

MECH 5051/5052 Senior Design: ASME/K-16 and IEEE/EPS Student Design Challenge – Additively Manufactured Heat Sink

SENIOR DESIGN GROUP 27 (CEAS EXPO GROUP 33)

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IEEE, IEEE ELECTRONICS PACKING SOCIETY, GE ADDITIVE MANUFACTURING (SPONSORS)

4/24/2024

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Executive Summary

Group 27's capstone project is the participation in an additively manufactured heat sink design competition annually run by ASME and sponsored by GE. On February 4th, the team submitted a design to the competition, accompanied by a white paper which describes its design and a simulation file. The submitted design incorporates wavy fins which induce turbulence in the passing air, thereby increasing convective heat transfer (8). Mentioned in the paper, is a critical length of the fins. This was not considered in the design as the fin length is irrelevant due to how short and thin the fins and support structures are.

After scoring of the white paper (Table 2), Team UC was selected as a semi-finalist. GE Additive then contacted the team with design revision suggestions for binder jet 3D-printing using 316L stainless steel. The design changes made from GE's feedback, and the design that will be 3D-printed and sent to the competition organizers for testing, is shown in (Figure 24). If Team UC's design scores highly according to (Table 3), an invitation to present at the ITherm conference on May 28th will be extended.

Because the duration of the senior design course extends past the February 4th design submission deadline, Team UC retroactively created more heat sink designs. These designs are shown in (Figure 25, Figure 26, Figure 27, and Figure 28). By creating these designs, Team UC aims to aid future UC teams participating in the competition by giving them design inspiration and possibly a starting point.

To experimentally test heat sink designs, a physical test setup was built in-house (Figure 18). This test setup has the same functionality as the one described in the competition guidelines (2). In addition to the alternative designs, the test setup will aid future UC teams as they can use it for experimental testing.

To validate simulation results of Team UC's design submission, experimental data was collected using the test setup. Unfortunately, sourcing a metal model of the heat sink proved to be difficult. The challenges Team UC faced are documented in the 3D Printed Metal Model Results section. As a result, only designs made of PLA were experimentally tested (Figure 56). Because the support material was exceedingly difficult to remove, and the very low thermal conductivity of PLA, the results are not representative of design performance or simulation accuracy.

Introduction

The basis for Team 27's capstone project is an additively manufactured heat sink design competition run by ASME and IEEE. The competition is also sponsored by GE, as they will 3D print semi-finalists heat sinks using 316L stainless steel with binder jet technology. Shown below are the key dates and deadlines of the competition (2):

Key Competition Dates:

- White Paper & Design Model: Due February 4, 2024
- Semifinalist Design Revisions: Approximately February 18, 2024 — February 25, 2024
- Printing and Testing: Approximately February 25, 2024 — April 30, 2024
- Finalist Announcements: Approximately April 30, 2024
- Finalist Presentations at ITherm 2024: May 28, 2024—May 31, 2024

The heat sink's performance is evaluated under forced convection conditions, where air passes across the heat sink at varying flow rates (1m/s and 5m/s) inside a standardized test apparatus. The test apparatus is modeled after the Armfield HT19 (1). Shown in Figure 1 is the schematic of the front-face of the test apparatus. The schematic was taken from the competition guidelines provided by ASME (22).

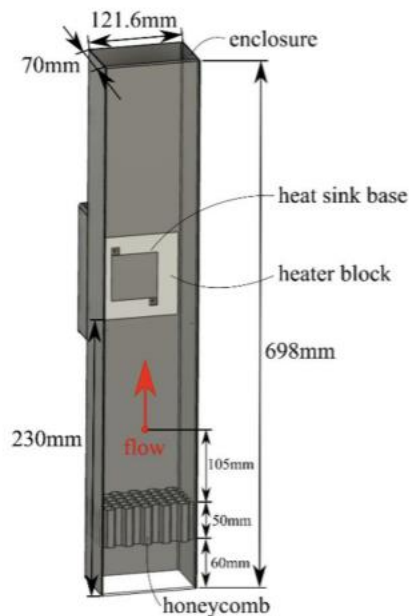


Figure 1: Overall Test Apparatus Schematic

On the backside of the test apparatus is the heater block subassembly (Figure 2) as shown in the competition guidelines (2). It is composed of 7 different components (aluminum heater block, cylindrical heating elements, POM mounting bracket, aluminum housing, a k-type thermocouple, insulation, and the housing cover which is not pictured). The aluminum heater

block, which is fastened to the POM mounting bracket, contains four cylindrical heating elements. Between the heater block and the heat sink, is a layer of thermal interface material. A k-type thermocouple is placed at the center of the thermal interface material, measuring the temperature of the base of the heat sink. Prior to being installed to the main enclosure, the heater block subassembly is stuffed with insulation.

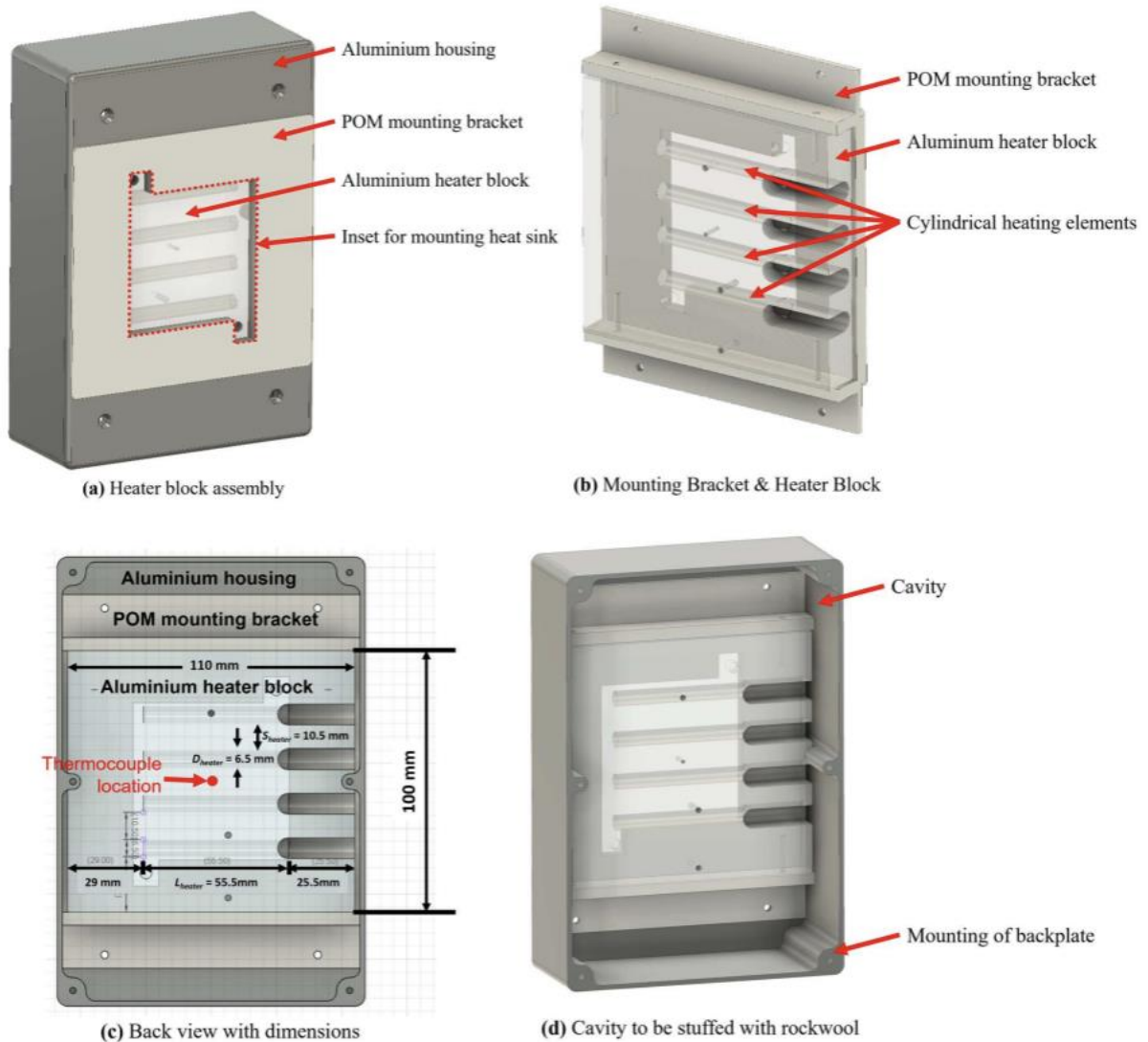


Figure 2: Heater Block Subassembly Schematic

Figure 3 shows an explosion of the mechanical components in the heater block subassembly. This figure includes alterations to the housing and heater block which are discussed in the Test Setup section. The thermal interface material is omitted.

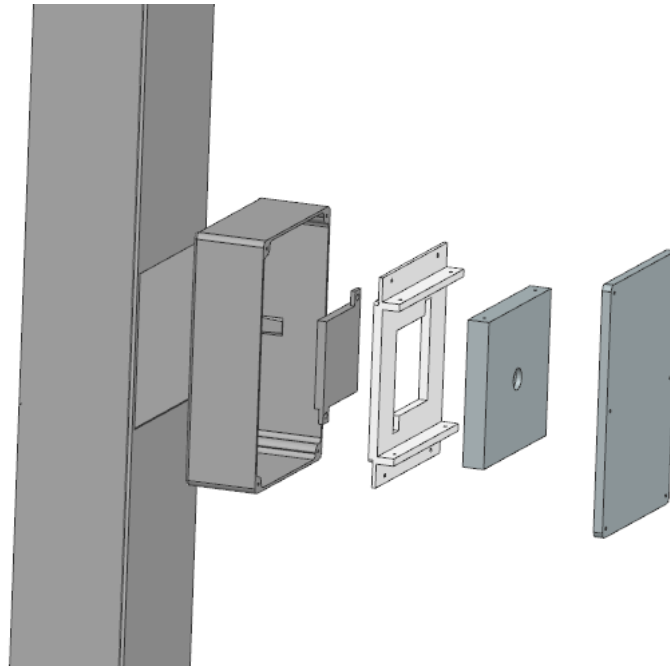


Figure 3: Heater Block Subassembly (Explosion of Structural Components)

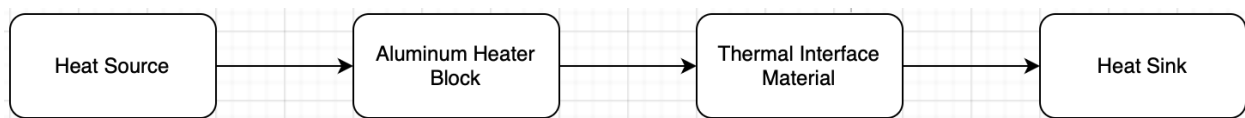


Figure 4: Path of Heat Flow

Figure 5 depicts the heat sink baseplate as shown in the competition guidelines (2). The baseplate, which is physically part of the heatsink itself, has two tabs at its corners for mounting purposes. A screw (unspecified thread type) is pushed through the hole in each tab and into the female-threaded matching holes in the aluminum heater block. Thus, the heat sink is in direct contact with the thermal interface material and the thermocouple.

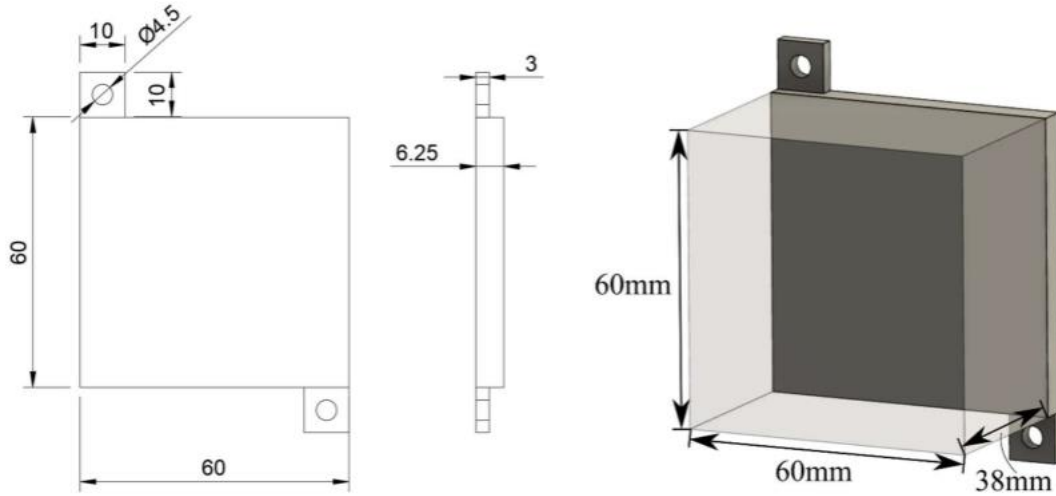


Figure 5: Heat Sink Baseplate and Design Profile

Table 1: Details of the Experimental Setup

Component	Type	Operating Condition
Vertical Enclosure	Armfield HT19	Forced convection
Data Acquisition and control box	Armfield HT10XC	Connected to laptop via USB
Heating block	Armfield HT19 Generic aluminum	Estimated thermal conductivity of 170 W/(m*K). Single K-type thermocouple mounted in hole using glue.
Heaters (x4)	Cylindrical resistance heaters, 24 V up to 50 W (each)	Total power set to 3W
Thermal interface material	RS Pro 794-3973	Graphite, 10 W/(m*K), 0.16mm thickness
Insulating mineral wool	Generic Rockwool	Thermal conductivity of approximately 0.035 W/(m*K)
Fan	Centrifugal fan (part of Armfield HT19)	Measured channel velocity of 1 m/s and 5 m/s

During heat sink testing, a total of 3 watts are supplied to the cylindrical heating elements. Ambient air temperature and steady state heatsink temperature (measured by the thermocouple) are recorded. These three measurements are used to calculate the thermal resistance of the heat sink at each airflow rate (1 m/s and 5 m/s). Equation 1 illustrates this calculation. The j subscript denotes the airflow rate.

Equation 1: Thermal Resistance Calculation

$$R_j = \frac{T_{meas} - T_{amb}}{Q_{meas}}$$

Using the calculated thermal resistance values, along with the mass of the heat sink (in kilograms), the figure of merit can be calculated (Equation 2).

Equation 2: Figure of Merit (FOM) Calculation

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

To compete in the design competition, teams must first design a heat sink and submit its CAD model, a simulation file, and a white paper which includes the following sections: design description, design analysis (simulation data), and benefits to the design provided by the use of additive manufacturing. Below, Table 2 documents the scoring of white paper submissions. It should be noted that the predicted FOM is determined by simulations run by the competition organizers.

Table 2: Scoring metrics for the white paper (= as determined by organizers)*

Metric	Assigned point value
Predicted FOM*	25
Analysis and modelling	25
Effective use of AM (Additive Manufacturing)	35
Writing style and formatting	15

Semi-finalists are chosen from the grading of white paper submissions. It is unknown to Team UC exactly what the success criteria and/or the cut-off score is. However, Team UC was selected as semi-finalists.

Semi-finalists are then contacted by GE additive with design revision suggestions for manufacturability using binder jet 3D printing. If the final design submitted to GE is not manufacturable, then the team will be penalized or disqualified.

Manufacturable designs are then 3D printed by GE and sent to Southern Denmark University (SDU) to be experimentally tested on the aforementioned test apparatus. The top experimentally performing semi-finalist designs are then selected as finalists and invited to present at ITHERM 2024. At ITHERM 2024, the winning design team is selected based on the scoring criteria documented in Table 3.

Table 3: Scoring metrics for the final competition

Metric	Assigned point value
Experimental FOM	40
Effective use of AM	35
Presentation Quality	15

Comparison to Existing Work

The design challenge competition has been hosted since 2019, and competition guidelines have changed from year to year. For example, the following table summarizes notable differences between the 2021 competition guidelines (University of Utah) and 2024 competition guidelines:

Table 4: 2021 vs. 2024 Competition Guidelines

Attribute/ Year	2021	2024
Convection Conditions	Natural Convection	Forced Convection at 1 m/s and 5 m/s
Conduction Conditions	25 W power input	3 W power input
Design Constraints (L*W*H)	1.75 in * 2.00 in * 1 in	60 mm * 60 mm * 38 mm
Material	A357 Aluminum	316L Stainless Steel
Figure of Merit (FOM)	$FOM = \frac{1}{h_{heatsink}(T_{base} - T_{amb})}$	$FOM = \frac{1}{m_{hs}(R_1 + R_5)}$

	Where $\\$_{heatsink}$ is the cost of heat sink, T_{base} is temperature at base, and T_{amb} is ambient temperature	$R_j = \frac{T_{meas} - T_{amb}}{Q_{meas}}$ Where m_{hs} is heat sink mass, R_j is thermal resistance at j m/s, T_{meas} is temperature measured at base center, T_{amb} is ambient temperature, and Q_{meas} is measured power input
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Compared to other additively manufactured heat sink designs, the submitted design was drawn “by hand” using Siemens NX and did not incorporate functions such as topology optimization or other complex CAD and CAE features due to overall unfamiliarity. However, the group started to explore the benefits of using such features, and attempted to use NTopology to refine meshes for simulation towards the end of the project.

Engineering Standards and Codes

The following standards and codes were incorporated or will be taken into consideration for prospective work:

ASHRAE Handbook - Fundamentals

This handbook contains information on heat transfer principles, including conduction, convection, and radiation.

ANSI/ASHRAE Standard 41.2-2022: Standard Methods for Air Velocity and Airflow Measurement

The most pertinent sections to the project are Section 5.3.1.4.3: Steady-State Air Velocity Criteria for Test Points, and Section 5.3.1.4.4: Steady-State Air Velocity for Targeted Set Points. Due to the use of a commercially available hot wire anemometer, an instantaneous air velocity reading was taken directly from the device's display. Had a data acquisition unit and software been used, incorporating this standard would assist in experimentally determining the mean of the sampled air velocity and operating tolerance limit.

ISO 5801:2017: Fans – Performance Testing Using Standardized Airways

The standard outlines methods for testing fans used in air-circulating systems, including those for cooling heat sinks, by determining fan performance characteristics like airflow rate and power consumption. ISO also provides measurement uncertainty estimates and conversion rules.

ANSI/ISA-61010-1: Safety Requirements for Electrical Equipment for Measurement, Control, and Laboratory Use

This safety standard will be incorporated in any future refinement of the test setup. The standard accounts for protection against electric shock, mechanical hazards, spread of fire, hazards of fluids, radiation, and explosive gases. The physical test setup has not shown any serious hazards and has been built using commercially available parts and materials.

