UNIT-CELL-BASED CUSTOM THERMAL MANAGEMENT THROUGH ADDITIVE MANUFACTURING

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Abstract

Using previously-defined effective thermal conductivities for structural unit cells, a custom thermal-management structure has been developed for a powered ankle-foot orthosis. The structure provides the requisite personal safety for wearable medical devices. Minimal mass was achieved through the employment of these unit cells. Fabrication of the resultant structure is made practical by additive manufacturing. Results of the virtual testing are reported, as well as the preliminary results of an energy-based comparative-performance analysis of natural versus forced convection. Future work includes the integration of phase-change materials and thermoelectric generators.

Introduction

A. Purpose

The purpose of this research was to design an integrated, compact, minimal-mass thermal-management structure (TMS) that would protect the wearer of the new portable, powered, ankle-foot orthosis (PPAFO) (Figure 1), being developed in the National Science Foundation's (NSF) Center for Compact and Efficient Fluid Power (CCEFP) Engineering Research Center (ERC) [1,2], from the high operating temperatures of the integrated engine, while also preventing the engine from overheating. The orthosis is to provide one hour (1hr) of continuous, powered, walking assistance, and weigh less than one kilogram (1kg).

For maximal system efficiency, and minimal system mass, natural convection was employed as the mode of sinking the heat generated, in the present application. This is of particular importance for mobile and portable power systems. Additive-manufacturing-based fabrication methods were required to produce the resultant, complex, multifunctional structure.

The goal of this paper is to convey the potential of this multifunctional-design methodology, and lessons learned on this project, to the additive-manufacturing (AM), thermal-management and generative-design communities. To that end, the procedure and results-to-date are discussed herein.

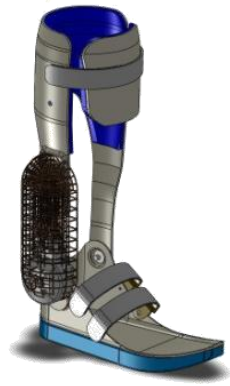

Figure 1: Conceptual model of the PPAFO showing an integrated TMS for the power source and pneumatic rotary actuator. This structure also bears mechanical loads.

B. Scope

This is an application of continued research that defines the geometry-dependent effective thermal conductivities of lattice unit cells [3].

Goals

The primary goals for this development are to maintain an engine temperature below 550K (277℃) over a one-hour operating period, and a contact-surface temperature of the TMS below 314K (41℃), the FDA mandate for medical devices [4]. Additional goals include minimizing mass and improving the efficiency of the system.

Challenges

Maintaining a surface-contact temperature of the structure at 314K (41℃) presents a significant challenge. The structure must not be "obtrusive:" if it is too voluminous, the orthosis will be impractical for every-day use; and, the patient will likely not use theirs. If such a voluminous orthosis were worn, it would be highly susceptible to damage. Therefore, a large temperature differential must be developed across a short distance; yet, the 50W of waste heat, projected to be produced by the small internal-combustion (IC) engine, must be effectively dispersed and sunk to prevent the engine from overheating. Ideally, to minimize mass, this structure would also be mechanically integrated into the orthosis, bearing loads; but, the whole system (excluding fuel and batteries) must weigh less than one kilogram (1kg).

Design

Gradient, lattice-based, thermal-management structures were the only ones considered here. These are effectively solid-fluid composites. Foams, conventional heat sinks and solid-solid composites were previously deemed inappropriate for this PPAFO application [3,5,6].

The bulk material of the design volume shall be discretized for the optimized assignment of structure type, material and feature sizes. Presented here, unit cells were grouped into layers to minimize the manual effort of this optimization. Development of automated algorithms to handle this optimization at the unit-cell level is a research goal, but not within the scope of research presented here.

Natural convection was chosen as the primary mode of sinking heat. Forced-convection means are expected to be too heavy and inefficient, at the system level. This determination is currently being addressed. Thermal radiative dissipation can be significant; however, it is not formally considered here. That additional mode of sinking waste heat further reduces the engine and contact-surface temperatures; so, just as convective through-flow is not modeled, leaving out thermal radiation is designing the TMS for worst-case operation.

In addition to optimally sinking heat, these structures can also be designed for optimal thermal-energy storage, recovery and thermoelectric conversion. Two applications of primary interest are phase-change materials (PCM) and thermoelectric converters of waste heat.

The Grasshopper® plugin for Rhinoceros® was selected as the software tool for the automated generation of the lattice elements.

Fabrication

Laser sintering was the mode of additive manufacturing selected for this research, with nylon as the material. These parts are; durable, good patterns for investment casting, and amenable to electroplating if necessary. Further, because this process embeds the geometry into a particulate (powder) cake, no supports are required during the fabrication, allowing for the fabrication of complex geometries with little post-processing effort: compressed air, and bead blasting, is generally sufficient to remove the loose, extraneous particulates.

C. Background

Energy transfers and conversions have inefficiencies; and, for systems, these inefficiencies are compounded. Primarily, this waste energy manifests as thermal energy; and, too often, that energy is sunk into the atmosphere, and is lost. Worse, available power-plant energy is used to provide forced-convection self cooling, such as a vehicle's engine pumping the liquid through the radiator, and powering the fan. Passive means of thermal management, those that do not detract from the available power-plant energy, are preferable, but can be more challenging to design effectively and fabricate.

