cell across the thickness, mass reduction was only possible in the height-wise direction of each fin. Consequently, a low velocity application heat sink was chosen analysis/design since, in low velocity applications, heat dissipation from the pin-fin heat sink is not overly sensitive to air-flow direction [11]. This then justifies the use of a uniform heat transfer coefficient for all surfaces of pin fins. Based on these idealizations, a manageable study of TO can be conducted on the heat sink with approximately accurate, optimized geometry.

For the first case study, a heat sink with an array of 6 x 6 square pin fins was chosen as the base design from Ref. [11]. The design configuration and dimensions are tabulated in Table 1 and also shown in Figure 2. For comparative purposes, a heat transfer coefficient of 25 W/m²K (as used in Ref. [11]) is specified. Since the design has been thermally optimized for a power of 2 W, the current study uses the selected design and evaluates the results from a TO tool such as the one

provided by ANSYS 2019 R2. For the second case study, a unique gyroid-based heat sink, as shown in Figure 1, is used for “seeding” the TO routine and the subsequent designs are presented. In both case studies, AM constraints for a maximum overhang angle of 45° are imposed so that the designed solutions are more manufacturable via AM. While materials with high thermal diffusivity such as copper are desirable, their availability for common AM processes is currently limited. Hence, an aluminum-based feedstock, AlSi10Mg, which is more widely available for use in common AM systems, is used for all cases in the current study. Devices fabricated with AlSi10Mg have been found to achieve near pure aluminum thermal properties after post heat treatment [12]. Additionally, the laser beam diameter and process parameters employed for L-PBF typically dictates the minimum thickness of the part fabricated. This constraint is accounted for by establishing a minimum thickness of 0.2 mm within the design space.

Thermally-driven TO in ANSYS is currently supported by a “static-thermal” component which is based on thermal compliance minimization while meeting the constraints imposed in the optimization process. The optimized solution results in a material distribution which provides optimal heat transfer for a given design space. The constraints for thermal design can be chosen between minimizing the mass or by setting a maximum allowable temperature for the design. Thermal constraints such as the maximum allowable temperature is particularly very useful in designing heat sinks for electronic cooling applications because of the maximum tolerable temperature of central processing units and other power electronics devices. However, the current study focuses on the minimization of a device’s mass. It should also be noted that the base plate (i.e. substrate) is excluded from optimization so that initial L-PBF heat transfer (first few layers) does not influence the TO of the major heat dissipation surfaces.

Table 1: Heat sink design configuration used for the study

Pin fin Array	25 x 25 x 15 mm³
Pin configuration	6 x 6
Pin cross section	1.5 x 1.5 mm ²
Base thickness	2 mm
Heat source power	2 W
Heat transfer coefficient	Uniform at 25 W/m ² ·K Gradual (from 50-25 W/m ² ·K; -5 W/m ² ·K per row)

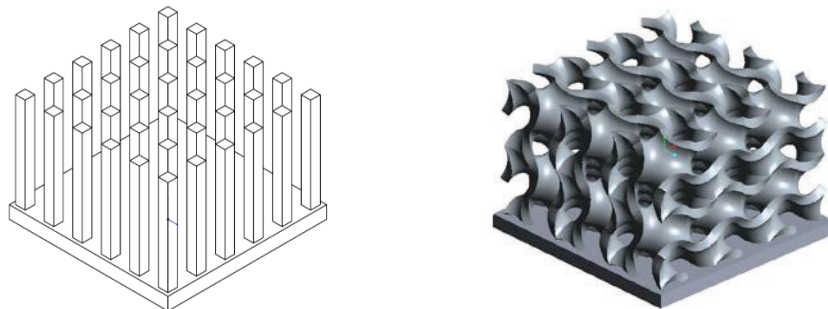


Figure 2: Pin fin heat sink (left) and gyroid heat sink (right) used for topology optimization

To set up the software workflow, a steady-state thermal analysis must first be completed on the original/baseline geometry, i.e. Figure 2. Then, the TO is performed to minimize thermal compliance while meeting design constraints. Upon successful optimization that meets target objectives, the resulting geometry is transferred ‘downstream’ to a new steady-state thermal analysis for further validation. The components and the links of the software workflow are shown in Figure 3.