Constraints

The designs were primarily judged based on the Figure of Merit given in the competition but there were several other considerations in mind. These considerations focus on the ease of manufacturability via binder jet additive manufacturing, such as printing orientation, support placement, after-print cooling, and weighting. Also, there was only one major specification, the build area is a 60mm x 60mm x 38mm build area. Features such as fins did not have any constraints, allowing for an open design.

One major advantage of additive manufacturing is the complex geometry the process can produce. Additive allows users to manipulate infill percentage, allowing improved heat flow within the part. Along with changing infill percentage, different infill patterns can be used to improve airflow. Wall thickness can also be reduced to 200 microns, improving flow through the walls of a printed part. With reduced walls and infill, additively manufactured parts are typically lighter than traditionally manufactured materials.

Another major advantage of additive manufacturing is that the heat sink can be produced in one print. In traditional manufacturing the fins and base first must be formed separately, then the parts would have to be brazed together, and finally the part would be welded. For additive manufacturing, a user would set up the print and the machine would print the fins and base, fully attached, in one print. This saves time and money as an expert does not have to be there throughout the entire process.

Additive Manufacturing also reduces material costs and material waste. All holes can be printed into the part with minimal support, compared to traditional manufacturing where the material would have to be cut out of the part and the excess material is typically discarded. This decreased waste, increasing the health of the environment and in turn helping public health.

A disadvantage of additive manufacturing is that the parts require post processing. This means that users must have machines or tools to finish the part. This can include CNC machining, Hot Isostatic Pressing (HIP), and Annealing. This can initially cost more money and can sometimes take more time than traditional manufacturing. These processes increase the sustainability of the product.

Because the use of these heat sinks cannot be anticipated, there are no ethical constraints that need to be considered for the scope of this project. Adhering to the codes and standards relevant to the project would put the work completed in good standing with the organizational bodies that present the codes and standards.

Specifications

One constraint of Additive Manufacturing is that parts must be designed to withstand both the printing and sintering process. During sintering parts can warp due to the high heat, so there are certain design guidelines that GE had semifinalists follow. The first major design guideline was to have a medium to low ratio of big surfaces to fine surfaces. If the ratio is too big, the fine features and surfaces are at risk of collapsing or warping in the sinter. The second

design guideline was to have support on the outside of the body to ensure that the fins were printed without decencies. The added supports can be seen in the picture below.



Figure 6: External Supports

Simulation Specifications

Continua

The model selections for the conduction and convection continua are shown in Figure 38 and Figure 39. Note the selection of the k-Omega turbulence model. In early simulations, the k-Epsilon model was used, but was switched to k-Omega as it is said to have better performance near walls. This is relevant since the top surface of the base from which the supports and fins protrude is in line with the backside vertical enclosure wall.

Regions

Figure 40 shows the regions and their respective boundaries. The CAD models used included a heat sink model and a subtract model. The subtract model was created by drafting a rectangular prism with cross sectional dimensions of the vertical enclosure and extrusion dimension. A subtract function with the prism set as the target body and the heat sink model set as the tool body was done, creating a model that represents the surrounding air in the enclosure wherever the heat sink was not present.

The inlet and outlet are defined on their respective faces on the subtract model, with the inlet experiencing the specified 1 m/s or 5 m/s air speed, and the outlet being a non-pressurized outlet. For the heat sink model, the base is given the thermal specification of 3 W.

Interfaces

Interface 1 is a boundary that is seen in Figure 40. The interface allows for the conduction and convection regions to interact with each other, or else any physical specification would act independently within their own region. The interface uses the Fins boundaries defined in each region and are an exact match since the subtract model was created using the exact dimensions of the heat sink model.

Stopping Criteria

Simulation results yielded high residuals, so residuals were not used as the stopping criteria. A high iteration count of approximately 10,000 steps was used to allow residuals values to level out.

Test Setup Build Specifications

To collect experimental results, and to validate Team UC's simulation files, a physical test setup was built. The primary objective was to build the test setup as similar to the specifications provided in the competition guidelines as possible. Deviations from the outlined specifications were made to reduce costs and complexity without impacting functionality.

The team began by creating a list of the important components needed to build the test setup (Table 5). Test Setup BOM depicts the complete bill of materials.

Table 5: Test Setup Part List

Metal Components	3D Printed Components	Electrical Components	Miscellaneous Components
Enclosure	Ducting	Logic/control board	Insulation
Aluminum Heater Block	POM mounting bracket	Thermocouples	Hardware (nuts, bolts, brackets)
Aluminum Honeycomb Flow Straightener	Heater block subassembly housing	Hot-wire Anemometer	Table/Stand
	Heater block subassembly housing cover	DC Power Supply	Enclosure cover
		Heat Source	Thermal interface material
		Computer Fan and controller	

Metal Components:

It was determined that the main enclosure would be made of bent aluminum. Because there were no significant stresses or heat tolerance requirements applicable to the test setup, the only factor to consider when choosing which aluminum alloy to purchase was its bendability. It was for this reason that aluminum alloy 5052, known for its formability, was chosen for the enclosure and heater block subassembly housing.

The first notable deviation from the test setup outlined in the competition guidelines is the aluminum heater block. Figure 2 depicts the heater block as having four holes bored through

its center for placement of the cylindrical circular heaters. This is unnecessary. The use of heating pads placed on the back-face of the heater block is sufficient as the surrounding insulation prevents heat from flowing anywhere but to the heater block. Additionally, Figure 2 fails to specify exactly how the thermocouple is mounted. To solve this challenge, a countersunk through-hole was added at the center of the heater block for thermocouple mounting. Figure 7 shows the finalized drawing of the heater block. Because the competition guidelines described in Table 1 indicate that “generic aluminum” should be used for the aluminum heater block, aluminum alloy 6061 was chosen.

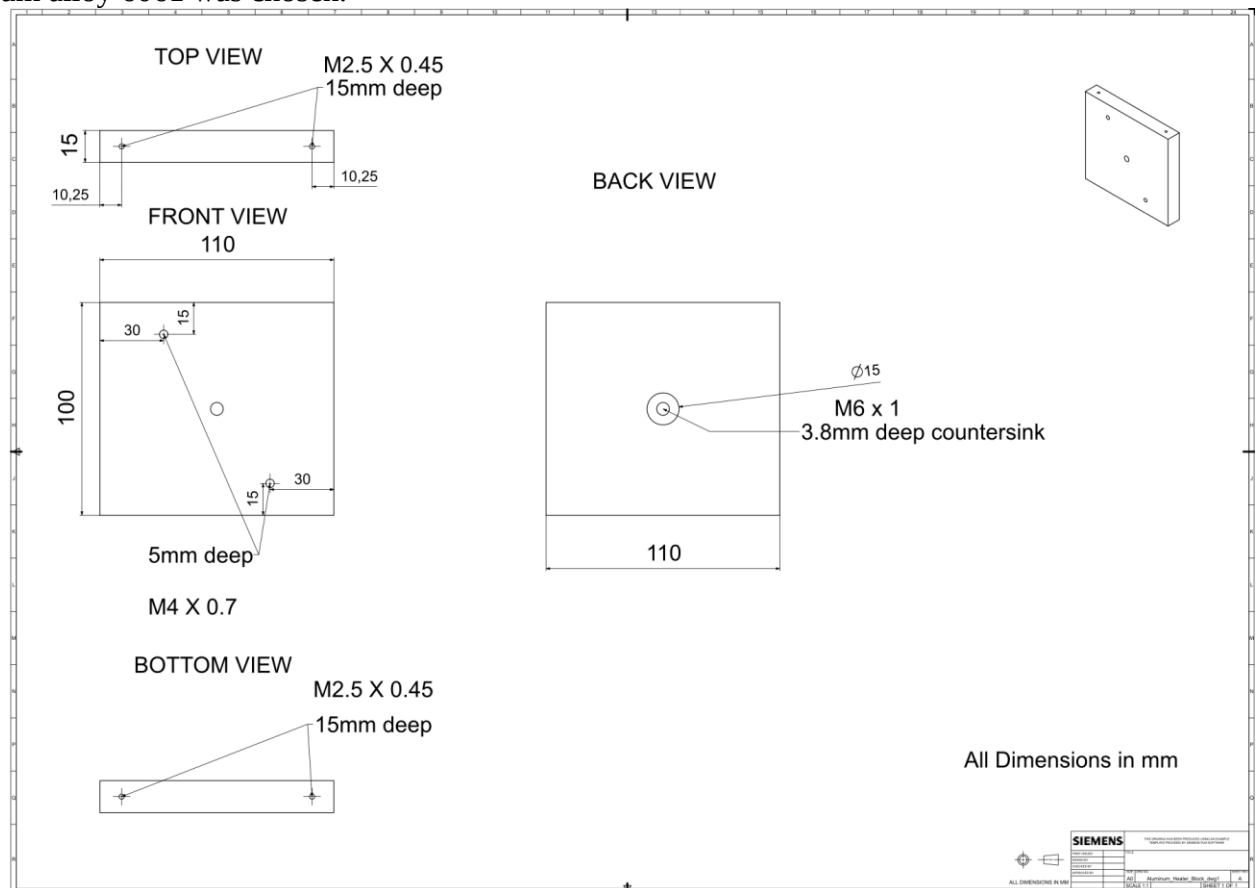


Figure 7: Engineering Drawing of Heater Block

While the material choice of the honeycomb flow straightener is unimportant, the team decided to use aluminum because it is the material used in the test apparatus described in the competition guidelines, it is readily available, and it is low-cost.

3D Printed Components:

To simplify manufacturing and lower costs, three components in the test apparatus outlined in the competition guidelines were 3D printed. These include the heater block subassembly housing, its cover, and the POM mounting bracket. As shown in Figure 2, the heater block subassembly housing and the POM mounting bracket each have intricate

geometries. Specifically, if the housing were to be made of aluminum, then a large block would need to be purchased and nearly all of it would be milled out to create the edges and the mounting holes for its cover. This would have been a very wasteful and unnecessary decision as the high thermal conductivity of aluminum is not needed for these two components. The heat sink is only in contact with the aluminum heater block. Additionally, the housing has a lip with mounting holes for the cover at the center of its left and right edges (Figure 2). These mounting points were removed because they are unnecessary and interfere with the placement of the POM mounting bracket and aluminum heater block. This change is shown in Figure 8.



Figure 8: Interior of Heater Block Subassembly Housing

To route the entirety of the airflow produced by the fan into the enclosure, ducting was required. Because of the odd dimensions of the enclosure, it was decided to use 3D-printed custom ducting. One end of the ducting (airflow entrance) was designed with four mounting holes for the fan, while the plenum at the airflow exit end was designed to have an identical cross-sectional area as the enclosure.

It was at this stage in the test setup design that the method of securing the enclosure upright was decided. By adding a flange to each side of the exit-end of the ducting, the enclosure could be secured by using angle brackets, nuts, and bolts. The upper portion of the angle brackets are secured to the enclosure on the left, right, and rear sides. The lower portion of the angle brackets (sitting on top of the table) then secure the enclosure to the ducting by a bolt going through the table and the flanges of the ducting. A nut can then be fastened to the bolt, holding both the ducting and the enclosure in place. This is illustrated in Figure 9, Figure 10, Figure 11 and Figure 12 below.

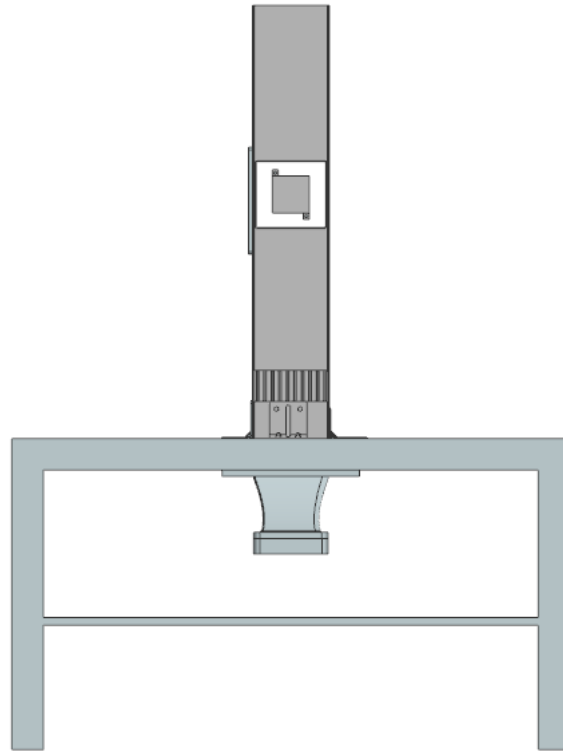


Figure 9: Test Setup Assembly

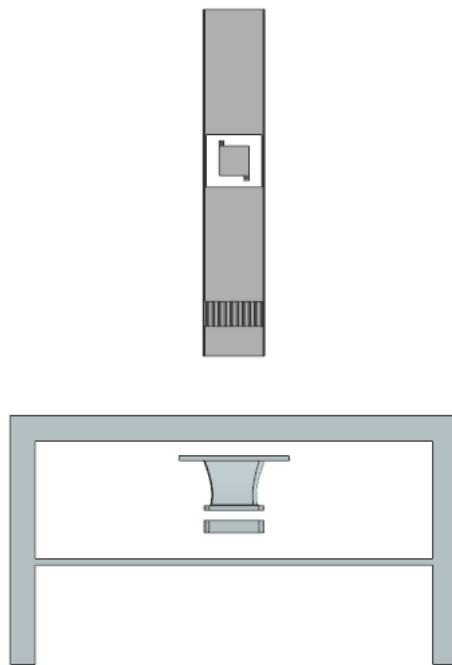


Figure 10: Front-View Explosion of Test Setup Assembly

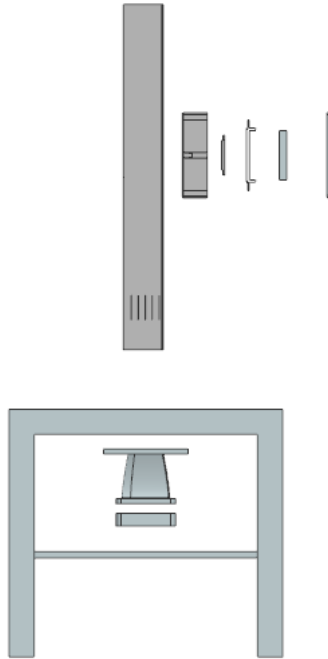


Figure 11: Side-View Explosion of Test Setup Assembly

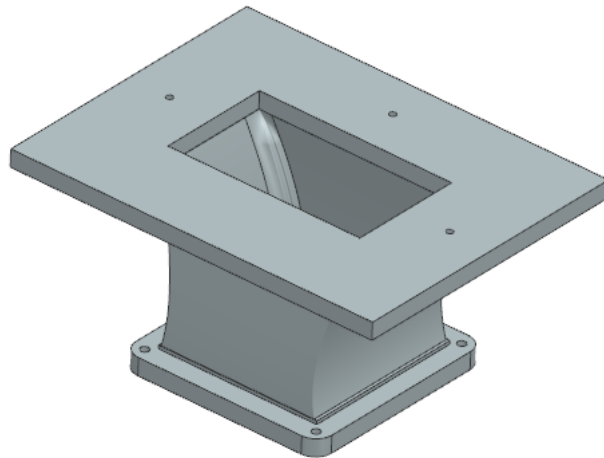


Figure 12: 3D Model of Ducting

Electrical Components:

To calculate FOM using Equation 1 and Equation 2, there are four measurements that the test setup must take. These are airflow speed, temperature of the heat sink, ambient temperature, and the power input.

To measure the speed of airflow, a hot-wire anemometer was chosen. This type of anemometer is preferable to cup anemometers and vane anemometers as they have a significantly lower footprint.

To measure ambient temperature and the temperature of the heat sink, MAX6675 cold-junction compensated K-type thermocouples were used (3). These thermocouples operate at 3.0-5.5V and include a digital converter with 5 pins: Vin, GND, CS, SCK, and SO. The MAX6675 reads temperatures at a resolution of 0.25°C, which is sufficient for evaluating the difference in heat sink FOM scores.

Arduino was chosen for data acquisition. This is for a couple of reasons. Firstly, Arduino is capable of supplying power at 3.3V and 5V, which are both sufficient for the MAX6675 thermocouples. Additionally, the digital pins on Arduino boards can be used as the CS, SCK, and SO pins for the MAX6675 thermocouples. Power to the Arduino is supplied via USB connection to a laptop. Thermocouple data is also outputted in the serial monitor of the Arduino IDE on the laptop. Another benefit of using Arduino was the team's eagerness to learn how to use Arduino.

The specific logic board chosen was the Arduino Mega 2560 Rev3 (4). Admittedly, the team had little Arduino experience at this time in development of the test setup and chose this model as it contains 54 digital pins. In the end, only 6 pins were required to connect the thermocouples. For this reason, an Arduino Nano should have been selected and presents an area of improvement, as it is not only cheaper, but also integrates directly into the breadboard—giving a more aesthetically pleasing look.

Flexible circular heating pads with adhesive backings were used instead of the four cylindrical heating rods outlined in Figure 2. As mentioned above, this choice was made to simplify manufacturing because the use of cylindrical heating elements would have required holes to be bored out of the heater block. Adhering heat pads to the backside of the heater block is sufficient because the surrounding insulation stuffed inside the heater block subassembly provides ample thermal resistance so that nearly all the heat flows directly into the heater block.

Team UC's initial plan was to use a single circular heat pad placed directly in the center of the rear-face of the heater block. So, the largest sized circular heater that fits on the heater block (3" diameter) was purchased. The picture of the heating pad on the manufacturer's website indicated that it may be possible to drill a hole through the center for thermocouple placement. This decision was made because the heating pad is flexible, and because they came in a pack of three. If one failed after having a hole drilled through it, there would still be two more available. Unfortunately, the internal wires at the center of the heat pad did not provide enough space for the thermocouple to be placed through, and so ordering circular heat pads was a mistake.

Instead of ordering new rectangular heat pads, the team agreed that the best decision was to use two circular heat pads, each offset from the center to make room for the thermocouple. Due to its small size, neither heat pad is in full contact with the heater block. However, this is not an issue as the high thermal resistance imposed by the surrounding insulation routes heat to the heater block. Regardless, substituting the circular heat pads with rectangular heat pads that fully fit on the heater block would be an improvement.

An adjustable DC power supply was required to supply 3 watts of total power to the heat pads. By nature, the DC power supply measures the input power.

The last electrical component needed was the computer fan. The only requirement of the fan is that it can push 5 m/s of airflow through the enclosure. To ensure this, Equation 3 and Equation 4 are used to calculate the minimum volume flow rate required to achieve 5 m/s of airflow through the enclosure.