Regarding the development of technology, this applies to: controlled power generation (nuclear fission & fusion reactors, fuel burning, batteries); energy harvesting (wind, hydro, solar, acceleration); and, all of their subsystems (energy transfer and end use). This research was directed at applications in the advancement of fluid-power technology, working to improve the "state-of-the-art" system efficiencies that now average just 21%, while also making them more compact and effective. Specifically, the PPAFO development was targeted. This portable, self-sustained system must:

- Be compact (protrude less than 10cm)
- Provide sufficient motive power (~21J/step and a ~200W peak)
- Operate for one hour
- Have a contact-surface temperature of less than 314K (41℃)
- Not weigh more than 1kg

While the originally-targeted portable power plant was the small IC-engine/compressor being developed in the CCEFP, such a thermal-management structure is required to protect the orthosis wearer from the extreme temperatures of any portable power source, while transferring sufficient heat out of, or into, that source for maximal efficiency. It is important to note that compressed-CO_2 bottles are more efficient if isothermal expansion of the compressed gas can be achieved. This has profound implications for the design of many compressed-gas tanks and fluid-power accumulators, and the actuators themselves.

The options for TMS's include metal foams, as well as conventional finned heat sinks. Metal foams are too conductive, and have isotropic effective thermal conductivities and stiffnesses that prevent effective application in this challenging, custom design. Conventional heat sinks would also result in excessive surface-contact temperatures, and are not designed to bear mechanical load [3,5,6]. Such unitary functionality is prohibited in this development. These short-comings led to the development of multifunctional, lattice-based, thermal-management structures.

Approach/ Method/Options

A. Design Optimization

The method of design optimization used was similar to contemporary structural-optimization processes: the design volume, and its discretization, were both pre-determined; and, the effective material property (thermal conductivity) was the design variable. Bulk effective thermal conductivities for each layer were assigned in a finite-element solver to characterize the structure's performance, and were modified through multiple iterations, until the desired performance was achieved.

Using the previously-determined effective thermal conductivities of the lattice unit cells [3], the layers were populated with these unit cells; and, their struts were sized to match the required effective thermal conductivity.

For the prescribed design objectives and constraints, an optimal design was not quickly determined because the design was over-constrained. To proceed, two design approaches were attempted, each relaxing one of the most challenging constraints: the structure envelope volume, and the surface-contact temperature. These two extremal designs define the bounds within which an optimal design may be found.

B. Size-Constrained Design

The initial size-constrained design volume, the structure's section primarily responsible for thermal management, was set to a 9.6cm (3.8in) thickness, 6.0cm (2.4in) section height, and a length of 17.0cm (6.7in), providing significant surface area for thermal-energy dispersion (Figure 2). This, in conjunction with the gradient, effective, thermal conductivity, produces the requisite thermal gradient through the structure.

The presumed method of producing the metallic TMS was investment casting, for which, a selective-laser-sintered nylon part would be the expendable pattern. The minimum lattice-connective-element (strut) diameter that could confidently be cast was one millimeter (1mm). Fixing this dimension, the pre-determined relations for the effective thermal conductivities of these cells [3,6] were used to predict the "bulk" conductivities of the structure's layers, the regions demarcated by the isotherms. Due to the size constraint, however, the unit cells were more prismatic than cubic, especially those in the outer layers. The effective-thermal-conductivity relations will be less accurate in predicting the performance of these unit cells.

Figure 2: 2-D top-view sketch of the targeted, sized-constrained, thermal-management-structure design. The shaded regions represent a cross section through the aluminum engine's combustion chamber and exhaust manifold. The offset-concentric curves represent the targeted isotherms.

C. Rhino-Script Structure Generation

The design of these complex structures was simplified through the employment of generative-design scripts, using the Grasshopper® plug-in for Rhinoceros® [7]. Importing the desired thermal isosurfaces (isotherms) into Rhinoceros®, each surface was divided into a mesh of matching numbers of nodes. A C++ Grasshopper® function block was customized to automate the inter-surface node matching required for the chosen structure type. The simple Cube lattice unit-cell type [3,6] was employed here for minimal mass (Figure 3). Other unit-cell types can also be generated with these scripts, and would provide more structural integrity; but, the confidence-imposed 1mm-strut-diameter fabrication limitation for the casting process would result in higher effective conductivities for each cell, or larger cells, leading to a more voluminous structure.

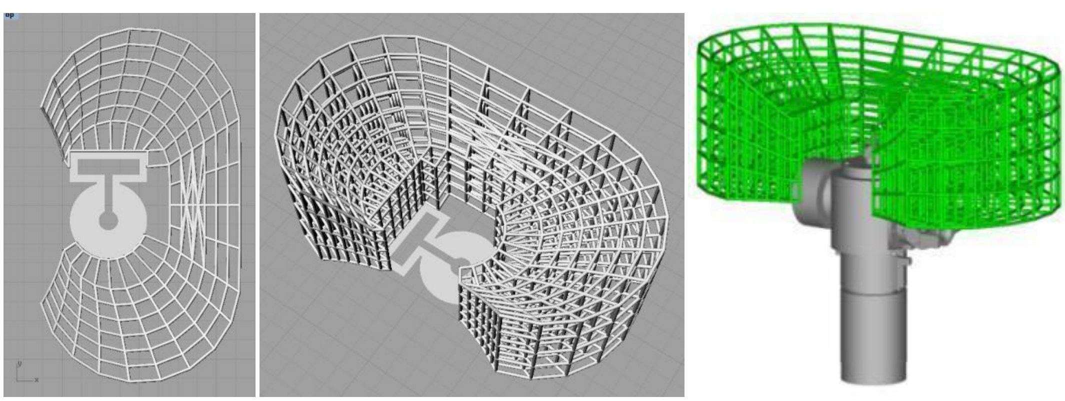

Figure 3: Top view (left) and isometric view (middle) of the Grasshopper®-automated structure generation in Rhinoceros®. (Right) Magics® rendering of the stereolithograhpy files generated, showing the engine integration with its size-constrained thermal-management structure section.