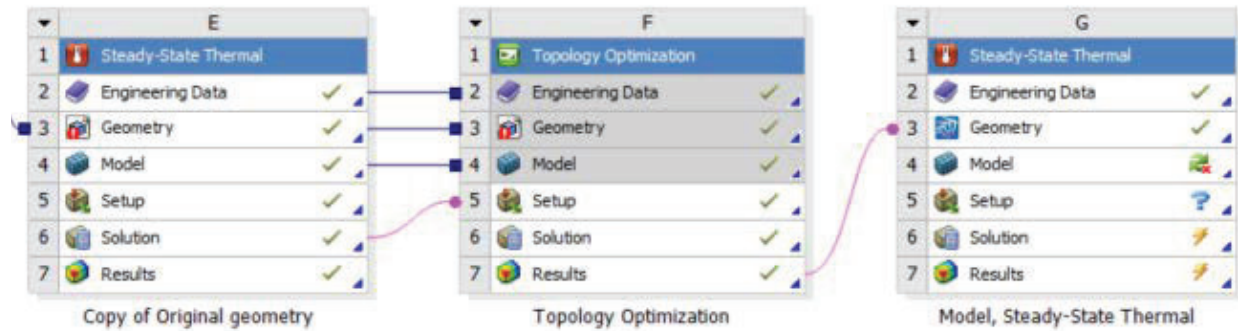


Figure 3: Topology optimization steps (for thermal loads) in ANSYS package 2019R2 showing linkage from preliminary thermal study to post-validation of topology-optimized geometry

Setting up the optimization routine based on the gyroid concept was found to be a more difficult process. The initial, implicit surface of the gyroid model was designed using K3DSurf v0.6.2 [13] and exported in the Wavefront (.obj) format. This file was then imported into SpaceClaim by ANSYS and surfaces were thickened to 1.5 mm. A base of thickness 2 mm was attached to one side of the gyroid. The gyroid heat sink had similar overall dimensions to the pin-fin heat sink.

Following the TO, the post processing of the geometry was performed using the SpaceClaim CAD modeler provided as a tool within the ANSYS workbench. The STL-based geometry created by the TO module resulted in a design consisting of discontinuities that required this post processing. Geometrical errors such as missing faces and vertices lying in non-manifold surfaces were eradicated by using the ‘shrinkwrap’ command while preserving geometrical features such as planar and cylindrical surfaces. It should be noted that several difficulties were faced while pre-processing the gyroid-based heat sink due to the triangular facet-based nature of the STL design file. For this study, surfaces required a higher mesh resolution in order to accurately capture the surface topology and allow for proper meshing within the design.

Results and discussion

The temperature distribution pertaining to the pin-fin heat sink prior to optimization (seed design) is shown in Figure 4. A heat sink thermal resistance of $11.7\text{ }^{\circ}\text{C}/\text{W}$ was calculated and this corresponds to $\sim 0.5\text{ m/s}$ in Ref. [11], which is within the low air flow regime as initially assumed. It may be seen that elements near the bottom of the fin are hotter compared to elements at the top of the fin. Alternate designs were proposed to lower the mass of each heat sinks by a prescribed value of 30%. The topology-optimized solution of the array heat sink provided a hollowed out cavity on the top of each fin resulting in branching of thinner wall projections along their top surfaces, as shown in Figure 5. The projections allow for increased surface area for thermal dissipation.