Equation 3: Cross Sectional Area Equation

$$A = l \text{ (mm)} * w \text{ (mm)}$$

$$A = 121.6\text{mm} * 70\text{mm} = 8512\text{mm}^2 = 0.008512\text{m}^2$$

Equation 4: Volume Flow Rate for Rectangular Ducts

$$Q \left(\frac{\text{m}^3}{\text{s}} \right) = V \left(\frac{\text{m}}{\text{s}} \right) * A(\text{m}^2)$$

$$Q \left(\frac{\text{m}^3}{\text{s}} \right) = 5 \left(\frac{\text{m}}{\text{s}} \right) * 0.008512(\text{m}^2) = 0.04256 \left(\frac{\text{m}^3}{\text{s}} \right)$$

Converting to cubic feet per second

$$0.04256 \left(\frac{\text{m}^3}{\text{s}} \right) * \frac{35.3146667 \left(\frac{\text{ft}^3}{\text{s}} \right)}{1 \left(\frac{\text{m}^3}{\text{s}} \right)} = 1.503 \left(\frac{\text{ft}^3}{\text{s}} \right)$$

Converting to cubic feet per minute

$$\text{Minimum CFM} = 1.503 \left(\frac{\text{ft}^3}{\text{s}} \right) * \frac{60(\text{s})}{1 (\text{min})} = 90.18 \left(\frac{\text{ft}^3}{\text{min}} \right)$$

As shown, the fan must be able to provide 90.18 cfm of airflow.

The 120mm Noctua NF-F12 IndustrialPPC-3000 PWM (6) was selected. This is because it provides 109.89 cfm of airflow, providing 21.86% headroom from the minimum required volumetric flow rate. Additionally, this fan is equipped with Noctua's Focused Flow™ frame which aims to straighten the airflow. Moreover, this fan has built in vibration dampeners.

The Noctua NA-FC1 4-pin fan controller (7) was also purchased to control the fan's rpm. This product acts as a potentiometer with a rotating dial. It was selected because it guarantees compatibility and receives power via USB connection—allowing the fan to be powered by USB.

Miscellaneous Components:

Non-crack acrylic was chosen for the cover of the enclosure so that the heat sink could still be viewed during testing.

Because heat flows from the heater block to the thermal interface material before reaching the heat sink (Figure 4), the team thought it would be best to use the same thermal interface material as what was given in the competition guidelines. The thermal interface material was viewed as a critical component that should not be deviated from.

According to the competition guidelines, the insulation used inside of the heater block subassembly housing (Table 1) is generic rockwool. Like the thermal interface material, this was viewed as a critical component—not to be deviated from. Unfortunately, sourcing this exact material proved to be difficult, as the only vendor who sells it is McMaster-Carr. At this time in the project, it was unavailable, and so the team chose to purchase generic R-19 fiberglass insulation, as it has a similar thermal conductivity and is readily available at Home Depot.

To save time during building, the Ikea LACK coffee table was purchased. This product is advantageous to building a custom table because of its low price of \$29.99, low weight of under 19 lbs., and its structural paper honeycomb interior is easy to cut-through.

Because all dimensions of the test setup and the measurements it takes are in the metric system, it was decided to use hardware specified in the metric system. M2.5 and M4 nuts and bolts were purchased from Home Depot, along with angle brackets for securing the heater block subassembly housing to the tower, as well as to secure the tower to the ducting.

Arduino Programming

Before building the test setup, the temperature measurement system was programmed and tested to ensure that it functions properly. Table 6: Thermocouple to Arduino Wiring depicts the Arduino pin number assigned to each thermocouple wire.

Table 6: Thermocouple to Arduino Wiring

Arduino Pin Purpose	MAX6675 #1	MAX6675 #2
V_in	5V	5V
GND	GND	GND
Chip Select (CS)	49	38
Serial Clock (SCK)	51	40
Data Out (SO)	47	36

The Arduino MAX6675 library (5) provided by the manufacturer was imported into the Arduino IDE and used in our script. The thermocouples' wires pin locations were assigned in the code and were used as input arguments in the MAX6675's read temperature function. Figure 37 in the appendix contains the script Team UC wrote in the Arduino IDE. Below, Figure 13 is a sample output of the temperature readings in the Arduino IDE serial monitor.



Figure 13: Sample Temperature Output

Physically Building the Test Setup

The physical test setup was modeled after the design provided by the competition guidelines, as can be seen in Figure 1 and Figure 2. The test setup was built as closely as possible to the provided design, but there were several differences because of available materials. Several differences in our physical test setup were non-critical materials, such as the insulation material, and the heat source (the physical test setup uses heating pads instead of cylindrical heating rods). Additionally, the honeycomb flow straightener used was half the width of the one in the design. These differences were deemed to not influence the functionality of the physical setup.

It was decided that using a table in which the vertical enclosure could sit inside would be the best method to replicate the test set-up provided by the competition guidelines. As a result,

the physical build was broken up into several parts, including the vertical enclosure, the table/ducting, and the heater subassembly.

The heater block subassembly housing was made of two 3D printed parts, the base and the cover. An aluminum block was press fit into a 3D printed mounting bracket which fit into the housing base, as seen in Figure 14. A circular heating pad was placed on the aluminum block and served as the heat source. The housing was stuffed with insulation and the housing cover was attached using screws.

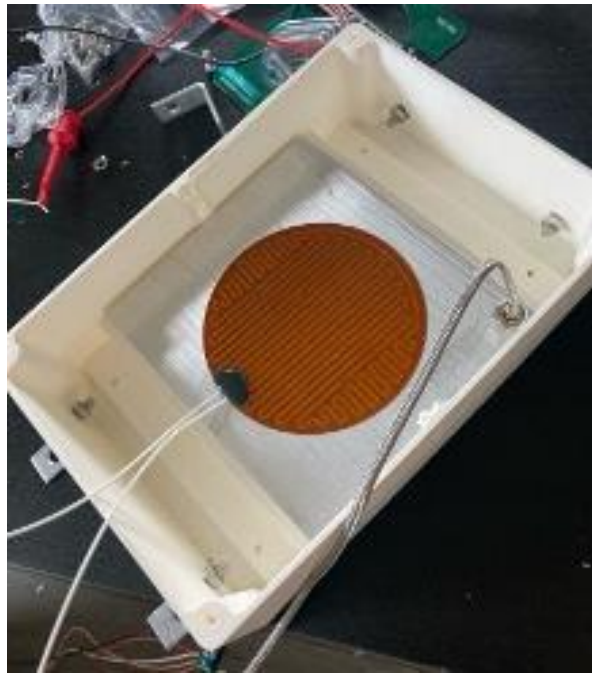


Figure 14. Built Heater Block Subassembly

The first step of building the vertical enclosure was cutting and bending the aluminum and cutting the acrylic. After this was completed, small angle brackets were used to attach the acrylic face to the aluminum vertical enclosure. Small angle brackets were also used to attach the honeycomb flow straightener and heater subassembly to the vertical enclosure. A hole was drilled into the side of the enclosure so that the anemometer could sit in the vertical enclosure. The vertical enclosure with the subassembly can be seen in Figure 15.



Figure 15. Built Vertical Enclosure with Heater Block Subassembly

The first step of building the table and ducting was measuring and cutting a rectangular hole in the face of the table in which the vertical enclosure would fit. After the hole was cut, long screws through the top of the table were used to secure the ducting to the bottom of the table, as seen in Figure 16. The ducting was lined up with the hole in the table and the fan was screwed to the bottom of the ducting. This created and directed the airflow.

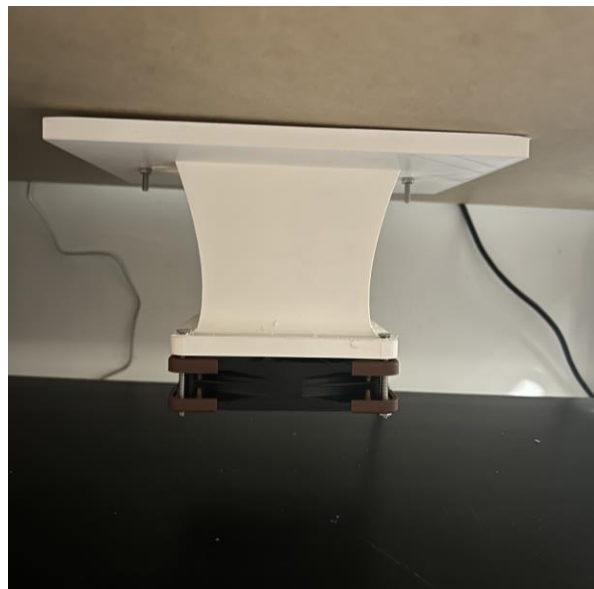


Figure 16. Built Ducting and Table

After the vertical enclosure and table were fully assembled, the vertical enclosure was placed into the table and secured using small angle brackets with nuts and bolts. The fully built test setup can be seen below in Figure 17 and Figure 18.



Figure 17. Built Test Setup Front



Figure 18: Built Test Setup

Table 7: Abbreviated BOM

Subassembly	Part	Quantity	Cost
Heater	Heater Block	1	\$30.58
Heater	Mounting Bracket	1	\$12.00
Heater	Heat Sink Baseplate	1	\$11.70
Heater	Housing Base	1	\$12.00
Heater	Housing Face	1	\$6.00
Heater	Housing Brackets	4	\$14.04
Heater	Housing Nuts	1	\$10.29
Heater	Housing Screws	1	\$13.84
Heater	Housing Washers	1	\$8.06
Heater	Thermal Interface Material	1	\$13.17
Heater	Insulation	1	\$49.83
Heater	Heating Pads	4	\$112.80
Enclosure	Vertical Housing	1	\$42.00
Enclosure	Plexiglass	1	\$17.68
Enclosure	Honeycomb Flow Straightener	1	\$27.00
Enclosure	Hot Wire Anemometer	1	\$148.00

Enclosure	Thermocouple	3	\$7.69
Enclosure	Enclosure Brackets	4	\$14.04
Enclosure	Enclosure Nuts/Screws/Washers	N/A	N/A
Auxiliary	Stand/Table	1	\$29.99
Auxiliary	Fan	1	\$27.95
Auxiliary	Ducting	1	\$34.00
Auxiliary	Fan Controller	1	\$24.08
Auxiliary	LCD Display	1	\$15.99
Auxiliary	Arduino Mega 2560 R3 Kit	1	\$65.99
Auxiliary	Power Supply	1	\$56.75

Time Schedule

The following list is a summarization of the schedule followed by Group 27. A scalable graphic of the Gantt chart used can be found in the appendix (Figure 41).

- First Iteration (1/8 - 2/4)
 - Week 1: Brainstorm/ generate ideas
 - Week 2: Draft CAD model for heat sink
 - Week 3: Develop simulation file
 - Week 4: Write white paper
 - Milestone: 2/4 - white paper/ CAE file submission
- 2nd Iteration (2/4 - 3/3)
 - Week 1: Make CAD changes/ Review Potential Use of NTopology
 - Week 2: Make simulation changes
 - Week 3: Plan/ Build experimental Setup
 - Week 4: Document Findings
 - Milestone: 2/23 - Design Review Presentation/ Progress Report
- 3rd Iteration (3/3 - 3/31)
 - Week 1: Brainstorm model revisions
 - Week 2: Make CAD changes
 - Week 3: Run simulations
 - Week 4: Document Findings
- Finalization (4/1 - 4/28)
 - Milestone: 4/2 - Project Video/ Presentation
 - Milestone: 4/9 - CEAS Expo
 - Milestone 4/22 - Presentation/ Final Report

Schedule Deviations

Seeing that the starting date of the semester was January 8th and the submission date for the competition was February 4th, there was not very much time to complete the first iteration. During the final presentation, grading professors alerted us that other design competitions accounted for this by starting their process much earlier, even as early as the fall semester. This was the first time that UC has participated in this competition and have learned a valuable lesson from this. Future groups representing UC that are looking to participate will benefit greatly from starting their design process much sooner as the quality of work suffered due to the time pressure.

The performance of the group would have also benefited from having a more concurrent schedule. Brainstorming and CAD model development could've occurred simultaneously on an individual level, and a case for concurrently learning about and developing the simulation file can also be made as the only major difference between simulations were the CAD geometry used for the heat sink and air domains.

The teleconference with GE Additive Manufacturing was another deviation from the schedule as model revisions needed to be made in a short time frame and resubmitted for printing. The organizers hosted the conference on March 12th and requested that changes be submitted by the end of the week on March 15th. The organizers reached out again to the team on

March 22nd and requested another model change. The second change was to be submitted by March 25th.

Another deviation not expressly listed on the above schedule is the acquisition of a metal 3D printed model for testing purposes. The following work occurred during the third iteration phase in mid-March. The group found obtaining a metal model from a reputable manufacturer for a reasonable price exceedingly difficult. The two printing solutions the group attempted to go with were printing using Direct Metal Laser Sintering (DMLS) method at the University of Louisville and binder jet method with Xometry.

Design Alternatives and Basis for Selection

Conceptual Genesis:

The departure from traditional straight fin designs was driven by the advent of additive manufacturing. With additive manufacturing, it is now possible to incorporate significantly more complex geometries. The group found inspiration from Dr. Jog's paper (3) which explores how wave-shaped fins induce turbulence in the passing air, thereby increasing convective heat transfer.

Initial Design:

Shown below (Figure 19) is a 3D model of our first design.

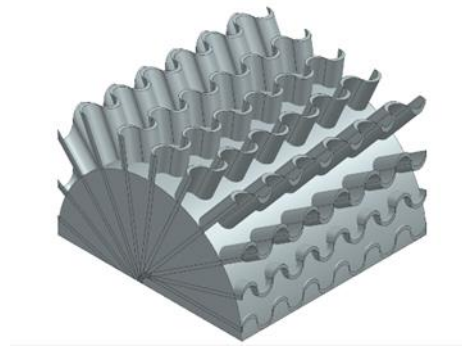


Figure 19: Initial Design

The original concept stemmed from the straight fin; constant thickness design similar to that presented in the outline. From past experiences modeling such heat sinks, much of the heat is gathered near the center of the base. The base was made to model traditional manufacturing, so it could later be improved for heat transfer utilizing additive manufacturing.

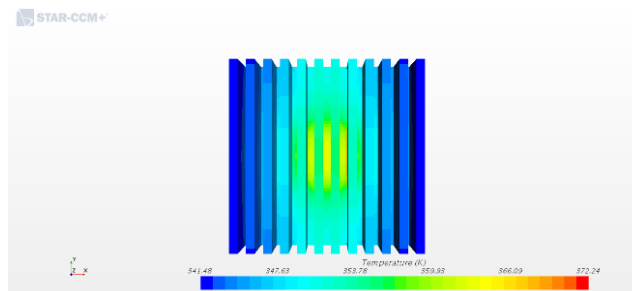


Figure 20: Past Simulation of Straight Fin Heat Sink

The radiating nature of the fins of the proposed design was an attempt to direct heat flow away from the center. In theory, not only would the heat be able to travel in any direction along

the surface of the base, but it could now also travel along any point of contact with the base. The wave shape of the fins aimed at causing the surrounding air flow to become slightly more turbulent, thereby increasing heat transfer.

First Iteration: Iterative Learning, Adapting, and Incremental Progress

Concerns surrounding thickness hindering airflow and impacting the Figure of Merit (FOM) spurred subsequent iterations, introducing skeletonization to enhance airflow dynamics. However, another major concern was that the solid semicircular base was too thick, which would impede flow significantly and negatively contribute to the FOM calculation. Having a solid base would have caused the air to move around the heat sink, only going past the ends of the fins. Allowing air to flow through the heat sink would maximize the turbulence-causing potential of the fin shape and expose the air to greater surface area. Pictured below (Figure 21) is the first iteration of the design.

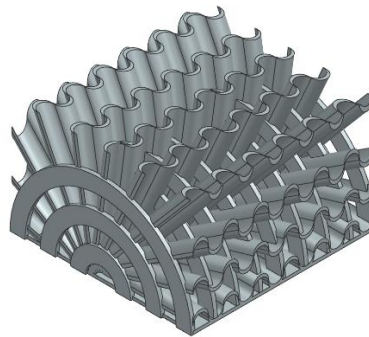


Figure 21: First Iteration

The skeletonization of the semicircular base involved creating semicircular rib plates to distribute heat evenly across the entirety of the fins. Interstitial material was removed to create air flow passages to minimize flow resistance.

This design proved to be a significant improvement over the first, largely due to the increased surface area and reduced flow resistance. However, there was still room for improvement.

Second Iteration:

The design changes planned for the next iteration focused on further reducing flow resistance. This was accomplished by reducing the fin count from eleven to nine, and by adding through holes across the length of the heat sink near the base. The second iteration (design submitted to the competition) is shown below (Figure 22).

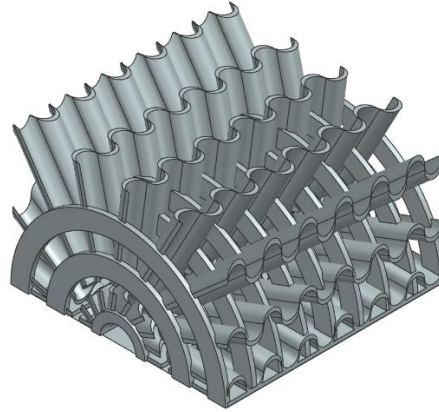


Figure 22: Second Iteration

GE Improvements First Iteration:

When the qualifying teams were announced, a meeting was set up with GE to optimize the parts for binder jet printing. The first design guideline given was to ensure parts were not too fine, as metal powder could get stuck in small features with no way of removing the material. The next guideline given was to ensure the ratio between large and fine features was not too high. If the ratio is too high the part's features could collapse or warp in the sinter. The final guideline was to create supports around the outside of the part to support the fins during printing in sintering. The first iteration of the part can be seen below (Figure 23).

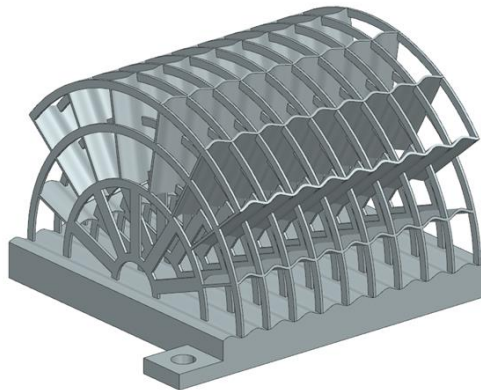


Figure 23: GE Improvement 1

GE Improvements Second Iteration:

GE once again contacted teams to further improve the part for binder jet printing. The main concern was creating more support along the edge of the fins, so they did not warp. Figure 24 is the part that GE is producing and the final iteration of the design.