Note that the surfaces used in this design were vertical extrusions of 2-D curves. This is not ideal, since the real isotherms will not match this. Further, the layers are not of constant thickness; so, a fixed strut diameter results in varying effective thermal conductivities of the lattice unit cells within each layer as well. The ideal structure-generation algorithm, one that works directly with 3-D finite-element-analysis data to optimize the selection and sizing of the unit cells, is in development [8,9].

D. Surface-Temperature-Constrained Design

The second design approach started with a cylinder 25cm in diameter (significantly larger than the 9.6cm-thick size-constrained design), determined from finite-element analyses of solid inconel and Moldstar22® to be of sufficient size to meet the maximum-temperature constraints of the power plant and the contact surface. That geometry was again sub-divided into concentric rings of gradient thickness; and, the effective thermal conductivities were once again assigned based on the one-millimeter minimum strut diameter. The thicknesses of the layers themselves were based on maintaining cubic lattice cells, in alignment with the temperature field, to ensure validity of the effective-thermal-conductivity relations used.

The lattice for this design evolved through three phases. First, the representative Cube unit cells populated the concentric-cylinder geometry. Second, the lattice was "streamlined," morphing the cells slightly for inter-laminar continuity, minimizing mass by removing redundant struts (Figure 4). Third, the structure was split and morphed about the vertical axis. This modification allowed the structure to wrap around the leg, while providing an air gap to insulate the person against the temperature of the power plant. Lattice or textile straps will connect these open edges to clamp the structure onto heat source, and protect the person against contact with the internal lattice structure (Figure 5).

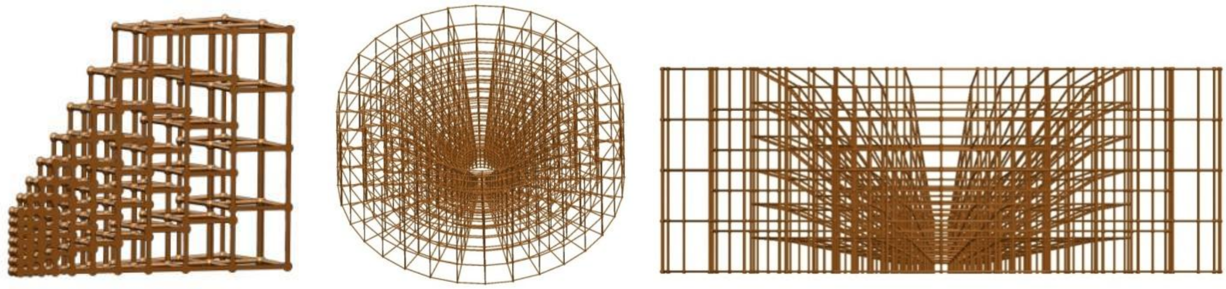

Figure 4: Solidworks® renderings of the surface-temperature-constrained structure design development. (Left) Slice of the concentric-cylinder structure showing the stacking of Cube unit-lattice cells in each layer of the structure. This is a "literal" translation of the layer effective conductivity into unit-lattice cells. (Middle and right) "Streamlined" morphing of the cells for inter-laminar continuity of the structure. Redundant struts were then also removed. This remains a non-ideal vertical "extrusion" of the desired isotherms.

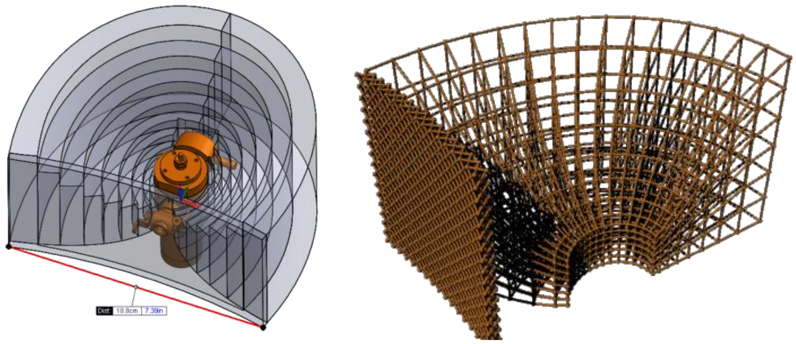

Figure 5: (Left) Solidworks® rendering of the; small IC-engine/compressor, target-isotherm-layered thermal-management structural section, and firewall. (Right) Rhinoceros® rendering of half of the TMS, including a lattice firewall.

E. Metallic-Structure Fabrication

Direct metal

Direct-metal laser sintering, including powder sintering and full melt, would be ideal for this development; unfortunately, the support structures required by most of these processes are prohibitive. Those structures can be thicker than the supported features. Further, the fabrication cost was highest of the three options considered.

Hybrid fabrication

Hybrid fabrication, the use of AM-component patterns for investment casting, has been employed in the past to produce a gradient TMS using the copper-aluminum alloy Moldstar22®. The AM pattern can be fabricated using a number of technologies. Primarily, the material may not expand in the burn-out process so much that it ruptures the ceramic shell. For thin-diameter lattice structures such as these, selective-laser-sintered (SLS) nylon has worked well; but, other processes, such as stereolithography (oriented for minimal support structure) or photopolymer jetting (e.g. Objet), may work as well, or better, leaving behind less ash residue.