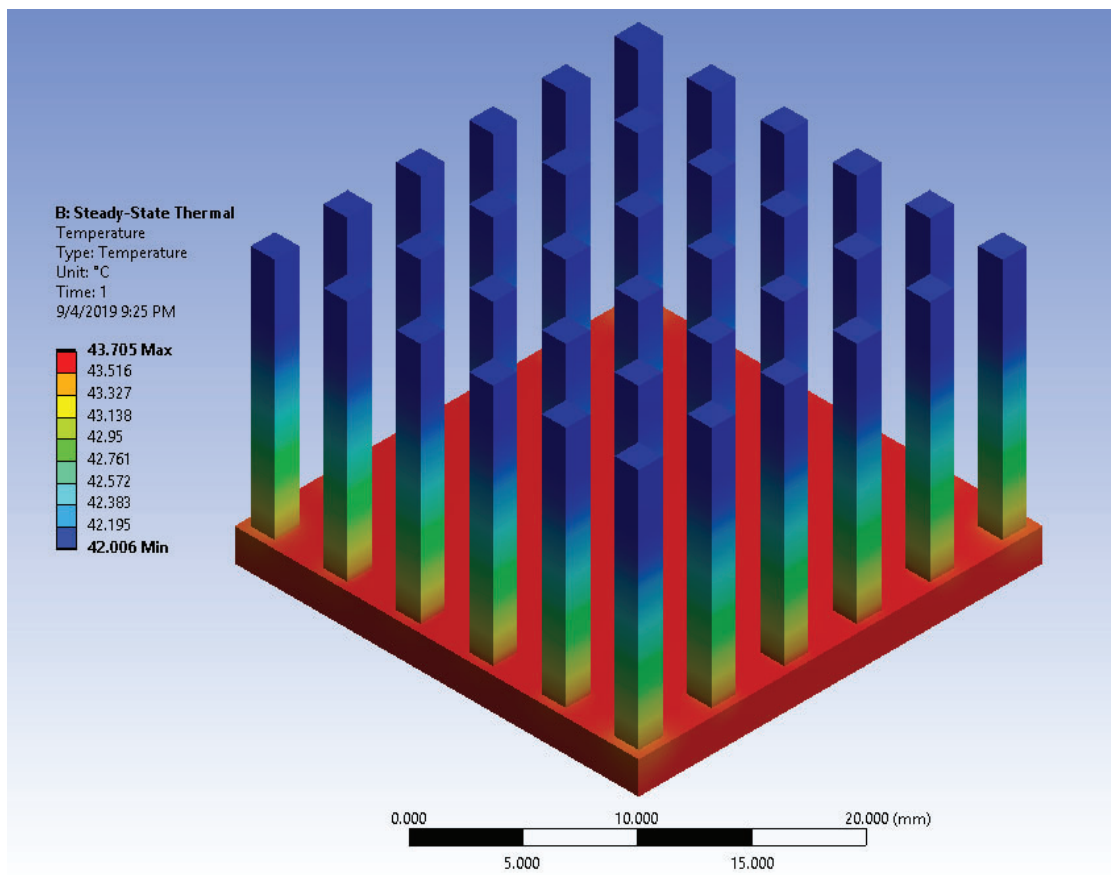


Figure 4: Steady-state temperature distribution of the heat sink before optimization with 2 W power source at the base and $25\text{ W}/\text{m}^2\cdot\text{K}$

The steady-state temperature distribution for the topology-optimized geometry is shown in Figure 6. In addition to the mass of the heat sink being reduced, it was found that the maximum

temperature at the fin base decreased slightly (by ~ 1.7 °C), thus maintaining the net thermal resistance.

It should be noted that although a coarse mesh solution of the pre-optimized geometry resulted in a similar thermal distribution, the numerical TO generated a geometry of a more conventional nature with shorter pin fins, as shown in Figure 6(b), instead of finer projections. This is because the lower mesh resolution in combination with the manufacturing constraint did not allow for higher surface to volume ratio. As a result, when coarse meshes are used, the formation of thinner regions was not possible. Consequently, higher temperature is observed at the heat sink base.