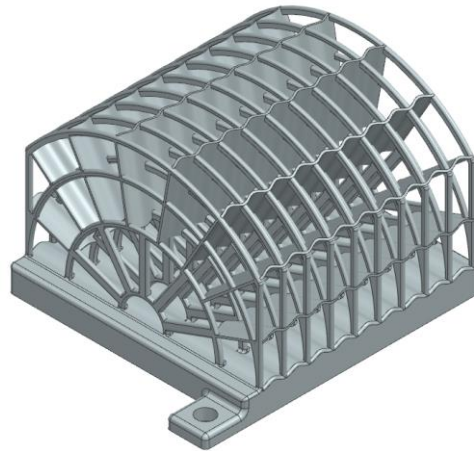


Figure 24: Final Design

Designs Made After Competition Deadline

Team UC created additional designs after the competition submission deadline. While simulations were not created for them, it is believed that they would perform well in the competition.

Shown below in Figure 25 and Figure 26 are 3D models of the lattice heat sink design. This design incorporates vertical wavy fins with staggered horizontal arches. The main goal of this design was to induce as much turbulence as possible in the passing air while keeping the flow resistance as low as possible.

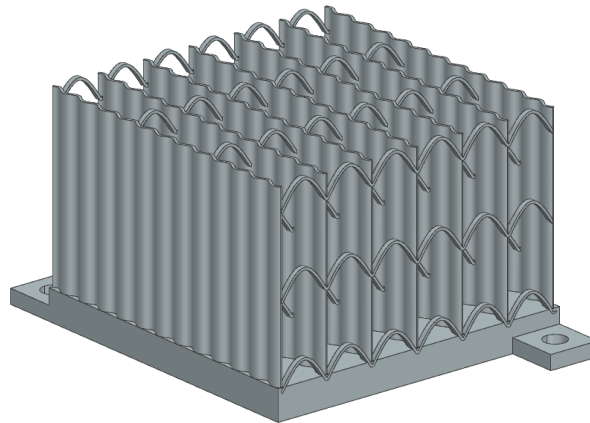


Figure 25: Lattice Heat Sink Design

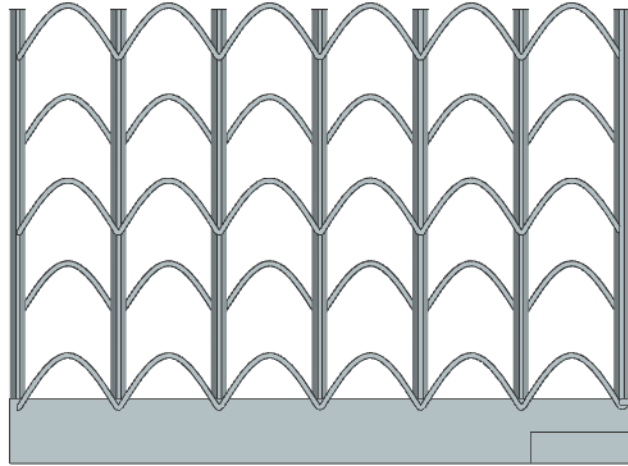


Figure 26: Front View of Lattice Heat Sink Design

Figure 27 shows the revolve funnel design. With this design, air enters the wider end of the funnel, and due to the conservation of momentum, must increase in velocity as it travels through the narrower end of the heat sink. Because FOM is evaluated based on the temperature of the center-base of the heat sink, this design should perform well in theory as that is the location where air is travelling at the highest speed.

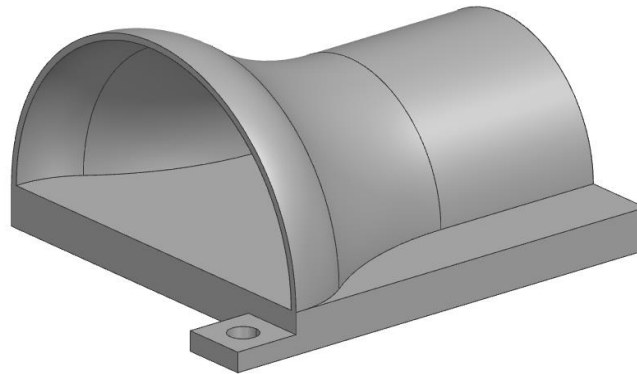


Figure 27: Revolve Funnel Design

The extruded funnel design (Figure 28) is a similar design to the revolve funnel design but incorporates narrow fins at its entrance to induce turbulence while sacrificing diametric constriction.

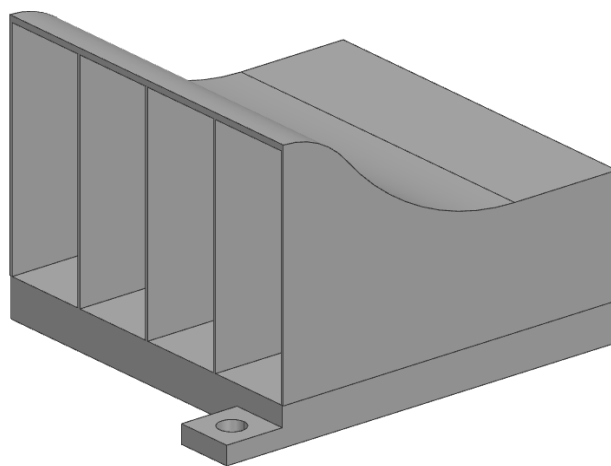


Figure 28: Extrude Funnel Design

Summary of Results

White Paper Simulation Results

The following table contains simulation and experimental results conducted on the initially submitted model provided for the white paper submission on February 4th. The associated contour plots for the two inlet velocities can be found in the appendix (Figure 47, Figure 48).

Table 8. White Paper Submitted Simulation Results

Parameter	Simulation Value	Experimental Value (1 m/s)	Experimental Value (5 m/s)
Givens			
Heater Power, q_{input} [W]	3	3.003	3.003
Ambient Temperature, T_{amb} [°C]	30	22.000	22.000
Inlet Velocity, V_{in} [m/s]	1, 5	1	5
Modeled Values			
Heat Sink Mass, $m_{heat\ sink}$ [kg]	0.180292	0.180292	0.180292
Heat Sink Base Center Temperature for 1 m/s, T_1 [°C]	61.237	37.500	
Heat Sink Base Center Temperature for 5 m/s, T_5 [°C]	38.453	33.500	
Thermal Resistance for 1 m/s, R_1 [°C/W]	10.412	5.162	
Thermal Resistance for 5 m/s, R_5 [°C/W]	2.818	3.830	
Figure of Merit, FOM [W/g·°C]	0.419241	0.616835	

Sample Calculations

Heat Sink Mass, $m_{heat\ sink}$ [g]:

$$\rho = 8000 \frac{kg}{m^3} \quad V = 2.296426e(-5) m^3 \quad Porosity = 2\%$$

$$m_{heat\ sink} = \rho * V * (1 - Porosity) = 8000 * 2.296426e(-5) * (1 - 0.02)$$

$$m_{heat\ sink} = 0.180292 kg$$

Heat Sink Base Center Temperature for 1 m/s, T_1 [°C]:

$$R_1 = \frac{(T_{meas} - T_{amb})}{Q_{meas}} = \frac{(61.237 - 30)}{3} = 10.412 \text{ °C/W}$$

Figure of Merit, FOM [W/g·°C]:

$$FOM = \frac{1}{m_{heat\ sink}(R_1 + R_5)} = \frac{1}{0.180292 * (10.412 + 2.818)} = \mathbf{0.419241\ W/g * ^\circ C}$$

White Paper Results Discussion

The group submitted the original white paper design without including the square base with mounting holes as part of the model. This would cause a difference in mass and would affect the conduction portion of the simulation due to the difference in base thickness. The actual mass would be higher than the reported mass, causing the FOM to decrease proportionally. The increase of the additional thickness to the base would increase thermal resistance. Heat would take longer to reach the surface from which the heat sink fins are protruding from, and much of the heat would aggregate in the base before moving in the direction of the fins.

Assuming that the thermal resistance values do not change, the new FOM accounting for the new mass would be:

$$m_{heat\ sink\ new} = (m_{heat\ sink} + m_{base}) = 360.748\ g$$

$$FOM = \frac{1}{m_{heat\ sink}(R_1 + R_5)} = \frac{1}{0.360748 * (10.412 + 2.818)} = \mathbf{0.209525\ W/g * ^\circ C}$$

The mass of the base was very similar in value to that of the originally submitted heat sink, so the FOM effectively halved.

Straight Fin Reference Model Simulation Results

The following table documents simulation results for the straight fin reference model provided by the competition organizers. Note that major changes include an increase in power input from **3 W** to **18 W** and a change in material, from **316L stainless steel** to **aluminum** that has a specified thermal conductivity of approximately **110 W/m-K** (changed from pure aluminum StarCCM+ material library default setting at **237.0 W/m-K**, maintained density (2702.0 kg/m³) and specific heat (903.0 J/kg-K) settings). These results are compared to the reference experimental data (Figure 46) to confirm for simulation fidelity. The contour plots for the test cases can be found in Figure 49 and Figure 50.

Table 9. Straight Fin Reference Model Results

Parameter	Simulation Value	Experimental Value (1 m/s)	Experimental Value (5 m/s)
Givens			
Heater Power, q_{input} [W]	18	18.20	18.27
Ambient Temperature, T_{amb} [°C]	30	31.1	27.4
Inlet Velocity, V_{in} [m/s]	1, 5	1	5
Modeled Values			
Heat Sink Mass, $m_{heat\ sink}$ [kg]	0.273438	0.2868	
Heat Sink Base Center Temperature for 1 m/s, T_1 [°C]	59.366	53.4	
Heat Sink Base Center Temperature for 5 m/s, T_5 [°C]	46.036	39.3	
Thermal Resistance for 1 m/s, R_1 [°C/W]	1.6314	1.23	
Thermal Resistance for 5 m/s, R_5 [°C/W]	0.98089	0.65	
Figure of Merit, FOM [W/g·°C]	1.4000	1.8547	

Straight Fin Results Discussion

Note that in Figure 46, the FOM reported for the straight fin reference model was 0.03097. Through calculations with the temperature and mass values provided, we were unable to obtain this number and instead found the FOM to be 1.8547 W/g·°C. Calculating for the simulation, the FOM is 1.4000 W/g·°C.

The simulated temperatures are consistently higher, with there being a 5.966 °C difference between T_1 and 6.736 °C difference between T_5 , leading to higher thermal resistance values. The simulated mass is slightly less than the experimentally reported mass, which would increase the FOM if all else were equal.

Figure 55 shows the residual plot for both the 1 m/s and 5 m/s cases. 1 m/s was run for 10,000 iterations before switching to 5 m/s for the remaining 11,000 iterations. The energy residual was the only residual to continue to converge while momentum, continuity, specific dissipation rate, and total kinetic energy were around the same values. The overall high residual values suggest that the model could have been better simulated, and this would most likely account for the temperature difference.

Final Submission (Revision 2) Simulation Results and Discussion

Mesh scene cross section views of the final submitted model can be found in the appendix (Figure 51, Figure 52). An expanded mesh scene cross section view of the originally submitted model can be found in Figure 53 and Figure 54.

A working simulation was unable to be run with the model due to difficulties in meshing the model. A few major problems arose outside of previously encountered issues (such as nonorthogonal cells). These problems stemmed from the fact that by reducing the overall

dimensions of the model features, far greater cells needed to be used to properly mesh. The width of the thinnest support on the model is 0.5 mm, meaning cells need to be even smaller, preferably a quarter to a fifth of the support width, to produce a sufficient mesh. The act of doing so raised the total number of cells from an average of two million cells to approximately thirty-nine million cells.

Possible solutions that would be considered for future work would be to remove cells from the outlet end of the air domain and to utilize NTopology for mesh refinement purposes. Removing cells from the outside end may not reduce the number of cells drastically depending on settings such as volume growth rate and prism layer cell settings but is still worth trying since these cells are not particularly important in understanding the heat transfer that is directly around the heat sink itself. The purpose of the simulation is to study how the incoming air cools the heat sink and is not overly concerned with the wake that the heat sink creates.

NTopology was mentioned early in the semester, but the true ability and proper use of the software was not brought to the group's attention until the CEAS Expo. An observer viewed the project and stated that his work was very similar to this as he also had designed additively manufactured heat sinks. A major talking point was his use of NTopology as his primary meshing tool. He also noted that NTopology could not run CFD simulations on its own, so after meshing, he would need to reimport it back into his CFD computational software to run the simulation. This would definitely be an avenue considered for future work as experimentation with the software showed that it was quicker than StarCCM+. Meshing in StarCCM+ for the final submitted model took anywhere from 0.5 to 1.5 hours and would sometimes crash depending on the complexity of the mesh, cell type, and settings. Meshing time for NTopology was on average fifteen minutes.

3D Printed Metal Model Results

As previously mentioned in the time schedule portion, the group was unable to obtain a 316L stainless steel model for testing and evaluation purposes.

The initial approach was the DMLS print with the University of Louisville. The additive manufacturing representative, although willing to print, quoted a price of \$1510 for the model, which seemed to be greatly over the market price for DMLS. In comparison, Xometry also offered a DMLS print and produced an instant quote of approximately \$900. Along with the undesirable price, the University of Louisville also noted that the process would involve printing additional supports that would be removed after the printing process, which would prove difficult to do due to the small dimensions and compactness of the model. Removal of the supports post-print would increase the chances of damaging features, producing a low-fidelity model that did not match the intended design. There was also the option of maintaining the supports in the model, but this would have an adverse effect as the purpose of the design was to have large channels that would allow air to flow through. These issues involving the use of supports seemed to be nonexistent with the binder jet printing process as described by GE Additive Manufacturing during the printing revision teleconference as no mention of supports were made. Despite these issues, the group still decided to initiate a print with the University of Louisville due to lack of options and time. Unfortunately, the print still failed even with the use of additional supports (Figure 42, Figure 43), which caused the group to continue looking for another printing solution.

The next option after the failed print was to submit a print job to Xometry. Requesting an expedited quote from the company was extremely difficult and very discouraging. Binder jet printing was offered, and using their instant quote feature, the total for a print of the final revised model was \$602.26 with a production lead time of fifteen business days, which did not include shipping time and cost. An account representative reached out and informed the group that there was an expedited quoting process that would require a quoting team to manually review and quote the printing process. This communication occurred while the University of Louisville was attempting the initial printing, so there was a perceivable delay in the group's response to this. However, immediately after the print failure, the group attempted to reach out again to inquire about the expedited quoting process. There would be a shocking lack of willingness to communicate on the manufacturer's end that would lead to the absence of any metal model whatsoever. The group followed up over email several times to no avail, and even directly contacted a sales representative to inquire about the expedited quoting process over the phone, but no response was ever received. Please refer to the instant quote (Figure 44) and Xometry email chain (Figure 45a to d) for more details.

Conclusion and Subsequent Development

Having been selected as semi-finalists for the design competition and having completed the test setup build, the team is proud of the work they accomplished. This project required a combination of problem-solving skills and creativity that resulted in a great learning experience. Some engineering skills that team members were able to improve upon include CAD modeling, simulation modeling, manufacturing, and 3D printing.

Future work can be divided into two categories: Near-future work and distant future work.

Near-future work

1. Procure metal models of the heat sink designs and collect experimental data for them. Then calculate their FOM scores.
2. Successfully mesh final competition model and simulate it. Calculate simulated FOM score.
3. Create simulations of new designs.
4. If invited, present at ITherm conference as finalists.

Distant Future Work

1. Incorporate a display into the test setup to show heat sink and ambient temperatures without a laptop.
2. Use Arduino Nano instead of Arduino Mega to clean up test setup wiring.
3. Replace circular heat pads with rectangular heat pads for the heater block so that heat pads lie entirely on the back of the heater block.

Team UC is grateful for the opportunity to participate in this competition and looks forward to hearing back from the competition organizers regarding a finalist decision.