The larger, surface-temperature-constrained design was not cast due to the estimated mass of the final metallic part. This structure, cast in Moldstar22®, was anticipated to weigh 320.5g, nearly one-third of the allowed system weight. To reduce this mass, while maintaining thermal performance, a polymer-metal composite was selected as the fabrication approach; and, electroplating was selected as the method.

Electroplating

Electroplating metal onto AM-component patterns is an established process; but, it is an option for creating TMS's that has not been previously explored, to the knowledge of the authors. Through this process, copper can be directly plated onto the AM pattern. The high conductivity of the copper, relative to the Moldstar22® alloy that the structure was initially designed for (400W/(m*K) vs. 43W/(m*K)), necessitated a new characterization of the Cube unit cells, one that includes the thermal conductivities of the nylon core structure and varying thicknesses of the copper shell. This work will be reported elsewhere.

Results & Discussion

A. Virtual Bulk-Material Testing

The performance of the size-constrained TMS was predicted virtually using COMSOL® finite-element analysis (FEA), assigning bulk effective thermal conductivities to the structure's layers, and assuming no convective flow through the structure. Natural convection was prescribed to the external surfaces; and, a total of 50W of waste heat were prescribed to the engine core. As shown in Figure 6, because the effective thermal conductivities are homogeneous in each layer, while the distance to the source varies, the contact-surface temperatures vary significantly. This analysis also shows that neither the surface-contact temperature, nor the engine temperature, target would be met. Greater discretization of the TMS is required for the optimal definition of effective thermal conductivities; however, this constrained size may still not allow for convergence of the optimization with the constraint on maximum engine temperature. Engine efficiency would likely need to be improved, reducing the waste heat generated, to achieve a TMS of this compactness.

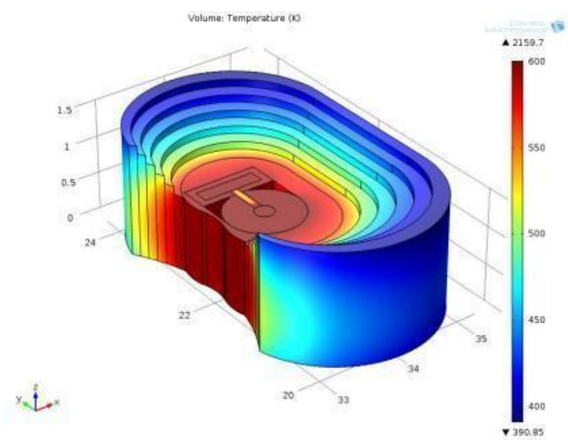

Figure 6: FEA of the size-constrained TMS, using effective thermal conductivities in the bulk layers. The waste-thermal-energy sources were prescribed as 40W from combustion, and 10W from the exhaust. The resultant minimum temperature is 391K, far above the targeted 314K surface-contact temperature, at 50W of waste heat.

Similarly, the performance of the "surface-temperature-constrained" TMS was predicted using COMSOL® FEA. The greater volume and surface area of this design allowed for greater dispersion and sinking of the waste heat. As shown in Figure 7, the predicted average surface-contact temperature of this TMS is well below the targeted 314K; and, the engine temperature is near its targeted value, 550K (277℃). Note the curvature of the isotherms relative to the vertically-extruded layers: these will be aligned through future optimizations.

Also shown in Figure 7 is the concentration of convective heat flux from the TMS around the IC engine, between the power plant and the person. This denotes a chimney-like flow between the engine and "firewall," the design intent: the real TMS will likely have convective through-flow to sink thermal energy too; but, this chimney is the performance safeguard.

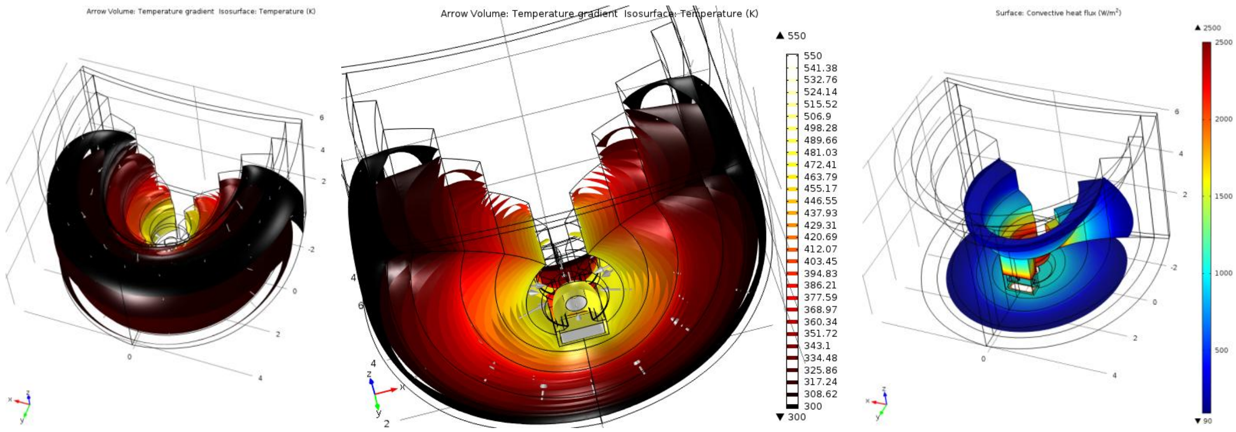

Figure 7: FEA of the surface-temperature-constrained TMS, using effective thermal conductivities in the bulk layers and surface-orientation-prescribed natural convection on the external surfaces. (Left and middle) Resultant isotherms. The surface-contact temperatures are well below the 314K target, at 50W of waste heat. (Right) The convective-heat-flux-magnitude threshold is set at 90W/(m^{2}K), below which the surface temperature is likely below the 314K target. This region is well within the structure, indicating that the person wearing the device will be safe from excessive temperatures.