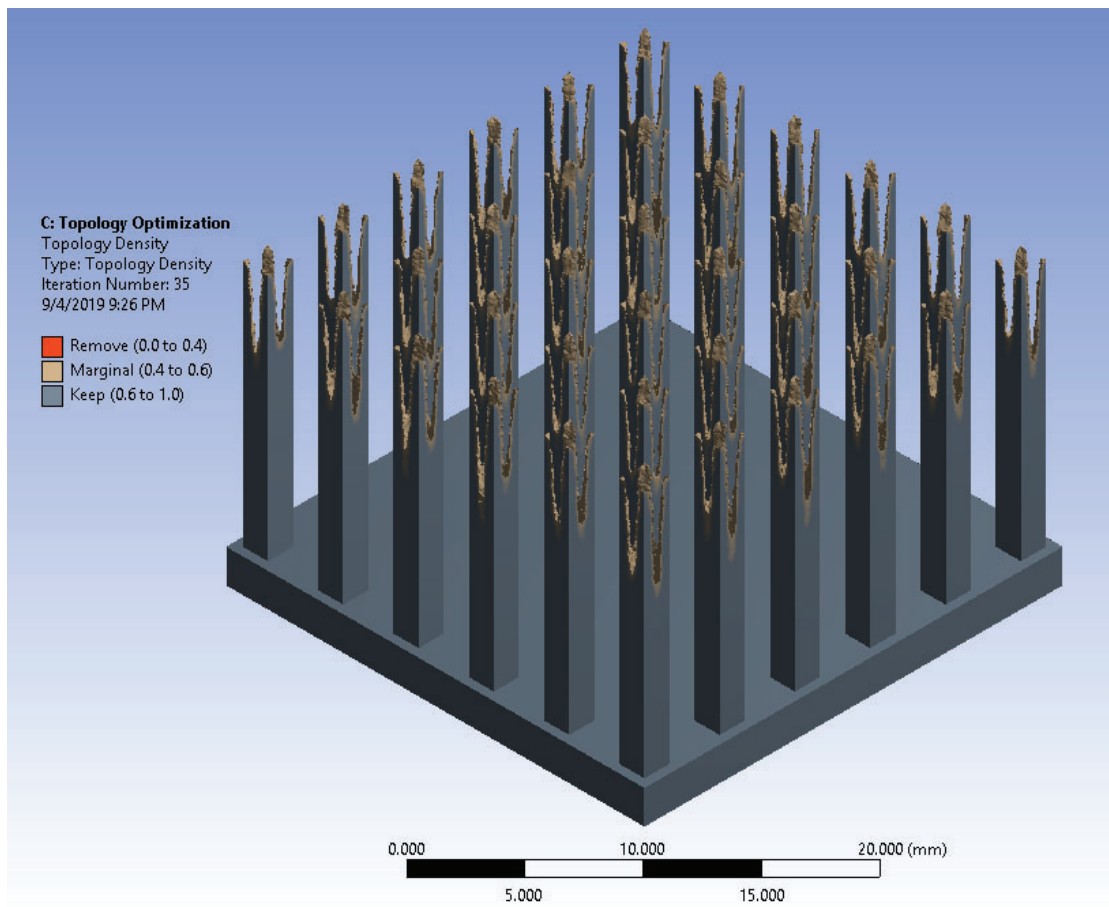


Figure 5: Topology-optimized pin fin heat sink for convection coefficient of $25 \text{ W/m}^2 \cdot \text{K}$ showing thin projections and hollowed cavity on top surface of the fins