References

- 1 [Armfield HT19 Data Sheet](#)
- 2 [Competition Guidelines](#)
- 3 [MAX6675 Data Sheet](#)
- 4 [Arduino Mega 2560 Rev3 Data Sheet](#)
- 5 [MAX6675 Library](#)
- 6 [Noctua NF-F12 IndustrialPPC-3000 PWM Data Sheet](#)
- 7 [Noctua NA-FC1](#)
- 8 [Dr. Jog Wavy Fin Paper.pdf](#)
- 9 [Dr. Jog Forced Convection Paper.pdf](#)
- 10 [Dr. Jog Plate Fin Paper.pdf](#)
- 11 [Hot Wire Anemometer Amazon Product Page](#)
- 12 [DC Power Supply Amazon Product Page](#)
- 13 [Test Setup BOM](#)

Heat Sink Competition. IEEE ITherm Conference. (n.d.). <https://www.ieee-itherm.net/heat-sink-competition/>

ISO 5801:2017. ISO. (2023, November 9). <https://www.iso.org/standard/56517.html>

University of Utah Department of Mechanical Engineering - ITherm Heat Sink Design Competition. (n.d.). <https://www.mech.utah.edu/wp-content/uploads/2021/04/Team-12-S21s.pdf>

Appendices

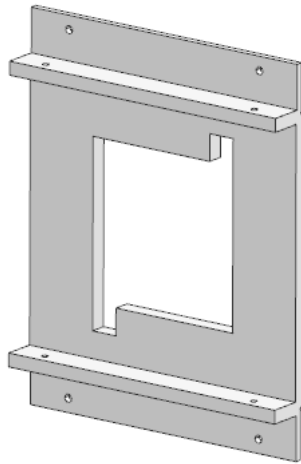


Figure 29: 3D Model of POM Mounting Bracket

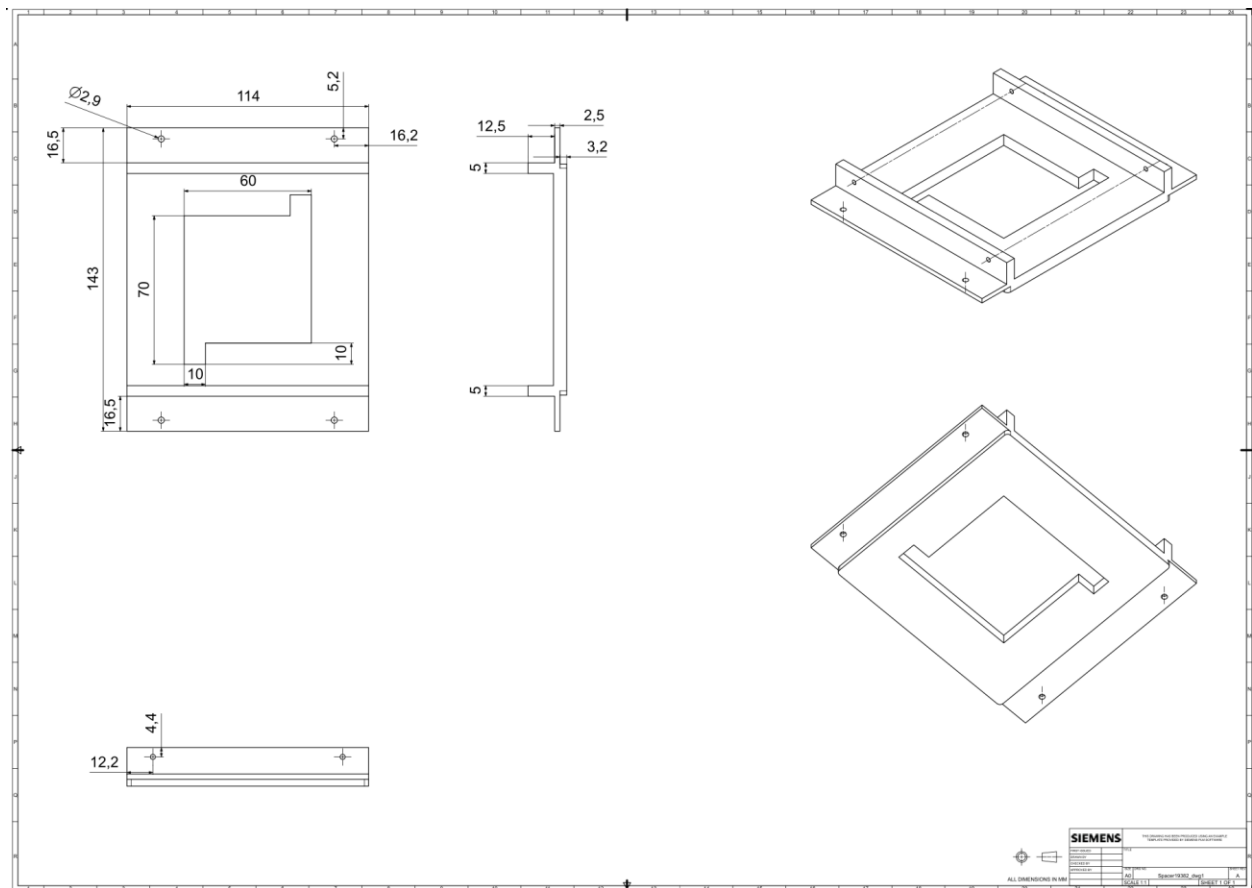


Figure 30: Drawing of POM Mounting Bracket

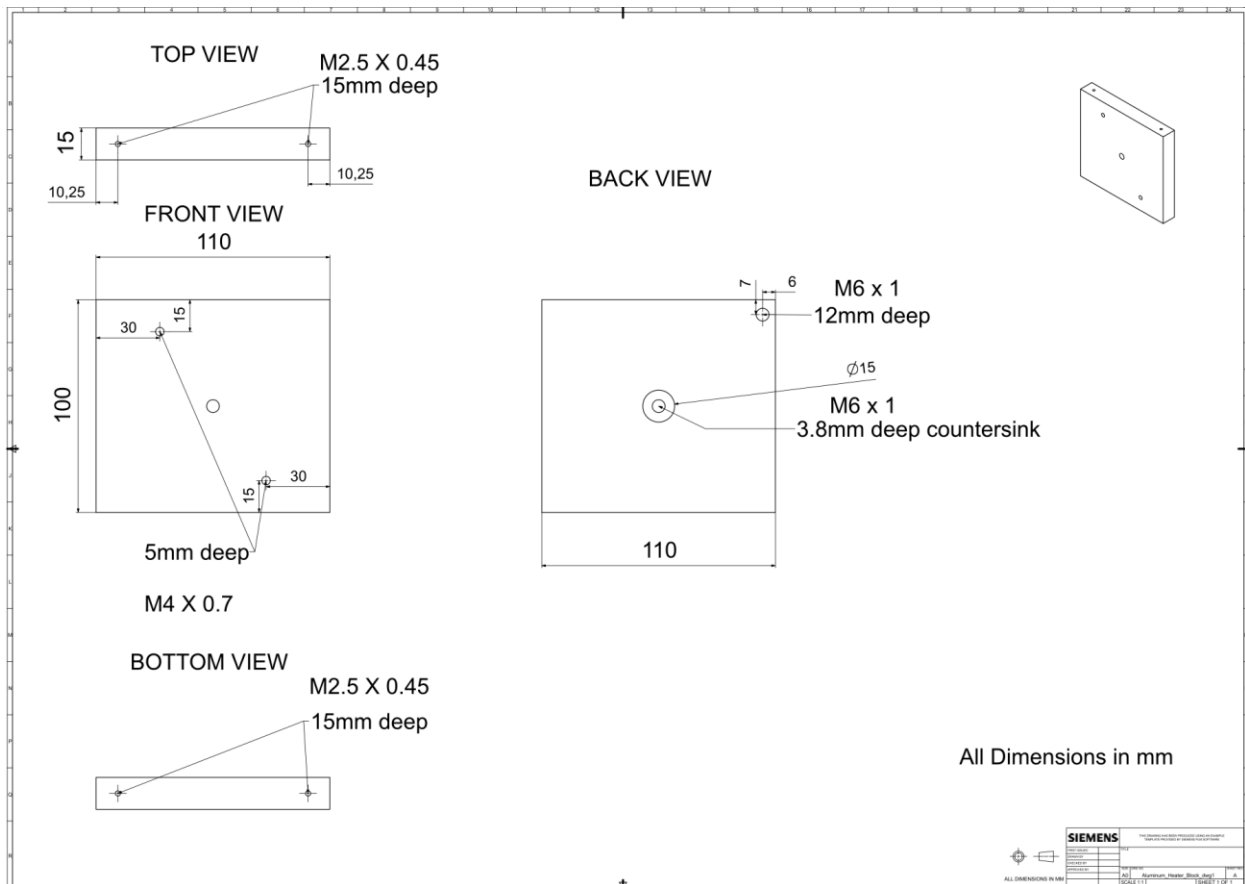


Figure 31: Drawing of Heater Block Inside of Test Setup

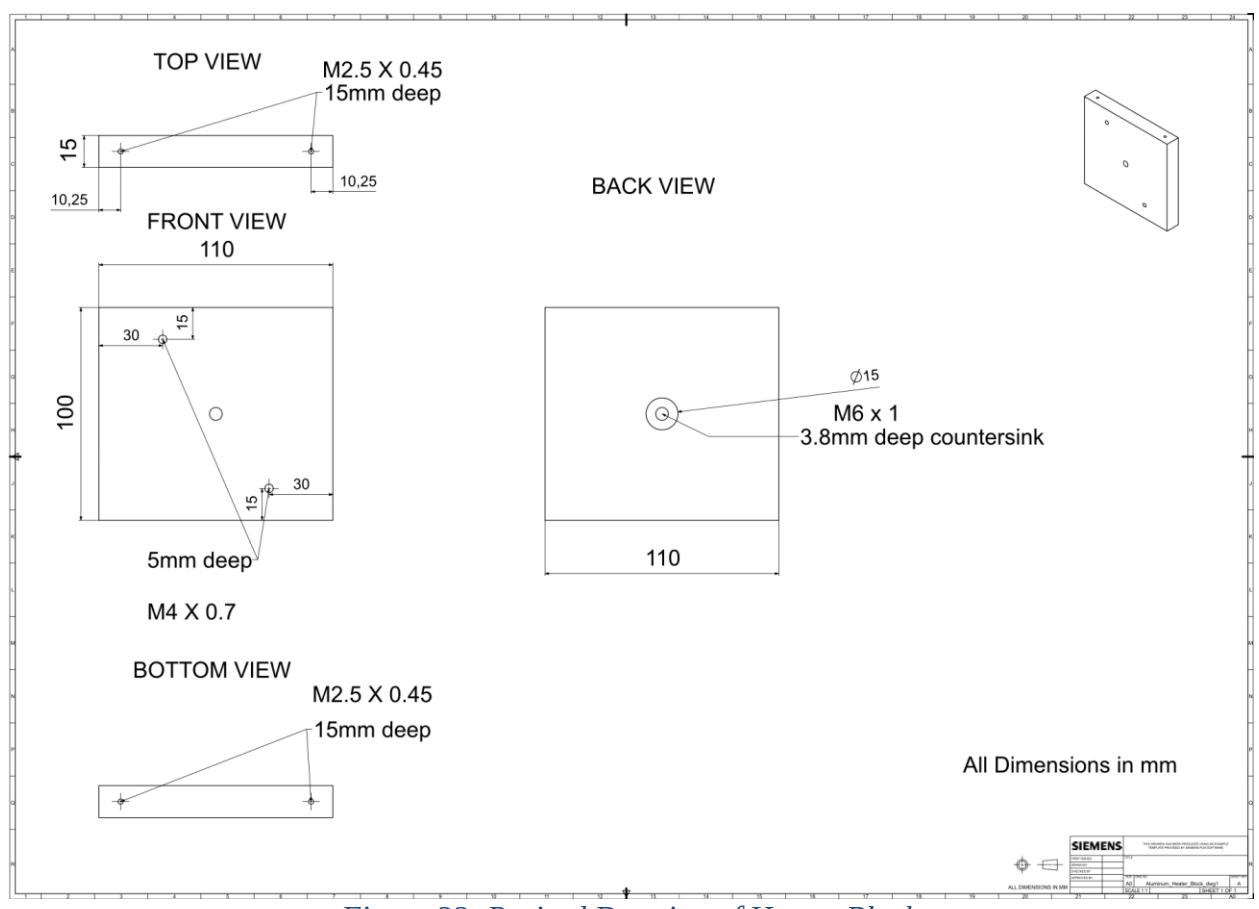


Figure 32: Revised Drawing of Heater Block

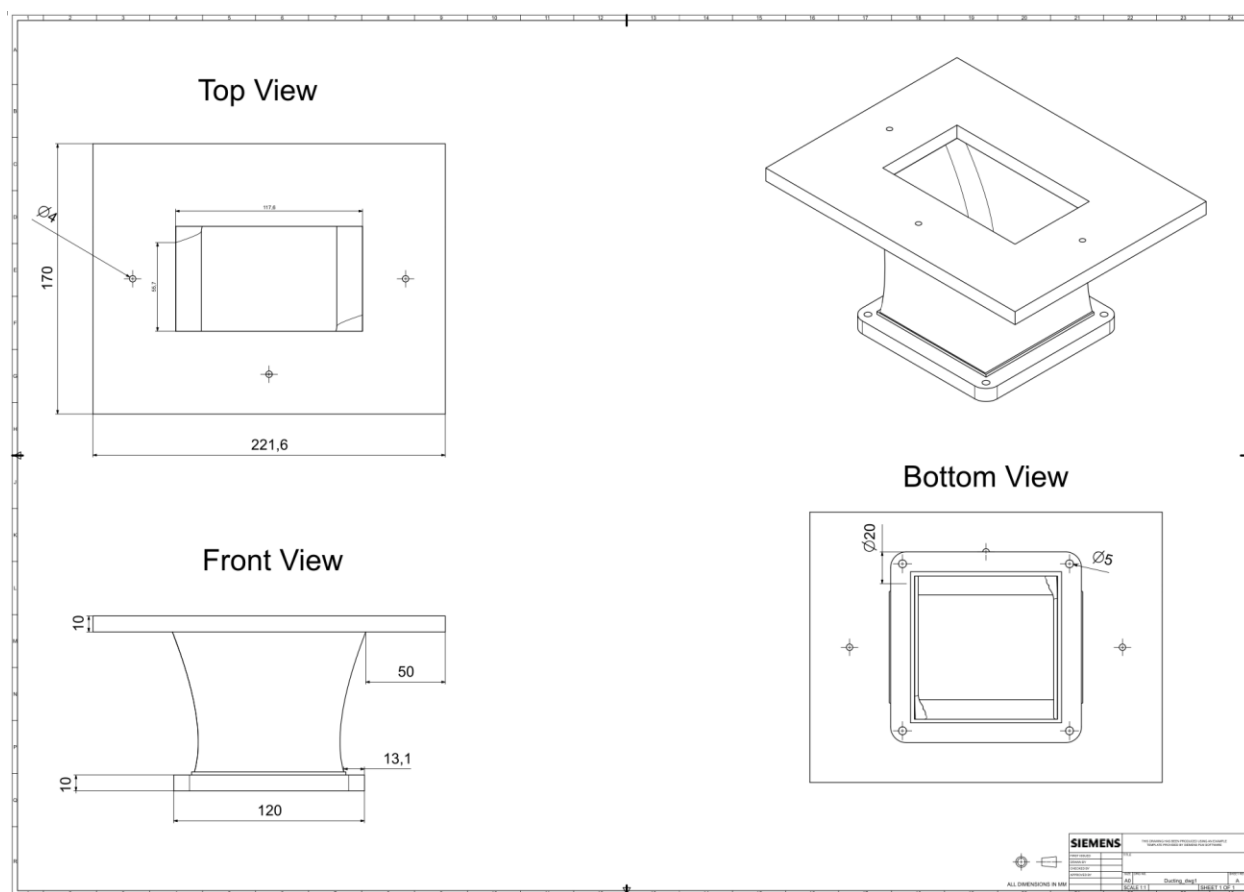


Figure 33: Drawing of Ducting

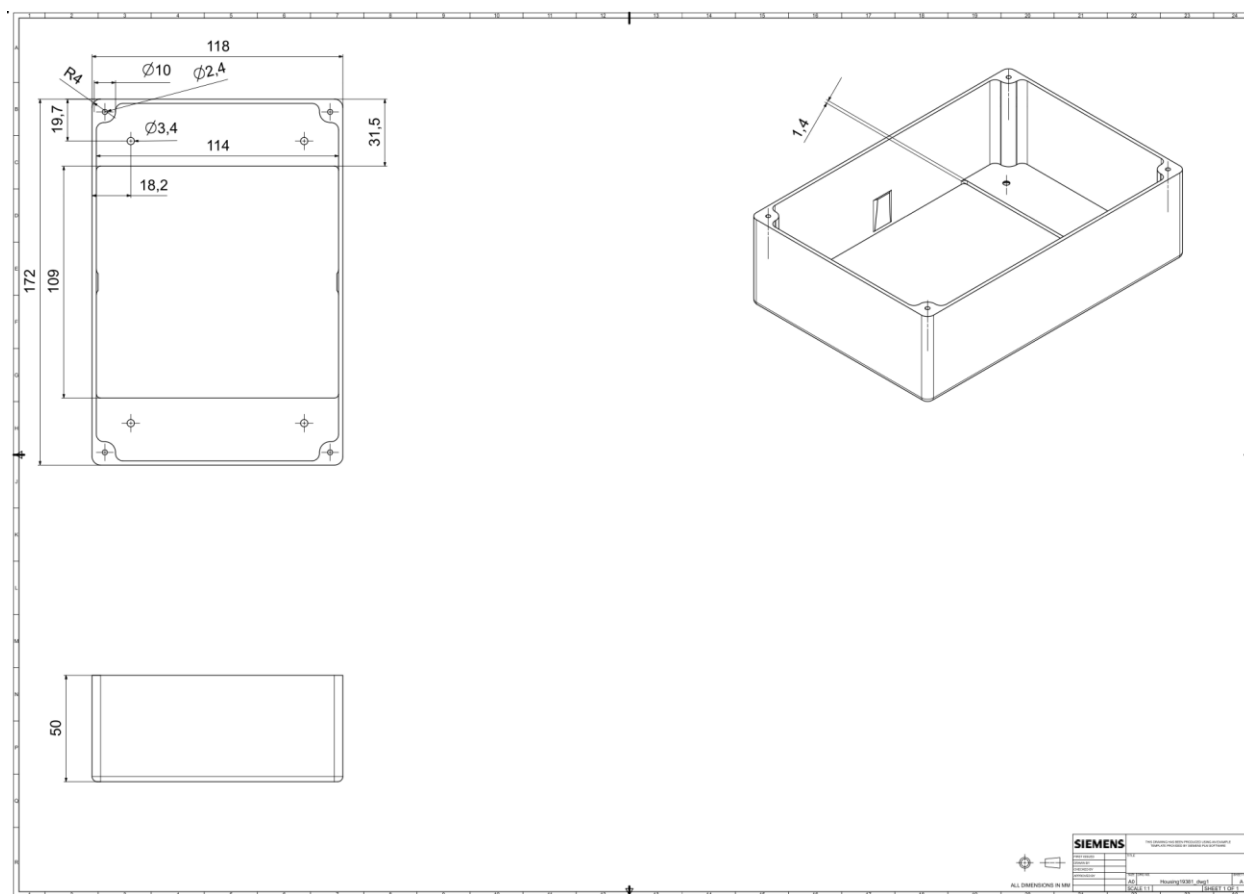


Figure 34: Drawing of Heater Block Subassembly Housing

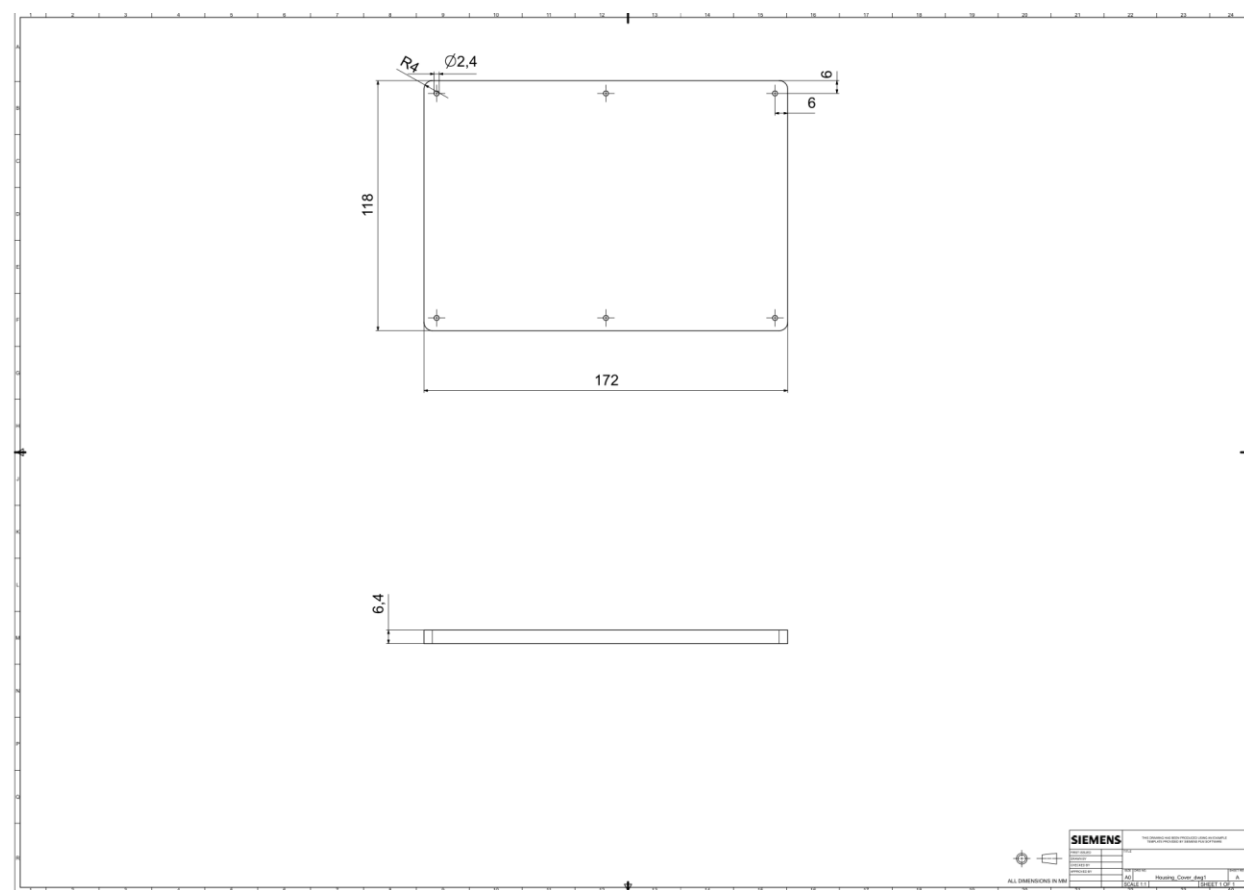


Figure 35: Drawing of Heater Block Subassembly Housing Cover

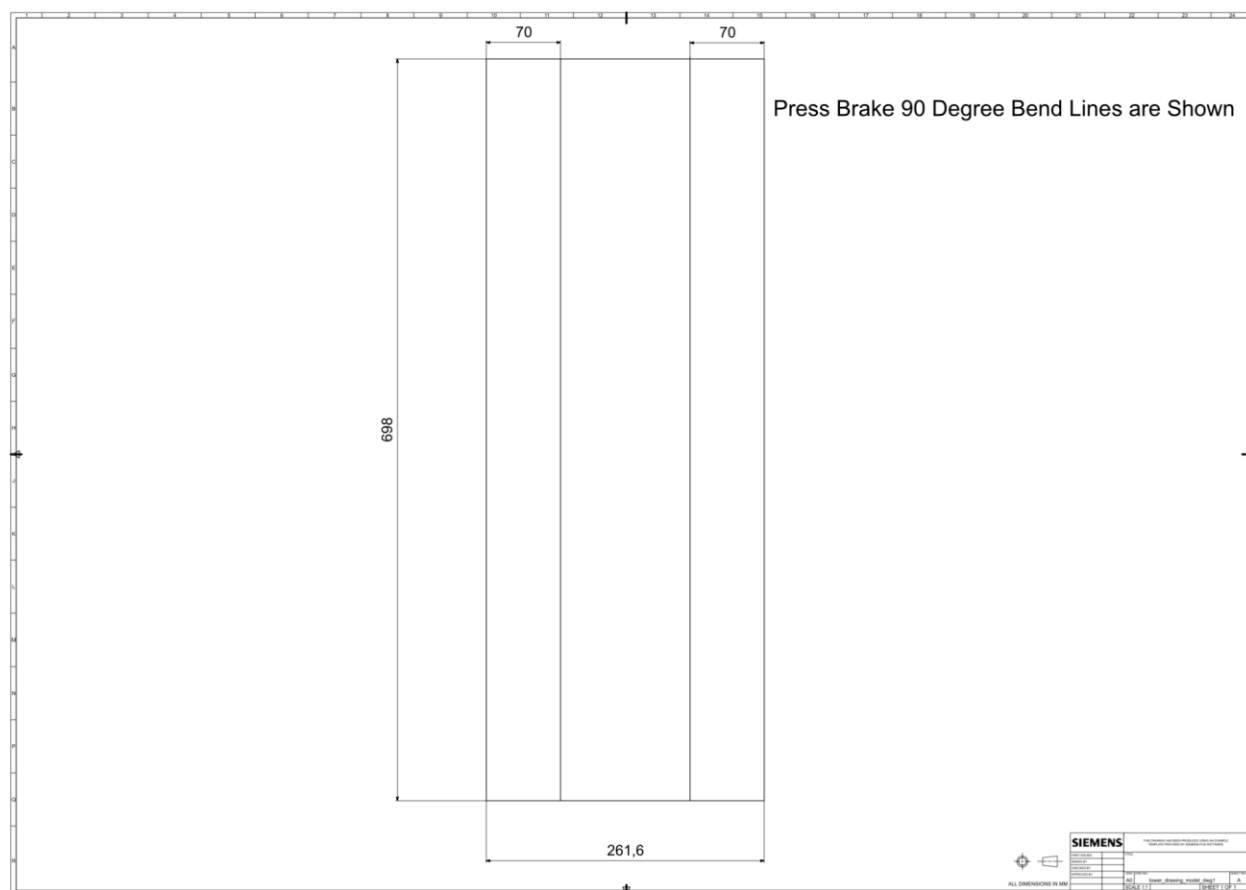


Figure 36: Drawing of Main Enclosure

```

#include "max6675.h" // max6675.h file is part of the library that you should download
from Robojax.com
//#include "Adafruit_GFX.h"
//#include "Adafruit_ILI9341.h"

int soPin1 = 47; // S0=Serial Out
int csPin1 = 49; // CS = chip select CS pin
int sckPin1 = 51; // SCK = Serial Clock pin

int soPin2 = 36; // S0=Serial Out
int csPin2 = 38; // CS = chip select CS pin
int sckPin2 = 40; // SCK = Serial Clock pin

#define TFT_MISO 8
#define TFT_LED 7
#define TFT_SCK 6
#define TFT_MOSI 5
#define TFT_DC 4
#define TFT_RESET 3
#define TFT_CS 2

//Adafruit_ILI9341 tft = Adafruit_ILI9341(TFT_CS, TFT_DC, TFT_MOSI, TFT_SCK,
TFT_RESET, TFT_MISO);

MAX6675 robojax1(sckPin1, csPin1, soPin1); // create instance object of MAX6675
MAX6675 robojax2(sckPin2, csPin2, soPin2); // create instance object of MAX6675

void setup() {

  Serial.begin(9600); // initialize serial monitor with 9600 baud
  Serial.println("Robojax MAX6675");

  //Serial.print("TC1          TC2")

  //pinMode(TFT_LED, OUTPUT);
  //digitalWrite(TFT_LED, HIGH);

  //tft.begin();
  //tft.setRotation(1);
  //tft.fillRect(tft.color565(0,0,255));

}

```

Figure 37: Arduino Code (Click to View All Code)

Enabled Models

- ☒ Steady
- ☒ Solution Interpolation <Not required by other models>
- ☒ Constant Density
- ☒ Gradients
- ☒ Segregated Solid Energy <Not required by other models>
- ☒ Multi-Part Solid
- ☒ Multi-Component Solid
- ☒ Three Dimensional

Figure 38. Conduction Continuum Model Selections

Enabled Models

- ☒ Steady
- ☒ All y+ Wall Treatment
- ☒ Wall Distance
- ☒ SST (Menter) K-Omega
- ☒ K-Omega Turbulence
- ☒ Reynolds-Averaged Navier-Stokes
- ☒ Turbulent
- ☒ Segregated Fluid Temperature <Not required by other models>
- ☒ Constant Density
- ☒ Gradients
- ☒ Segregated Flow
- ☒ Gas
- ☒ Solution Interpolation <Not required by other models>
- ☒ Three Dimensional

Figure 39. Convection Continuum Model Selections



Figure 40. Simulation Regions and Associated Boundaries

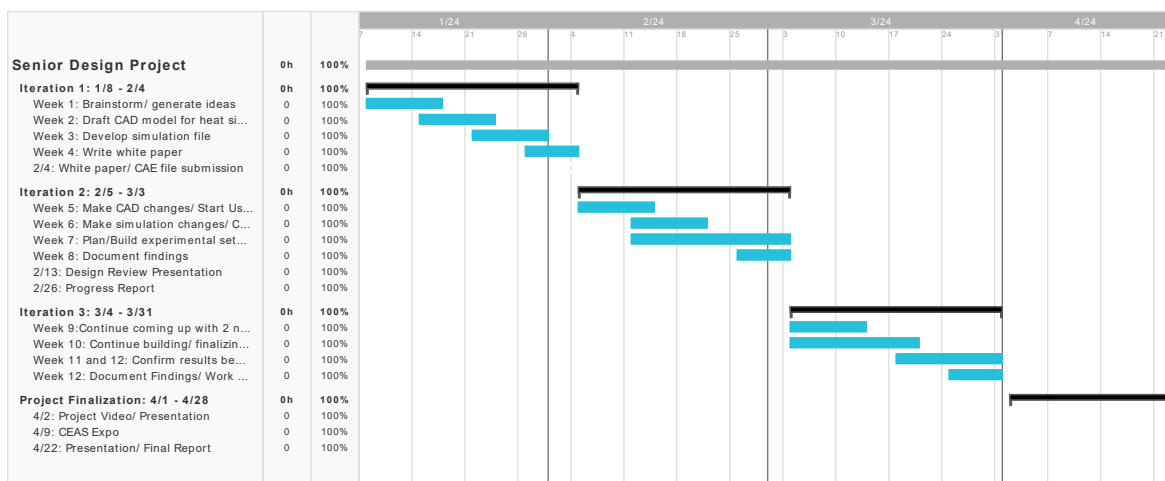


Figure 41. Project Gantt Chart

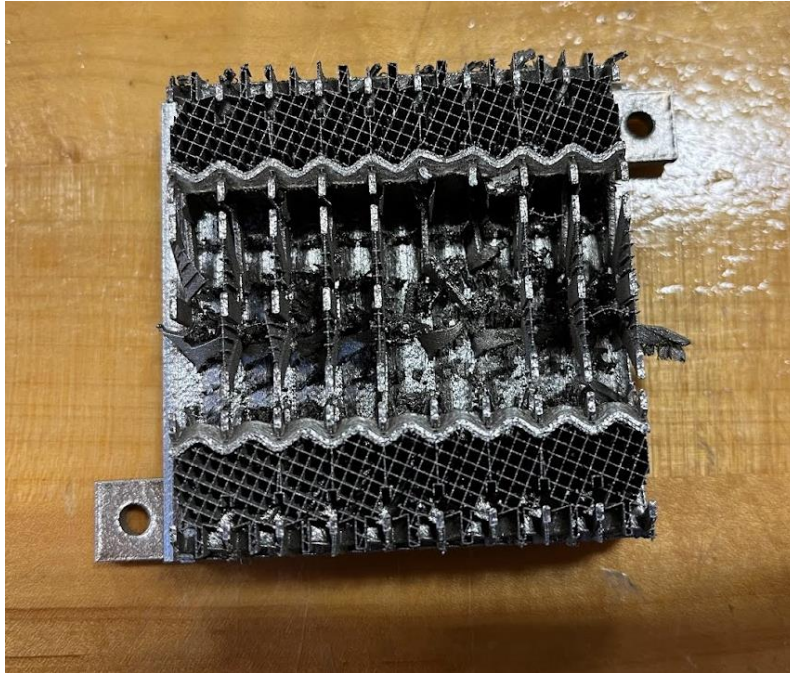


Figure 42. University of Louisville Print Fail - Top View

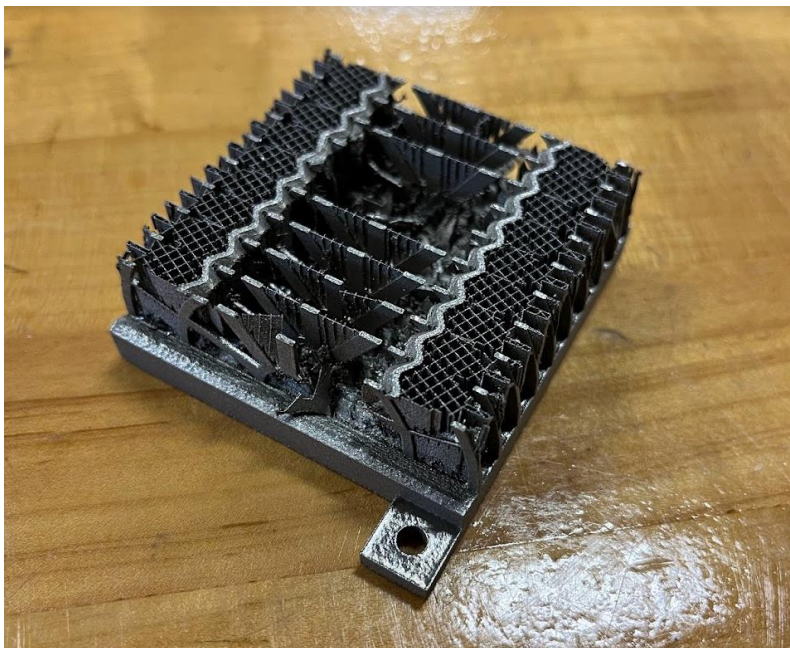


Figure 43. University of Louisville Print Fail - Isometric View



QUOTE Q86-0180-0498

QUOTED ON: 04/21/2024 2:09 AM EDT

SUMMARY OF ORDER: Calculated at checkout

PREPARED FOR

Justin Chen
chen4j@mail.uc.edu

SHIP TO

Calculated at checkout

QUOTE DETAILS

Lead time: 15 business days, order by 12PM EDT
Shipping: Calculated at checkout
Ship date: **Monday, May 13** (when ordering online by 12 PM EDT on Monday, April 22). Order requests emailed to support after 9 PM EDT will be processed the following business day.