B. Generative Structure Design

The overlapping dome-capped cylinders of various diameters and orientations were not practical to Boolean-union, without writing custom computational-geometry algorithms. Many potential routes, including Solidworks®, Rhinoceros® and Magics® were attempted. Ultimately, the thousands of individual entities, merged into a single stereolithography (STL) file, were sent to the SLS system for processing. Without the Boolean pre-processing, the SLS succeeded in fabricating the structure. It is not known, though, if the SLS process would succeed in fabricating millions of overlapping struts; so, finding an effective means of Boolean-uniting them remains a high priority.

The resultant sharp-transition intersections of the struts within the lattice structure are stress concentrators. A means of automating a “roller-ball” style surface filleting is being sought to generate smooth transitions at each intersection, minimizing these concentrations. Uformia Symvol®’s “Union Blend” [10] may also be an option, if the struts can be; generated in that voxel-based format, placed, and blended using script automation.

It should be noted that the large “X” patterns in the center of the size-constrained design (Figure 3) were the result of surface inversions. This was determined after the fabrication of that structure, but is now checked for in the generation of these structures using these scripts.

C. Virtual Lattice Analyses

After the cylindrical surface-temperature-constrained TMS was generated as a “stacked-Cube” lattice (Figure 4), a two-cell-wide slice was cut out, and analyzed using COMSOL® FEA. To ease meshing, 2mm-diameter struts were generated in place of the 1mm-diameter ones; and, alumina (27W/(m*K)) was assigned as the material instead of Moldstar22® alloy (45W/(m*K)). Figure 8 shows the results of this analysis, for a prescribed convection coefficient of 7 W/(m^{2}K) on all surfaces, except the source and slices. The threshold shown is at the 314K target, suggesting that the outermost layer of the structure could be removed now that convective through-flow is being considered.

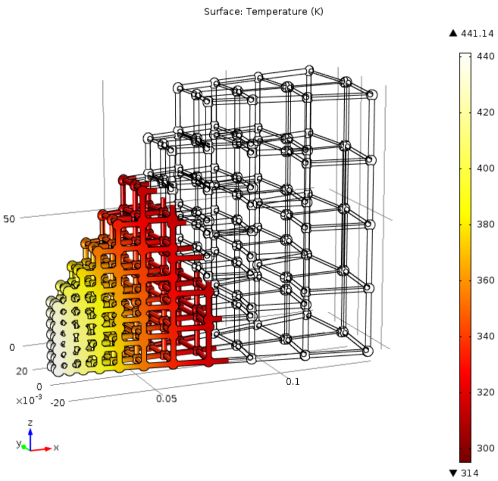

Figure 8: FEA of a two-cell-wide slice of the surface-temperature-constrained TMS. The threshold is set at the 314K target temperature.

Later, a more realistic FEA of the streamlined lattice (Figure 4) was conducted. A one-cell-wide slice of the lattice was generated, using the targeted 1mm-diameter struts; and, the Moldstar22® alloy properties were applied. A parametric analysis was performed, sequentially varying the prescribed convection coefficient to determine the effected change in performance. Figure 9 shows the results of this analysis for two common values for natural convection. Here, the results suggest that the two outermost layers could be removed for a through-flow convection of 7 W/(m^2 K); and, they were in the final design.

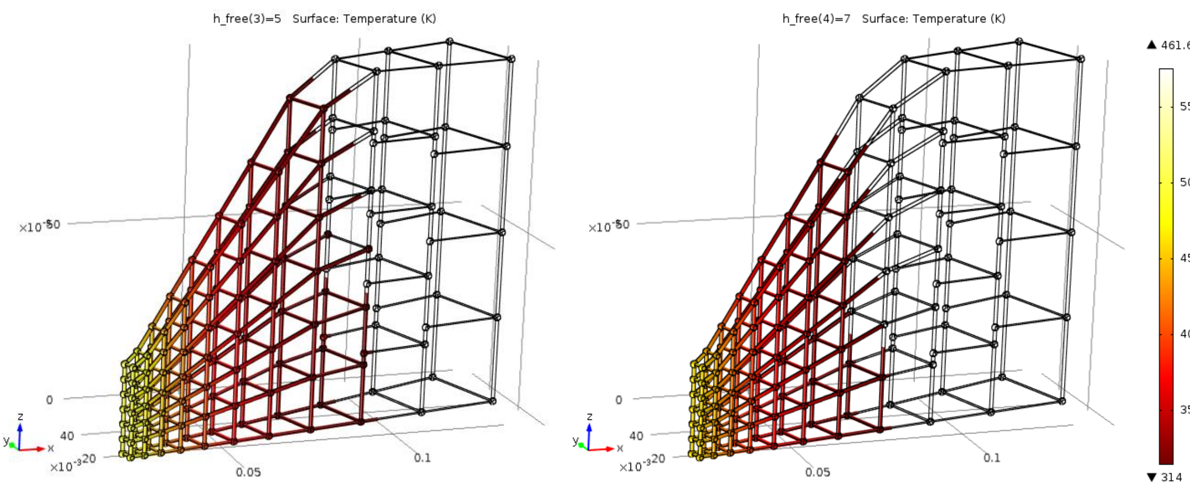

Figure 9: Parametric FEA of the streamlined lattice, varying the convection coefficient. The threshold is set at the 314K target temperature. (Left) h=5W/(m^2K). (Right) h=7W/(m^2K).