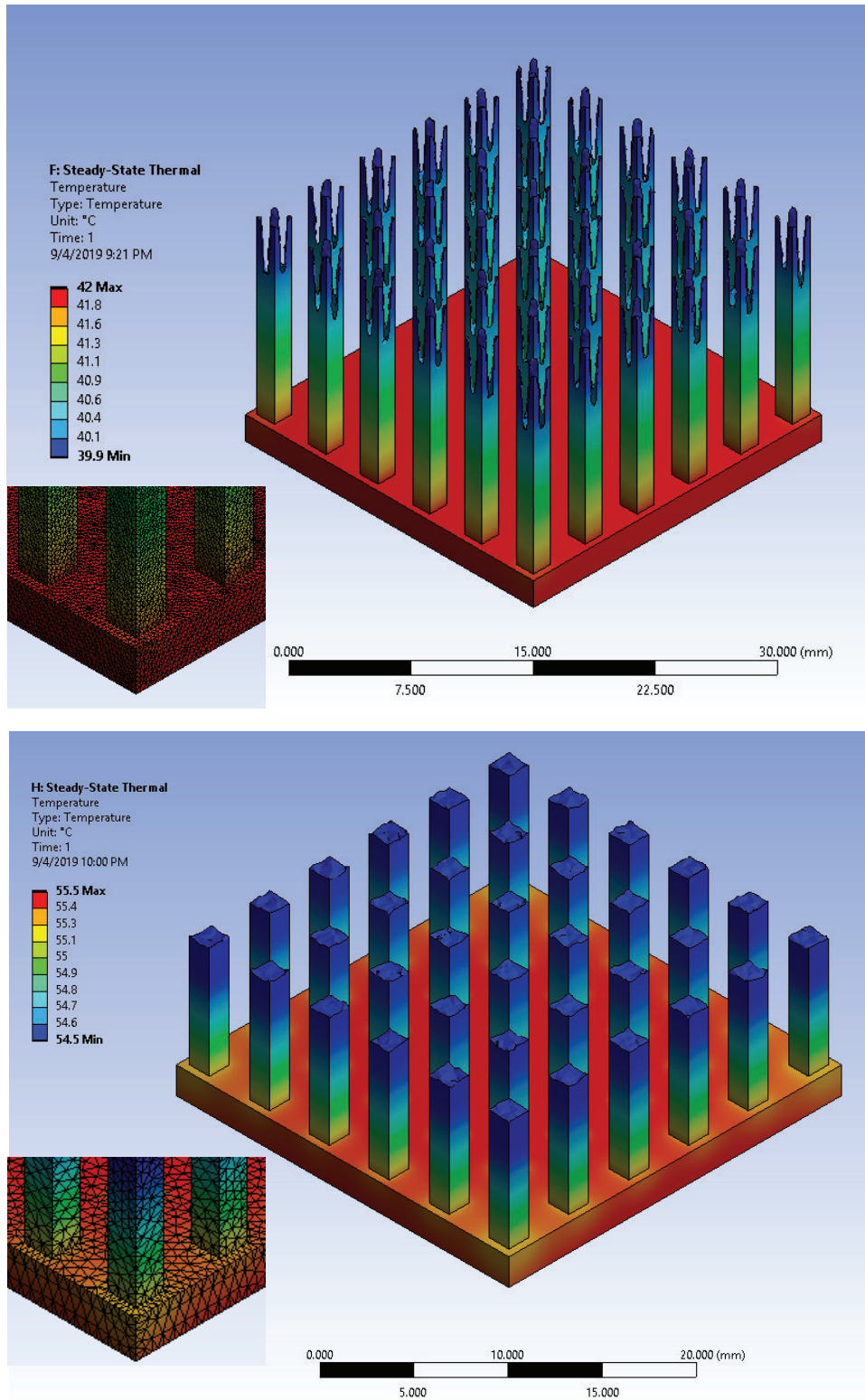


Figure 6: Temperature distributon of heat sink after topology optimization in low velocity applications when (a) fine mesh resolution and (b) coarse mesh resolution; mesh resolution is shown in bottom left of each figures

For the same flow arrangement and pin-fin design, another round of simulations and optimization was performed in which a variable convection coefficient that decreases linearly with each row from $50 \text{ W/m}^2\cdot\text{K}$ to $25 \text{ W/m}^2\cdot\text{K}$ was used. For air flowing from the side inlet to the opposite side exit, this setup mimics the more realistic nature of spatially varying convection coefficients rather than constant/uniform values. The corresponding temperature distribution, as well as the TO geometry output for 30% reduced mass, for the heat sink are shown in Figure 7. As expected, due to the higher dissipation ability in the first few rows of fins (relative to air flow), the temperature at the fin tip is lower than rest of the heat sink. As a result, the topology-optimized geometry suggests a reduced necessity to branch out the pin fins in the first few rows. For the last row of fins, however, the optimized part suggests an increased surface area requirement through longer, thin projections and deeper cavities for mass reduction on the rear end. This increased surface area would allow the pre-optimized geometry to dissipate more heat from the fins at the rear end of the heat sink.

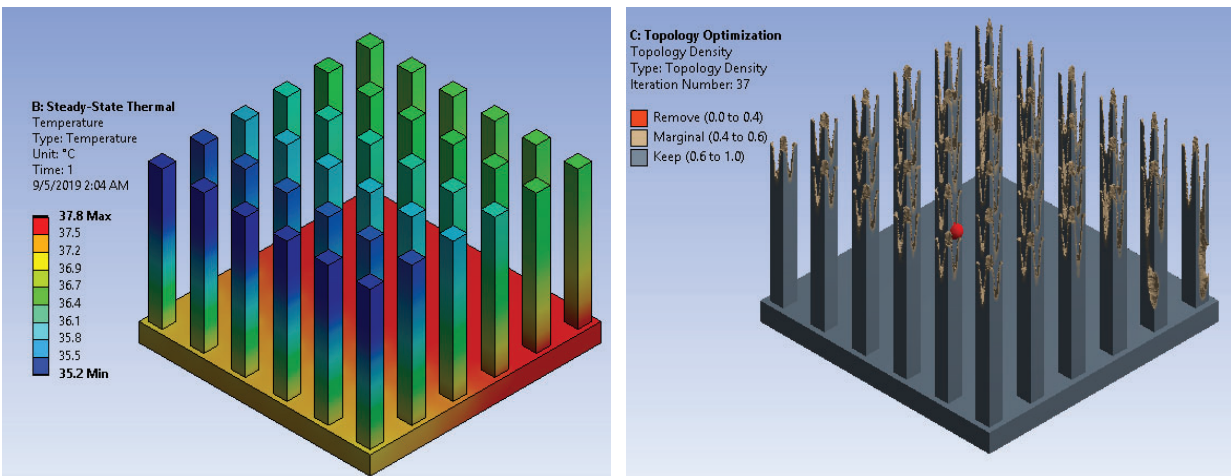


Figure 7: Steady-state temperature distribution (left) and optimized geometry (right) of pin-fin heat sink in presence of a non-uniform, more realistic heat transfer coefficient along the flow direction