ITEM	DESCRIPTION	QTY	UNIT PRICE	EXTENDED PRICE
1	Part Image Part Version 0 Made in USA PO Line Item Reference: Team UC - Print Revision 2.stl Part ID: 0633C7A Measurement: 80.00 mm x 60.00 mm x 44.25 mm 33523.16 mm³ / 3.150 in x 2.362 in x 1.742 in 2.046 in³ Process: 3D Printing Technology: Metal Binder Jetting Material: 316L SS Finish: Zirblast Inspection: Standard Inspection Notes: Talked with phone representative about expediting printing process. Wanted to confirm that model can be printed in the Cincinnati or Lexington locations, and also wanted to discuss the possibility of picking up the part in person.	1	\$602.26	\$602.26

SUBTOTAL	\$602.26
SHIPPING	Calculated at checkout
TAX	Calculated at checkout
TOTAL	Calculated at checkout

[Checkout at Xometry.com](#)

We want to earn your business.

If you get a lower quote, send it to us. We will try to beat it.

Contact:

240-252-1138

support@xometry.com

The Xometry Customer Service Agreement (www.xometry.com/service-agreement), Manufacturing Standards (www.xometry.com/manufacturing-standards), and website Terms of Use (www.xometry.com/terms) are incorporated by reference into this Quote and any order which results from this Quote and shall exclusively apply, notwithstanding any conflicting or additional terms in your purchase order or any other communications with us.

Figure 44. Xometry Instant Quote

Re: I'm your dedicated University of Cincinnati account lead

Ethan Horton <ethan.horton@xometry.com>

Tue 4/2/2024 3:17 PM

To: Chen, Justin (chen4ji) <chen4ji@mail.uc.edu>

External Email: Use Caution

Hey Justin,

Sorry I missed these. Somehow the above messages ended up in my spam folder.

On Mon, Apr 1, 2024 at 8:00 AM Chen, Justin (chen4ji) <chen4ji@mail.uc.edu> wrote:
Following up on last week's emails.

Regards,

Justin Chen

University of Cincinnati
College of Engineering & Applied Science
Mechanical Engineering
Class of 2023
chen4ji@mail.uc.edu
216-978-6346

From: Chen, Justin (chen4ji) <chen4ji@mail.uc.edu>
Sent: Friday, March 29, 2024 12:30 PM
To: Ethan Horton <ethan.horton@xometry.com>
Subject: Re: I'm your dedicated University of Cincinnati account lead

Hi Ethan:

Following up on this message. The printing service we went with was unable to complete our print correctly. Our deadline is being reevaluated, and if the timeline permits, we would be interested in working with Xometry to create our part.

Regards,

Justin Chen

University of Cincinnati
College of Engineering & Applied Science
Mechanical Engineering
Class of 2023

Figure 45a. Xometry Email Chain

chen4ji@mail.uc.edu
216-978-6346

From: Chen, Justin (chen4ji) <chen4ji@mail.uc.edu>
Sent: Monday, March 25, 2024 12:02 PM
To: Ethan Horton <ethan.horton@xometry.com>
Subject: Re: I'm your dedicated University of Cincinnati account lead

Hi Ethan:

Sorry for the late reply. Due to time constraints, we opted to go with a different service provider. However, we are definitely not pleased with the lack of quality, options, and pricing that they were offering. Our hard deadline for our project (printing/ related services, and shipping) would have needed to be 4/2, since we need time to test our model and collect data. At this point, we're highly considering Xometry for future prints, so we would like to know if it was possible to receive the product by the deadline, and if not, when would've been the soonest we could get it after the deadline.

Regards,

Justin

From: Ethan Horton <ethan.horton@xometry.com>
Sent: Wednesday, March 20, 2024 10:30 AM
To: Chen, Justin (chen4ji) <chen4ji@mail.uc.edu>
Subject: Re: I'm your dedicated University of Cincinnati account lead

External Email: Use Caution

Good morning,

Typically with 3D printing the answer would be yes. However, due to the complexity of this part is why you are just seeing the standard option. If you have time, I will send this to the manual quoting team to see if we can get this shortened down. Is Friday your deadline?

On Tue, Mar 19, 2024 at 6:28 PM Chen, Justin (chen4ji) <chen4ji@mail.uc.edu> wrote:
Hi Ethan:

I have a question regarding the lead time. I know the time generated by the instant quote said it would take a few weeks to complete and ship the part, but is there any way such as an expedited process that we can speed up the time to get our part by the end of next week?