This finite-element model was comprised of 11.6million tetrahedral elements, representing 17.3million degrees of freedom. The workstation used employs 12 processor cores and 96GB of RAM. This analysis required over 49minutes to complete, for a small section of the entire lattice, without the more realistic inclusion of fluid-structure interaction (conjugate heat transfer with convective flow). This demonstrates the “power” of the bulk unit-cell-based design approach: computation-power requirements are significantly reduced, resulting in quick design definitions. However, means of accurately predicting the requisite change in effective thermal conductivity based on through-flow convection are still in development [3].

D. Fabricaton

The new effective thermal conductivities for the copper-plated-nylon composite resulted in variable diameters for the different Cube sizes, for a constant 50.8μm-thick copper plating. Because the structure was not being investment cast, the minimum strut diameter was no longer fixed to 1mm: they ranged from 0.5mm, near the power plant, to 2mm, at the outer extremes. Note that this 0.5mm minimum diameter was the limitation for the SLS process itself, since it is about equal to the spot size of the CO_2 laser. Figure 10 shows a comparison of the 1mm-strut, solid-metal lattice and the variable-diameter, polymer-metal-composite lattice. The visible differences are subtle, but the characteristic differences are significant. The solid-metal TMS model has a volume of 45.4cm^3; while, the nylon-copper composite has 79.3cm^3. The composite has 75% more solid volume, within nearly the same envelope, but 50% less mass. The strength of the composite is likely also lower than the solid-metal lattice would have been. This requires testing for verification.

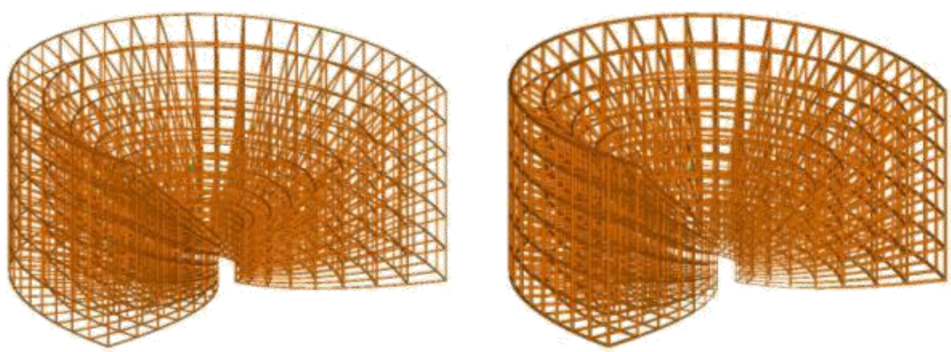

Figure 10: (Left) TMS with fixed 1mm-diameter struts throughout the lattice, intended for casting in Moldstar22®. (Right) TMS with variable-diameter struts, in a radial gradient, intended for the electroplating of copper onto the AM nylon base material.

Figure 11 shows a photograph of the SLS-fabricated nylon part, produced at Milwaukee School of Engineering’s Rapid Prototyping Center, and a rendering of the integration of the IC engine/compressor into its TMS.

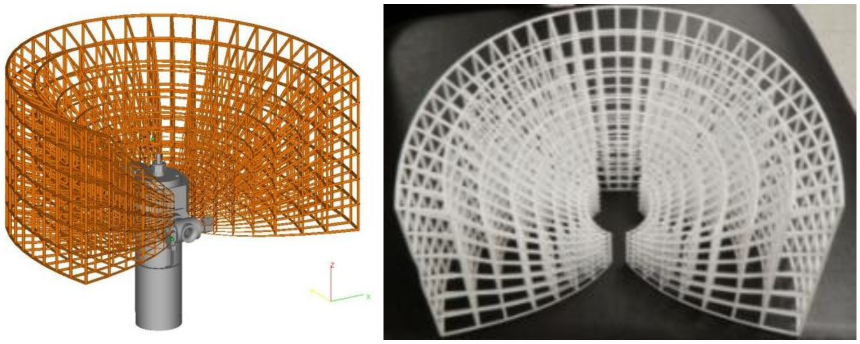

Figure 11: (Left) Magics® rendering of the IC engine/compressor within its thermal-management structure. (Right) Photograph of the SLS-fabricated nylon structure.

This nylon part was electroplated with 50.8μm of copper at RepliForm, via their RepliKote® process. Figure 12 shows photographs of the resultant polymer-metal-composite TMS structure.

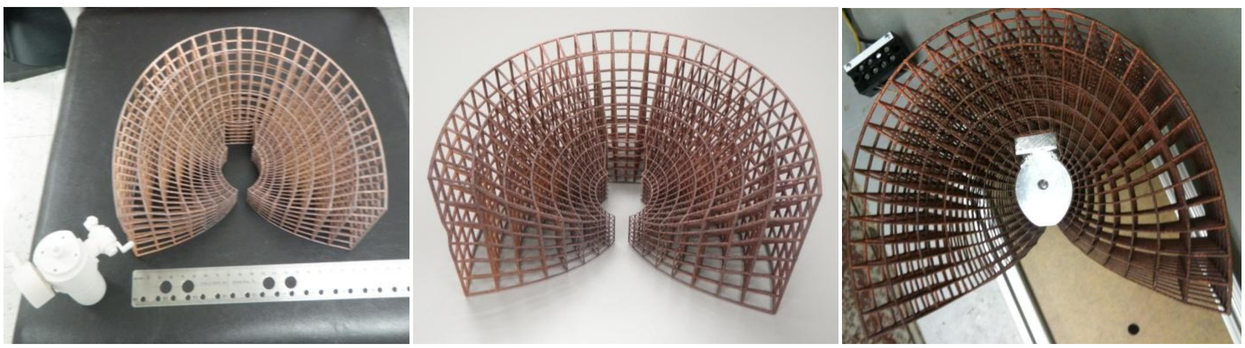

Figure 12: Photographs of the TMS showing the results of the 50.8μm-thick copper electroplating. (Left) A ZPrinter®-fabricated model of the small IC engine/compressor stands adjacent to its TMS. (Right) A surrogate aluminum block and cartridge heater was used to test the functionality.