Results from the validation study, conducted using finite element code within the ANSYS package, are shown in Figure 8. Simulation results for the topology-optimized heat sink indicate that, in addition to mass reduction, the maximum temperature in the heat sink is reduced by $\sim 1.1 \text{ }^\circ\text{C}$ as compared to the pre-optimized geometry with non-uniform convection losses. Despite the prescribed 30% mass removal condition, the post-processed output geometry only provided for 22% mass reduction. This is due to partial retention of elements with marginal topological density.

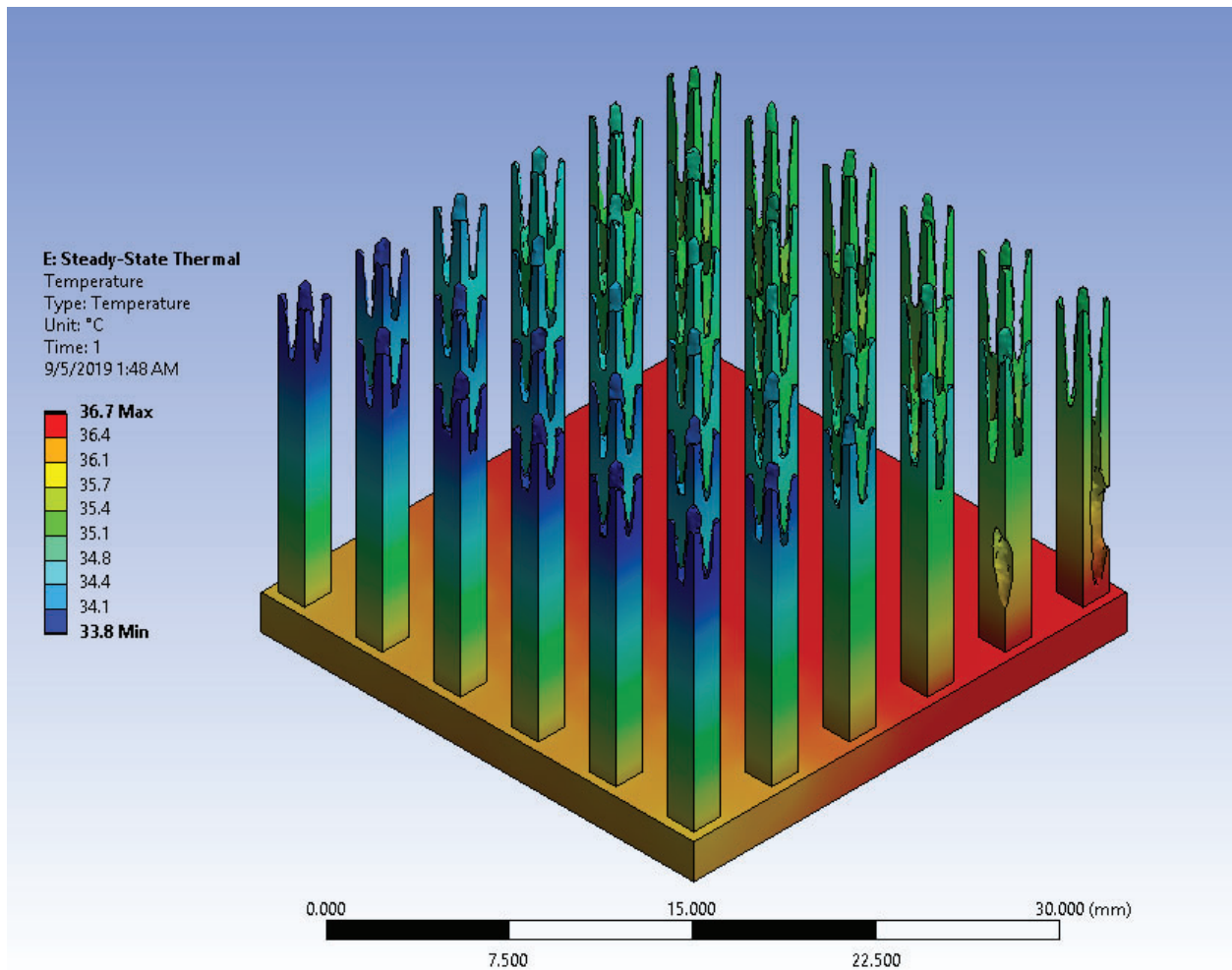


Figure 8: Temperature distribution of the topology-optimized pin-fin heat sink with non-uniform realistic convection coefficient