Regards,

Figure 24b. Xometry Email Chain

Justin Chen

University of Cincinnati
College of Engineering & Applied Science
Mechanical Engineering
Class of 2023
chen4ji@mail.uc.edu
216-978-6346

From: Ethan from Xometry <ethan.horton@xometry.com>
Sent: Monday, March 18, 2024 8:08 AM
To: Chen, Justin (chen4ji) <chen4ji@mail.uc.edu>
Subject: I'm your dedicated University of Cincinnati account lead

External Email: Use Caution

Hi there,

Thanks for quoting with Xometry. I'm Ethan Horton, the dedicated account leader for University of Cincinnati. My job is to help your project succeed by getting the most out of everything Xometry has to offer. We've been doing a lot of production work recently, so I'd be excited to learn more about what you are making! I can help you with all of [Xometry's processes](#) - CNC machining, injection molding, 3D printing, laser cutting, die casting, assembly, and much more.

If you have any questions, please reach out to me here any time. If you have any other project files, requirements, BOMs, etc. that you would like us to take a look at, just send those my way.

This e-mail's really from me and I love hearing from customers, so I will respond quickly.

Thanks,

Ethan

Figure 24c. Xometry Email Chain

Chen, Justin (chen4ji)
To: Ethan Horton <ethan.horton@xometry.com>


Mon 4/1/2024 7:59 AM

Following up on last week's emails.

Regards,

Justin Chen
University of Cincinnati
College of Engineering & Applied Science
Mechanical Engineering
Class of 2023
chen4ji@mail.uc.edu
216-978-6346

...

Chen, Justin (chen4ji)
To: Ethan Horton <ethan.horton@xometry.com>


Fri 3/29/2024 12:30 PM

Hi Ethan:

Following up on this message. The printing service we went with was unable to complete our print correctly. Our deadline is being reevaluated, and if the timeline permits, we would be interested in working with Xometry to create our part.

Regards,

Justin Chen
University of Cincinnati
College of Engineering & Applied Science
Mechanical Engineering
Class of 2023
chen4ji@mail.uc.edu
216-978-6346

...

Figure 24d. Xometry Email Chain Follow Ups

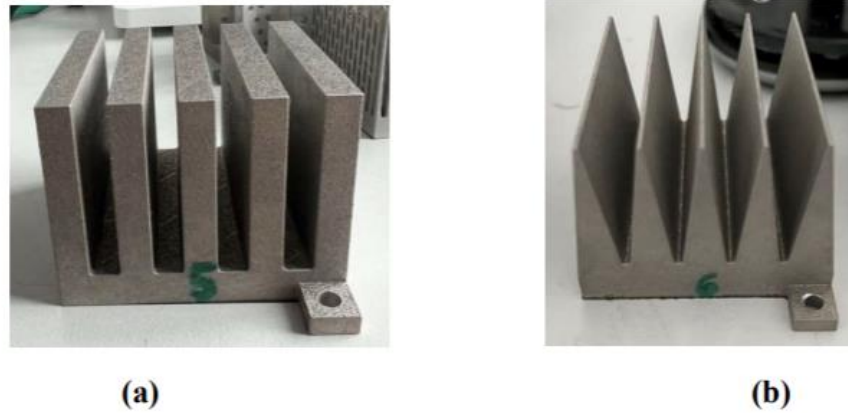
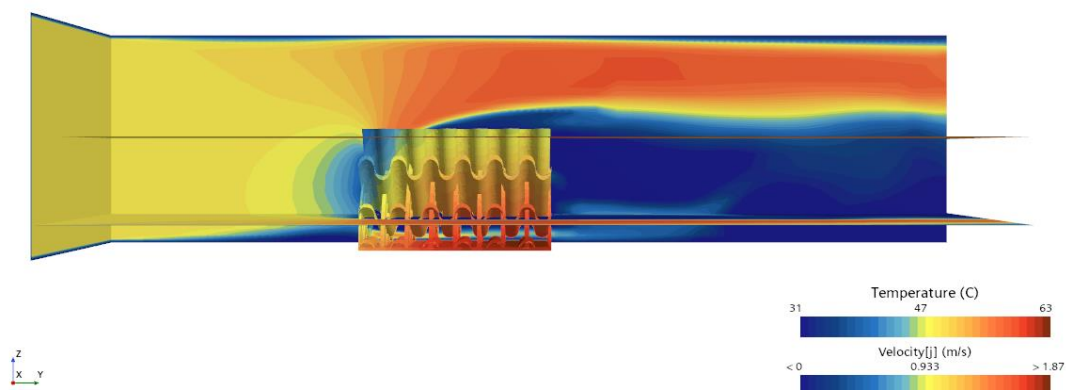


Figure 6: Reference heat sink geometries with fins of (a) constant thickness and (b) tapered thickness.

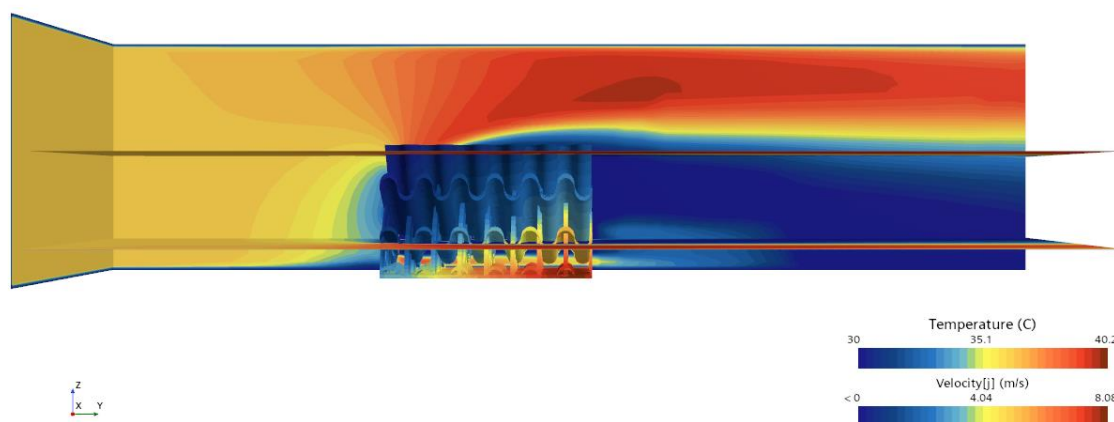
	Constant thickness		Tapered thickness	
Mass	0.2868 kg		0.2706 kg	
Velocity	1.0 m/s	5.0 m/s	1.0 m/s	5.0 m/s
Power	18.20 W	18.27 W	17.50 W	17.9 W
T_{amb}	31.1 °C	27.4 °C	30.9 °C	27.6 °C
T_{base}	53.4 °C	39.3 °C	55.2 °C	40.7 °C
R	1.23 K/W	0.65 K/W	1.39 K/W	0.73 K/W
FOM	0.03097		0.02905	