Higher-resolution fabrication, i.e. minimal strut diameters closer to 100μm (4mils), would afford smaller lattice cells, similar to conventional foam, and lead to a more predictable structure, since convective through-flow would be reduced. Further, stronger structure types, including their fractal subdivisions, could be produced that have similar weight, size and thermal performance as the TMS presented here. Removal of the unsintered particulates would become a significant challenge for selective laser melting (SLM) or sintering (SLS) fabrication, though. Those AM processes whose support structures can be liquefied, thermally or chemically, e.g. Objet, would be most practical.

E. Comparative Physical Testing

The surface-temperature-constrained, copper-electroplated TMS (Figure 12) was tested for its performance in both natural and forced-convection modes of thermal-energy dissipation. Figure 13 shows the resultant average surface temperatures of the TMS. Because the structure's core was nylon, its temperature was not allowed to exceed 473K (200℃). The central aluminum block reached this temperature at ~37W of waste heat; so, the temperatures at 40W and 50W were extrapolated (Figure 14). This TMS could be modified, replacing several of the innermost layers with a solid-metal lattice, to avoid softening or melting of the polymer, and structural failure, at 50W of dissipation. For natural convection, this modified TMS would achieve the targeted 314K (41℃) surface-contact temperature. Likewise, the engine would not exceed its targeted 550K maximal steady-state operating temperature.

Forced convection provides a significant increase in capability to sink thermal energy, as expected. For these experiments, a 40W shop fan was used. Further experimentation with smaller, lower-power, efficient fans remains.

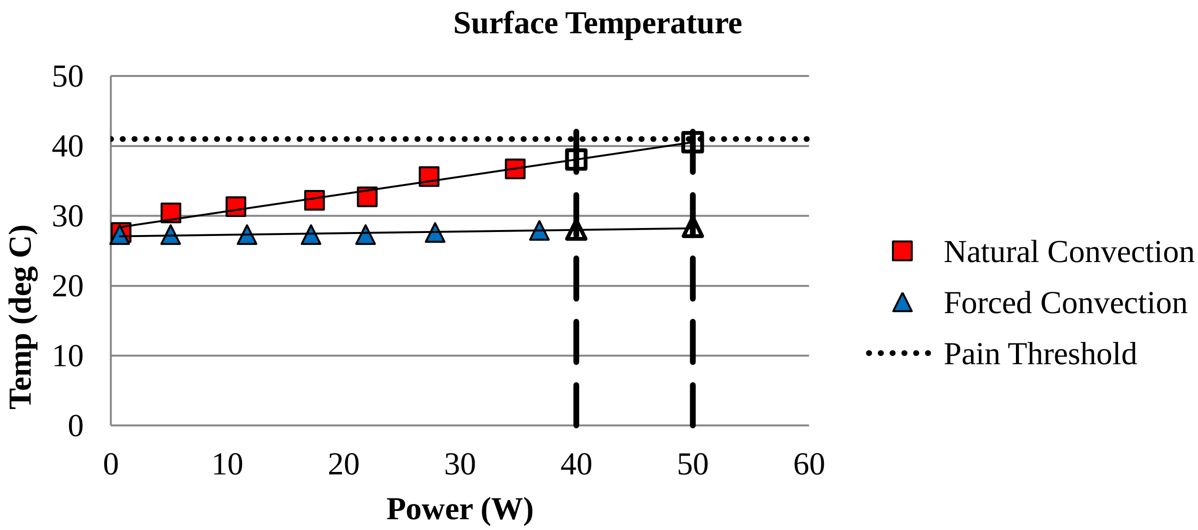

Figure 13: Experimental results for the copper-nylon-composite TMS, in natural and forced-convection modes of heat dissipation, showing the resultant contact-surface temperatures at varying magnitudes of waste heat. The light-colored data points are extrapolated.