For the second seed using gyroid structure, the initial temperature distribution and the topology optimized geometry is shown in Figure 9. Temperature plot indicate lowest temperature around the outer edges of the heat sink away from the base, and highest along the outer edges of the sink base due to lack of fins along the edges for thermal dissipation. As such, the topology optimized geometry shows material deletion from those regions to meet the material reduction constraint. The optimized geometry of the gyroid based heat sink shows that even though the surfaces are intertwined and connected, following the TO these triply periodic surfaces are broken down into thin projections at locations with lower heat flow. These thin projections which are well within the AM minimum thickness constraints allowed for mass reduction by 25% within the heat sink thus saving material cost. The area for convecting faces increased slightly by 2% despite material removal, and the surface to volume ratio of the optimized geometry increased by 32%. Despite the complexity of the gyroid based seed design, the resulting geometry contained no overhangs beyond the posed constraint allowing the new design to be easily fabricated by appropriate AM technologies.

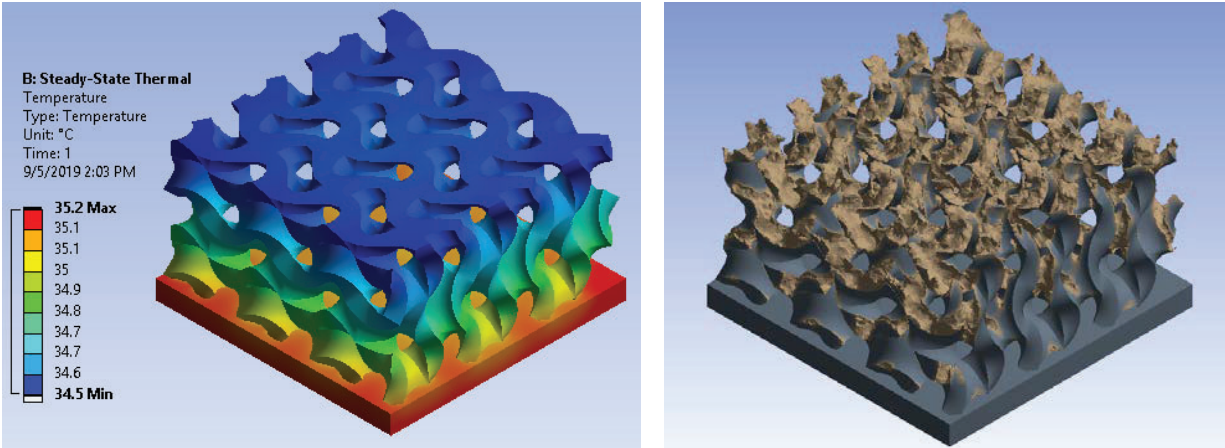


Figure 9: Pre-optimized temperature distribution (left) and topology-optimized geometry (right) for the gyroid heat sink operating at $P = 2 \text{ W}$ and $h = 25 \text{ W/m}^2 \cdot \text{K}$