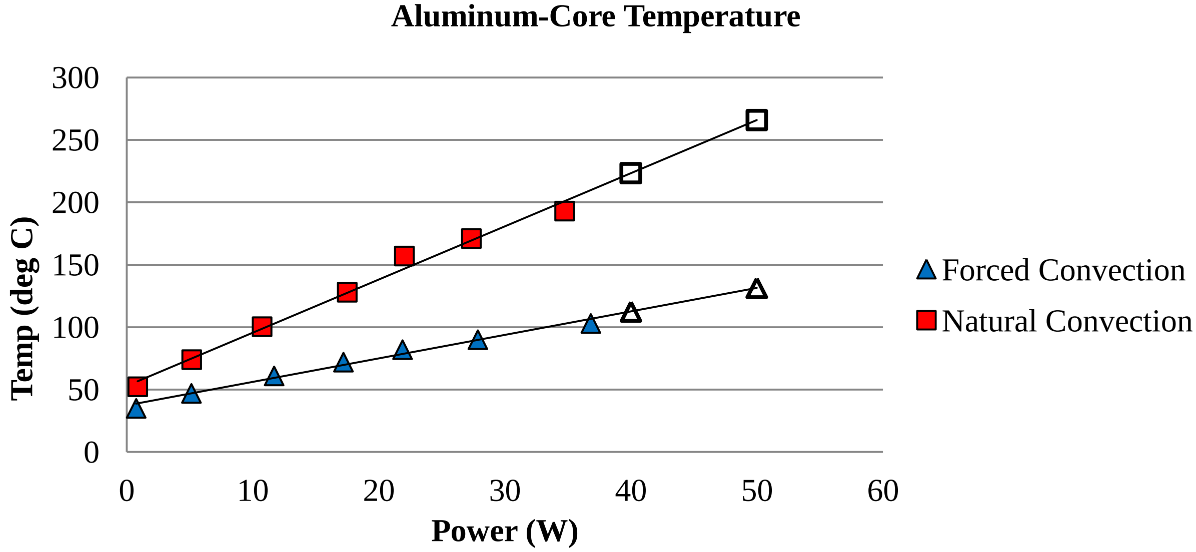

Figure 14: Experimental results for the copper-nylon-composite TMS, in natural and forced-convection modes of heat dissipation, showing the resultant solid-metal-core temperatures at varying magnitudes of waste heat. This core represents the IC engine. The light-colored data points are extrapolated.

F. Discussion

While this structure performed as designed, it is too large to be integrated into the PPAFO, or even worn practically. Cutting it down results in higher surface-contact and engine temperatures. If the power source cannot be made more efficient, the waste heat must be treated with additional technologies.

Forced-convection cooling is one option, but must not reduce system efficiency, or significantly increase mass. Symbiotic energy recovery, e.g. using thermoelectric generators (TEG), is a potential means of providing this cooling power, but adds the fan's mass [11].

TEG's are a passive means of recovering some of the thermal energy generated by component inefficiencies; and, the electrical power garnered reduces the total generation requirement, thereby improving system efficiency [12]. A better application for TEG's is the conversion of waste heat to power electronic sensors, etc., reducing the required battery size and weight. This would also be beneficial for radio-controlled and other unmanned craft.

Another option is the use of phase-change materials to temporarily store that wasted thermal energy, and release it over a longer time period. PCM's store thermal energy as latent heat in that phase-change process, while maintaining a constant temperature [13, 14]. This is to be exploited in maintaining a safe surface-contact temperature for the orthosis. Other medical devices employ PCM's in a similar manner, typically water, paraffin wax or solder [4]; but, they are not multifunctional in design: AM enables this. Figure 15 shows how these might be integrated into this TMS. These materials do add mass to the system; but, further investigation is required to determine if their inclusion would afford a reduction in the TMS size, thereby balancing mass.

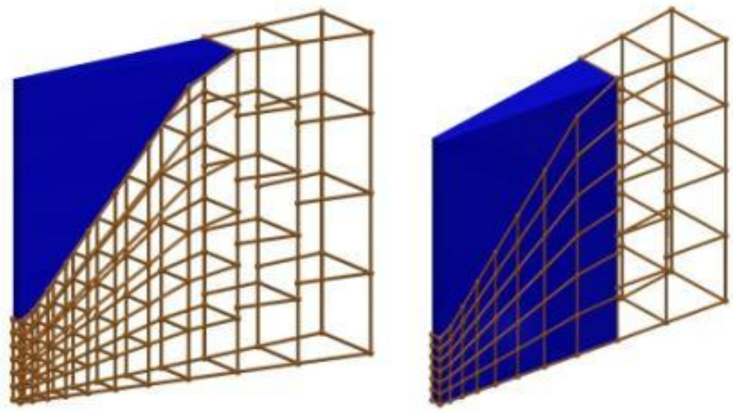

Figure 15: Design options for integrating phase-change materials into the thermal-management structure. A one-cell-wide slice of the structure is shown.

G. Next Steps

There remain a number of tasks to complete, including:

- Finding a means of large-scale, high-resolution fabrication
- Finding a means for automatically Boolean-uniting millions of overlapping struts
- Completing the field-directed optimization algorithms, including cell-level sizing and material definition
- Sizing a TMS for the next-generation PPAFO power source
  - Isothermal CO2 bottles
  - Battery-powered pump/compressor
  - Stirling engine
- Integrating PCM thermal-energy storage
- Optimizing TEG integration
- Complete integration of TMS and engine body

A goal is the culmination of this research in the production of a high-efficiency "Walking Engine," currently being developed, that could power the PPAFO, and many other walking (legged) machines.

Conclusion

The unit-cell-based design approach to thermal management successfully predicted the structure's performance; and, its fabrication was made possible by additive manufacturing. Unfortunately, the design constraints imposed on the thermal-management structure could not all be met. If a more efficient power source for the PPAFO is not found, phase-change materials will likely be required to complement the TMS.

This approach to thermal management has a staggering number of potential applications in many industries; however, while the copper-plated-nylon structure was functional, its operating-temperature range is limited, as well as its strength. AM-based hybrid fabrication is one option for creating solid metallic structures. A direct-metal AM process, with a wide selection of materials and alloys, would be ideal; but, the support structures employed by contemporary systems are impractical. This must be addressed.

Regarding the lattice-design procedure used, automated structure-generation algorithms are quite effective; but, a means of automatically Boolean-uniting the large numbers of entities, and smoothing out their intersections, is required. Ideally, a field-directed optimization algorithm would also drive this design, minimizing manual effort.

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- James Yauch (MSOE ME Dept.) – custom-part machining

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