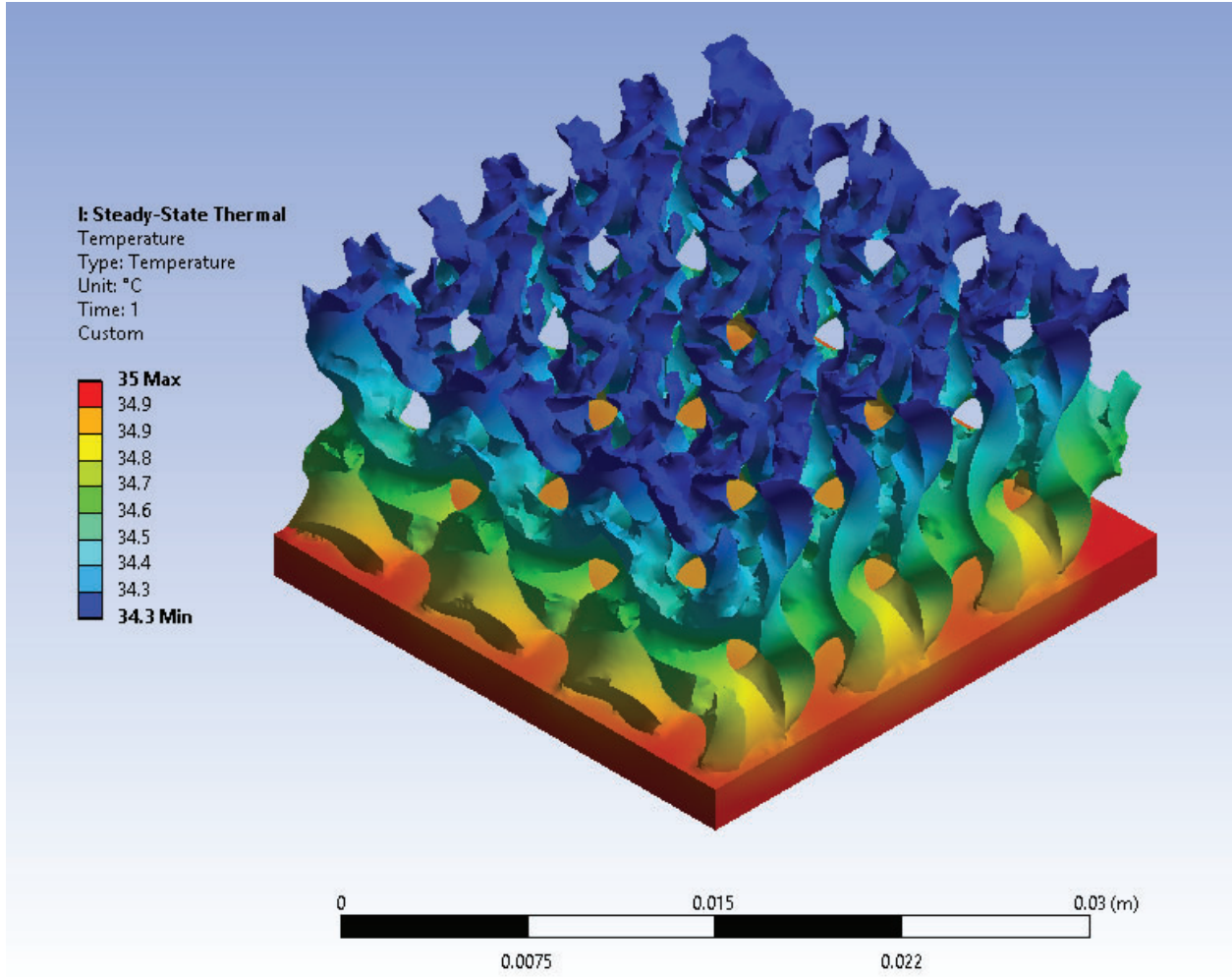


Figure 10: Temperature distribution of the optimized gyroid heat sink when operating at $P = 2 \text{ W}$ and $h = 25 \text{ W/m}^2 \cdot \text{K}$

A comparison of the maximum temperature in the gyroid heat sink against the array heat sink shows reduced values. Although both pin fin array heat sink and gyroid heat sink occupy similar footprint and fin thickness, the gyroid heat sink provides increased surface area due to intertwined and wavy nature of the gyroid. Also, note that the mass of the gyroid heat sink is approximately twice that of array heat sink. Regardless, temperature results, as shown in Figure 10, from the validation study of the optimized gyroid heat sink shows no negative consequence on the thermal performance (maximum temperature in the heat sink only got reduced by <1 °C) of the heat sink despite the reduction in the mass. Some enhancement in thermal dissipation can be attributed to the clawed projections on the top of heat sink.

Conclusions

The current study explores the topology optimization tools with respect to thermal devices using the new-found ability of ANSYS software package. Two different initial designs were investigated for design exploration with constraints related to AM printability. In both cases, it was found that the software proposed designs were well within the material reduction constraint and showed at least comparable if not improved thermal performance. It was found that for decoupled physics with prescribed heat transfer boundary conditions, the current code provided reasonable ability to get innovative in the design space. The resulting optimal solution showed numerous projections of material within the thermal device to enhance convective heat dissipation. The study also highlighted the current limitations of the utilized solvers as well as the robustness of pre/post processors for working with CAD models in topology optimization and the subsequent analyses.

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