Figure 46. Guideline Provided Reference Baseline Results

Simcenter STAR-CCM+

*Figure 47. White Paper Contour Plot for 1 m/s*

Simcenter STAR-CCM+

*Figure 48. White Paper Contour Plot for 5 m/s*

Simcenter STAR-CCM+

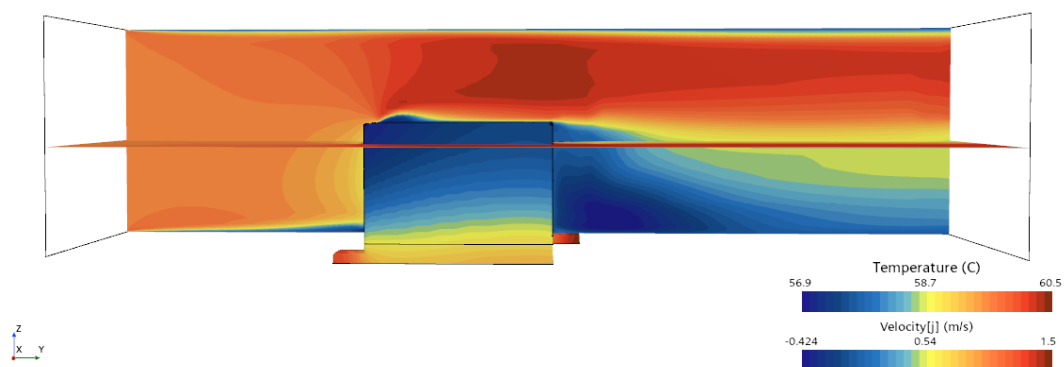


Figure 49. Straight Fin Aluminum Reference Model for 1 m/s

Simcenter STAR-CCM+

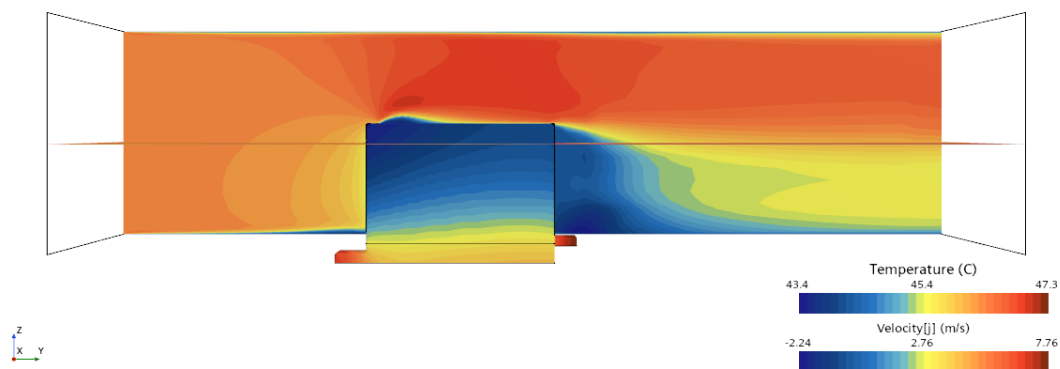


Figure 50. Straight Fin Aluminum Reference Model for 5 m/s

Simcenter STAR-CCM+

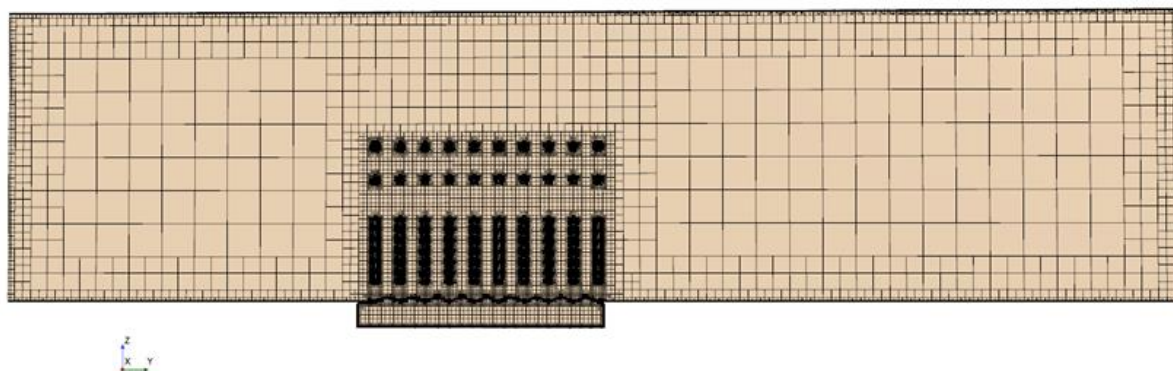


Figure 51. Final Submission Mesh Scene - Cross Section View

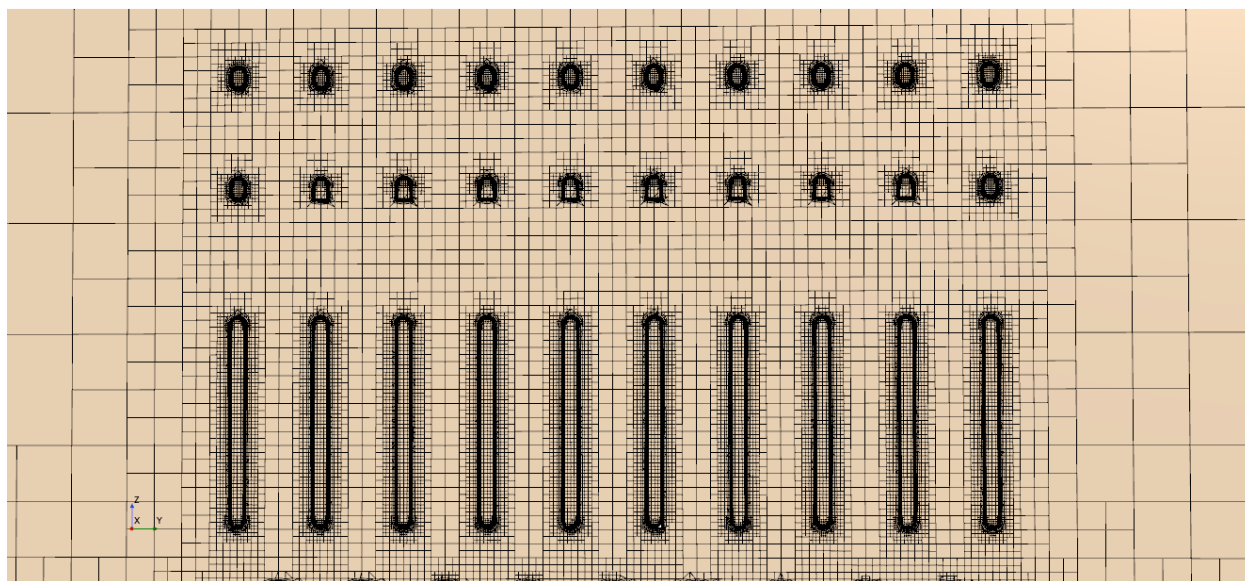


Figure 52. Final Submission Mesh Scene - Expanded Cross Section View

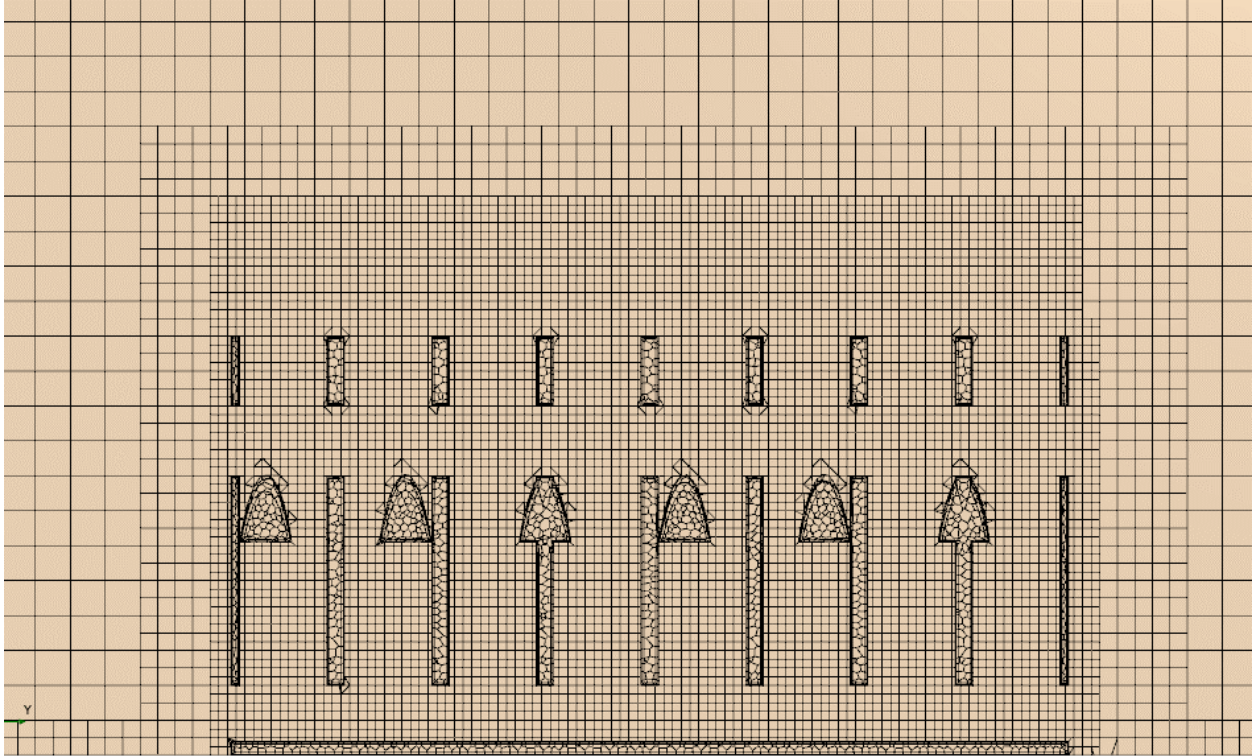


Figure 53. Initial Submission Mesh Scene – Cross Section View

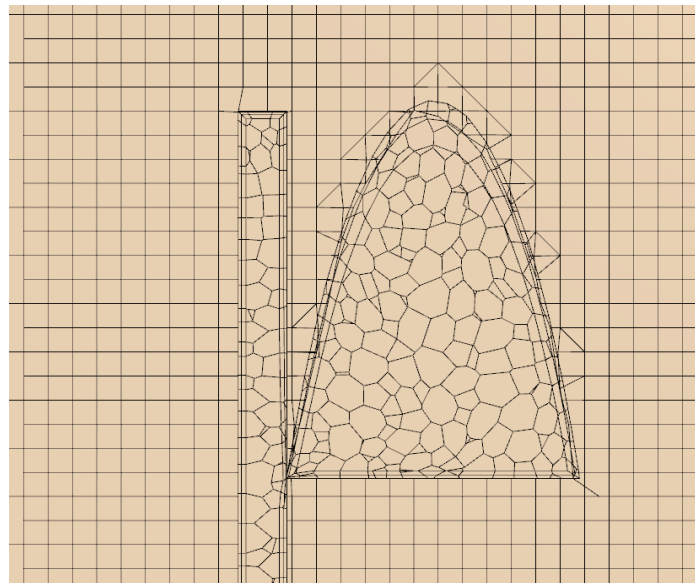


Figure 54. Initial Submission Mesh Scene - Expanded Cross Section View

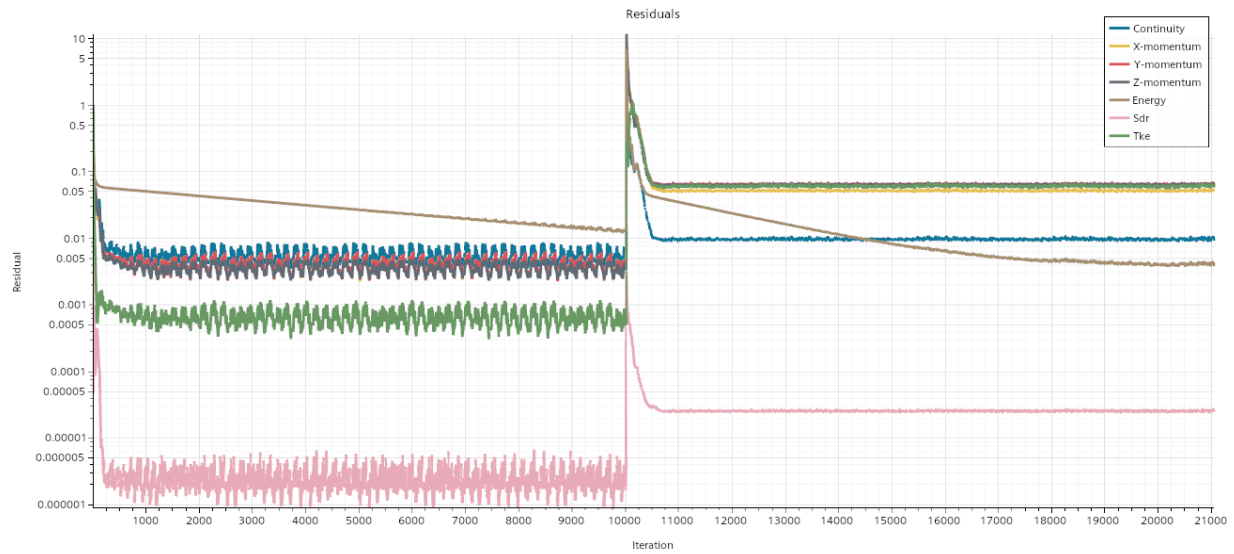


Figure 55. Straight Fin Reference Model Simulation Residual Plot

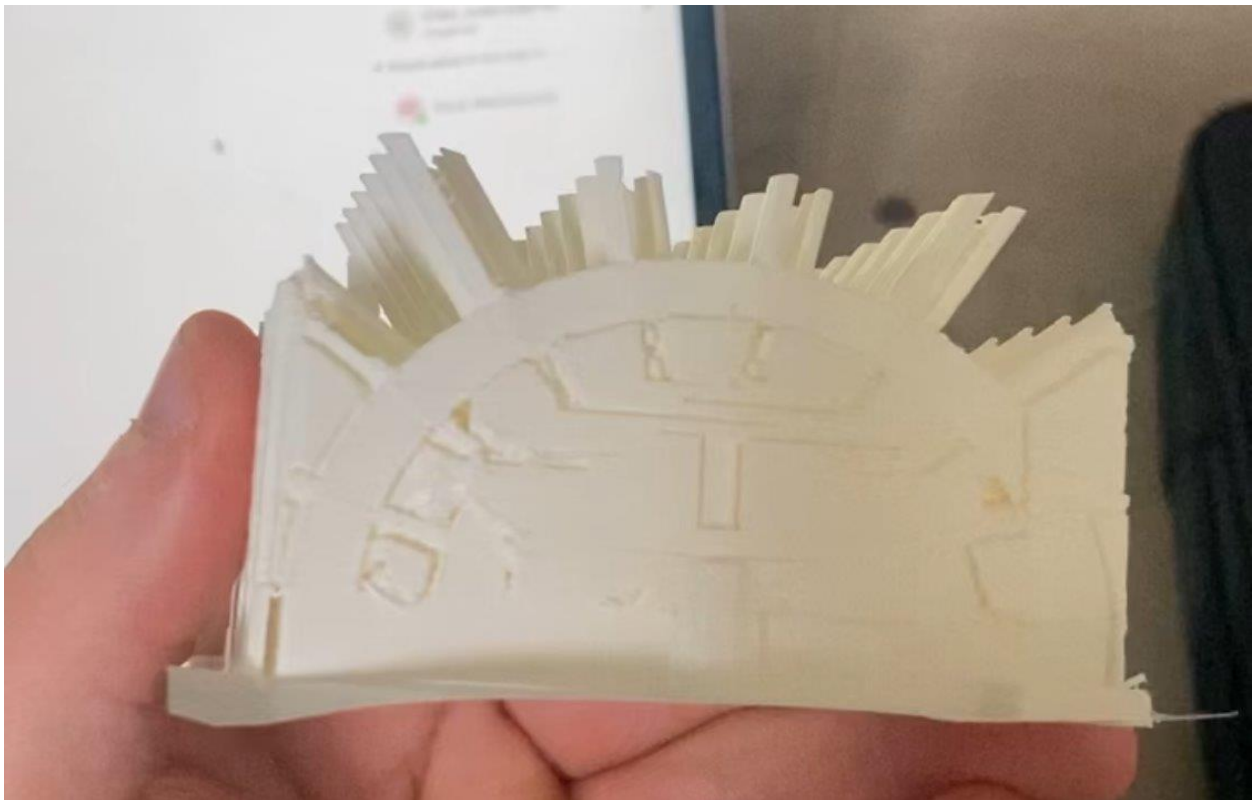


Figure 56: Example of Excessive Support in PLA 3D-Printed Heat Sinks

Time Labor Log

Name	Date	Hours Worked	Description of Work
Justin Chen	1/8/2024	1	Reviewed documents, updated white paper
Justin Chen	1/8/2024	1.5	Contacted grad students and Dr. Jog detailing 4 week plan, created polls for Dr. Huston meeting time, uploaded Dr. Jog's papers
Justin Chen	1/10/2024	1.5	Read Dr. Jog's papers, caught up on other 3d printed heat sink design competitions/ designs, looked into Starccm+ topology optimization
Amelia Bernard	1/10/2024	1.5	Reviewed documents, Read Dr. Jog's papers
Amelia Bernard	1/11/2024	1	Reviewed Strataysys White paper
Owen Koch	1/12/2024	1.5	Reviewed documents, Read Dr. Jog's papers
Justin Chen	1/13/2024	0.5	Weekly Meeting 1
Amelia Bernard	1/13/2024	0.5	Weekly Meeting 1
Nick Tucci	1/13/2024	0.5	Weekly Meeting 1
Owen Koch	1/13/2024	0.5	Weekly Meeting 1
Justin Chen	1/16/2024	0.25	Meeting with Dr. Huston
Amelia Bernard	1/16/2024	0.25	Meeting with Dr. Huston
Owen Koch	1/16/2024	0.25	Meeting with Dr. Huston
Nick Tucci	1/16/2024	0.25	Meeting with Dr. Huston
Justin Chen	1/20/2024	2	Reviewed competition outline, reviewed forced convection concepts regarding laminar/ turbulent flow, started design
Justin Chen	1/20/2024	2	Drew mock up design in NX, looked into other heat sink design concepts
Justin Chen	1/20/2024	1	Weekly Meeting 2
Amelia Bernard	1/20/2024	1	Weekly Meeting 2
Owen Koch	1/20/2024	1	Weekly Meeting 2
Nick Tucci	1/20/2024	1	Weekly Meeting 2
Amelia Bernard	1/21/2024	1	Obtaining Ntopology
Justin Chen	1/22/2024	1	Reviewed Strataysys White paper in depth, joined group 33 for Expo signup, applied for 4 licenses using Ntop link
Justin Chen	1/22/2024	4	Group meeting, meeting with Dr. Jog, worked on Starccm simulation file
Amelia Bernard	1/22/2024	2.5	Group meeting, meeting with Dr. Jog
Owen Koch	1/22/2024	2.5	Group meeting, meeting with Dr. Jog
Nick Tucci	1/22/2024	2.5	Group meeting, meeting with Dr. Jog
Justin Chen	1/23/2024	4	Met with Satya, worked on Starccm simulation file
Amelia Bernard	1/23/2024	3	Met with Justin, worked on Ntop
Justin Chen	1/24/2024	1.5	Worked on Gantt chart, started filling out expo registration form

Justin Chen	1/24/2024	1.5	Met with Satya, went over Boundary conditions/ simulation set up based on Reynolds number
Justin Chen	1/25/2024	1.5	Downloaded starccm and nx for better performance, worked on simulation file
Justin Chen	1/26/2024	1.5	Continued working on simulation file, submitted expo group registration assignment on canvas
Justin Chen	1/26/2024	1.25	Met with Satya and Shubham, went over fluid heat transfer portion of simulation, confirmed fidelity of conduction portion of heat transfer
Owen Koch	1/26/2024	3	Met with Nick to work on Heat Sink Design
Nick Tucci	1/26/2024	3	Met with Owen to work on Heat Sink Design
Amelia Bernard	1/27/2024	2	NTop work and Review
Justin Chen	1/28/2024	7	Reworked design, setup laminar flow file, met with Satya and Shubham regarding settings/ mesh
Justin Chen	1/29/2024	2	Initialized laminar flow file with results from file from Satya, shortened Subtract outlet, separating HS outline from wall region
Justin Chen	1/29/2024	4	Group meeting, meeting with Dr. Jog, meeting with Satya afterwards, need to change cross section of RE1 file and reimport table
Nick Tucci	1/29/2024	3	Meeting with group and Dr. Jog
Justin Chen	1/30/2024	5	Changed mass flow rate for interface, imported new table, attempted to get velocity profile, shortened inlet
Owen Koch	1/30/2024	2.5	Group meeting, meeting with Dr. Jog
Justin Chen	1/30/2024	3	Having trouble getting velocity profile, called Satya, created initialization table
Owen Koch	1/31/2024	2	Created CAD models of provided heat sink designs
Justin Chen	1/31/2024	2	Call with Satya and Shubham, verified velocity profile table
Justin Chen	2/2/2024	2	Created turbulent setup, RE1 turbulent initialization file/ table, laminar straight fin setup
Justin Chen	2/3/2024	4	Continued yesterday's work, mesh taking pretty long to generate
Amelia Bernard	2/3/2024	3	Research on Advantages of Additive
Justin Chen	2/4/2024	16	Attempted to get mesh fixed to no avail, tried conformal meshing to no avail, changed mesh size to get results faster, worked on description and analysis sections. Tried creating line probe (not showing?), ended up using monitor at point to get temperature read out. Need to figure out how to get heat transfer total at base, is assuming 18W input ok?
Amelia Bernard	2/4/2024	3	White Paper writing
Owen Koch	2/4/2024	6	Wrote design description portion of whitepaper

Nick Tucci	2/4/2024	6	Wrote design description portion of whitepaper with Owen
Justin Chen	2/5/2024	3	Recapped report, went over things to change, designated building tasks to Nick/ Owen, met with Dr. Jog to go over results
Amelia Bernard	2/5/2024	3	Met with group
Nick Tucci	2/5/2024	3	Meeting with group and Dr. Jog
Owen Koch	2/8/2024	4	Began test setup design
Justin Chen	2/12/2024	3	Group meeting, meeting with Dr Jog, started midterm presentation
Nick Tucci	2/12/2024	3	Group meeting, meeting with Dr. Jog, started midterm presentation
Amelia Bernard	2/12/2024	3.5	Group meeting, meeting with Dr Jog, started midterm presentation
Owen Koch	2/12/2024	4	Group meeting, meeting with Dr Jog, started midterm presentation
Nick Tucci	2/12/2024	1	Midterm slides
Owen Koch	2/13/2024	2	Worked on presentation and test setup BOM
Justin Chen	2/13/2024	3	Group meeting, worked on slides for midterm presentation, talked about assignments afterwards
Nick Tucci	2/13/2024	2	Midterm slides, presentation, meeting afterwards
Amelia Bernard	2/13/2024	3	Group meeting, worked on slides for midterm presentation, talked about assignments afterwards
Justin Chen	2/14/2024	1	Met with Satya, discussed submission outcomes, determined simulation was good, talked about next steps for simulation
Owen Koch	2/17/2024	2	Test Setup Design Planning
Owen Koch	2/18/2024	4	Test Setup Design and BOM
Amelia Bernard	2/18/2024	1	Ntop Simulation Work
Nick Tucci	2/19/2024	4	Worked on BOM, finding parts
Owen Koch	2/19/2024	2	Group Meeting
Justin Chen	2/19/2024	3	Group meeting, talked about Test Setup Design
Nick Tucci	2/19/2024	3	Group meeting
Amelia Bernard	2/19/2024	3	Group Meeting, Ntop Simulation Work
Justin Chen	2/20/2024	1	Started writing assigned parts for progress report
Amelia Bernard	2/20/2024	1.5	Started writing assigned parts for progress report
Owen Koch	2/21/2024	2	Engineering codes and standards of progress report, test setup BOM
Justin Chen	2/22/2024	1	Continued working on progress report (description of methodology, schedule, conclusion)
Amelia Bernard	2/23/2024	2	Writing portion of project report
Owen Koch	2/24/2024	2.5	Project Description section of progress report and formatting
Owen Koch	2/25/2024	2	Test setup BOM

Justin Chen	2/26/2024	5	Group meeting, met with Dr. Jog about PO, finished/ reviewed progress report
Amelia Bernard	2/26/2024	5	Group meeting, met with Dr. Jog about PO, finished/ reviewed progress report
Owen Koch	2/26/2024	5	Group meeting, met with Dr. Jog about PO, finished/ reviewed progress report
Owen Koch	2/29/2024	2	3D Modeled Fan to Enclosure Ducting
Owen Koch	3/1/2024	0.5	1819 Tour/Orientation
Nick Tucci	3/1/2024	0.5	1819 Tour/Orientation
Justin Chen	3/4/2024	3	Group meeting, worked on NTop simulation
Amelia Bernard	3/4/2024	3	Group meeting, worked on NTop simulation
Amelia Bernard	3/6/2024	1.5	Worked on Ntop
Justin Chen	3/7/2024	1.5	Gave dimensions to Dr. Jog for heat sink printing quote
Owen Koch	3/11/2024	1.5	GE meeting
Justin Chen	3/12/2024	2.5	GE printing revision call, met to discuss actions afterwards
Amelia Bernard	3/12/2024	2.5	GE printing revision call, met to discuss actions afterwards
Justin Chen	3/15/2024	6.5	Revised/ submitted new model, replied to Dr. Jog's emails about quotes
Owen Koch	3/15/2024	1	Purchased insulation and enclosure sheet metal from Home Depot
Owen Koch	3/18/2024	1	Team meeting, meeting with Dr. Jog
Nick Tucci	3/18/2024	1	Weekly meeting with team and Dr. Jog
Owen Koch	3/19/2024	3	Project consultation at 1819 makerspace, purchased iKEA table,
Nick Tucci	3/19/2024	3	Project consultation at 1819 makerspace, purchased iKEA table,
Owen Koch	3/20/2024	5	Discussed heat sink quote with Justin from UK + report out, Wiring thermocouples+display to arduino, programming
Nick Tucci	3/20/2024	1	Discussed heat sink quote with Justin from UK
Owen Koch	3/23/2024	4	Finished test setup assembly and finalized ducting designed. Ordered 3d prints of subassembly enclosure, ducting, subassembly enclosure cover, and POM spacer bracket at makerspace
Justin Chen	3/25/2024	6	Finished 2nd set of revisions for competition, added edge blends to everything, changed radial support thickness to 1 mm, added outer vertical support as shown in ppt, and checked scalability of model using scale feature in NX
Justin Chen	3/25/2024	2.25	Weekly meeting with Dr. Jog, group meeting, working on temperature measurement using Arduino

Owen Koch	3/25/2024	2.25	Weekly meeting with Dr. Jog, group meeting, working on enclosure build
Amelia Bernard	3/25/2024	2	Weekly meeting with Dr. Jog, group meeting
Nick Tucci	3/25/2024	3	Worked on test set-up and drawings in NX for machining
Nick Tucci	3/26/2024	5	Group meeting, met with Dr. Jog about PO, finished/ reviewed progress report
Justin Chen	3/26/2024	5	Watched videos regarding wiring thermocouples to Arduino, got accurate readings for thermocouples. Also configured arduino for screen
Owen Koch	3/26/2024	5.5	Met with Ron Hudepohl to build enclosure, created and submitted drawing of heater block for build, ordered necessary wiring and hardware components
Justin Chen	3/26/2024	3	Meeting with Owen/ Nick, picked up Arduino kit, went over machining processes
Nick Tucci	3/26/2024	2	Weekly meeting, went over machining processes
Justin Chen	3/27/2024	4	Attempted to diagnose screen issue, found that driver was most likely at fault (not an ILI9341 device, most likely ILI9841 device; see Amazon reviews)
Owen Koch	3/27/2024	0.5	Picked up 3d printed parts for test setup from 1819 makerspace
Owen Koch	3/28/2024	1	Waterjet cutting consultation (for test setup honeycomb flow straightener) at makerspace
Nick Tucci	3/28/2024	1	Waterjet cutting consultation (for test setup honeycomb flow straightener) at makerspace
Justin Chen	3/30/2024	1	Research posterboard setup ideas, started template for posterboard
Nick Tucci	3/30/2024	10	Building test set-up with Owen
Owen Koch	3/30/2024	10	Building test set-up with Nick
Justin Chen	3/31/2024	1	Worked on posterboard
Nick Tucci	3/31/2024	10	Building test set-up with Owen
Owen Koch	3/31/2024	10	Building test set-up with Nick
Justin Chen	4/1/2024	3	Continued working on posterboard, focusing on abstract and project description
Justin Chen	4/1/2024	5	Weekly meeting with Dr. Jog, group meeting, looked into anenometer issue and heat pad thermocouple placement issue
Owen Koch	4/1/2024	5	Weekly meeting with Dr. Jog, group meeting, looked into anenometer issue and heat pad thermocouple placement issue
Justin Chen	4/2/2024	10	Worked on and finished expo video, installed heater block after tapping new hole for thermocouple in the center, attempting to configure power supply
Amelia Bernard	4/2/2024	10	Worked on and finished expo video, installed heater block after tapping new hole for thermocouple in the center, attempting to configure power supply

Owen Koch	4/2/2024	8	Worked on expo video, installed heater block after tapping new hole for thermocouple in the center, attempting to configure power supply
Justin Chen	4/3/2024	7	Finished and submitted posterboard, planned worked for immediate future regarding collecting experimental data with plastic models and physical test setup
Amelia Bernard	4/3/2024	10	Started Attempt to 3D print heat sinks
Owen Koch	4/3/2024	7	Finished and submitted posterboard, planned worked for immediate future regarding collecting experimental data with plastic models and physical test setup
Amelia Bernard	4/4/2024	12	Attempted to 3D print heat sinks (printer broke)
Amelia Bernard	4/6/2024	10	Repairing 3D printer
Amelia Bernard	4/7/2024	8	3D printing reference heat sink
Amelia Bernard	4/8/2024	2	Finished 3D print, tried other material that failed
Justin Chen	4/8/2024	7	Completed simulations for straight fin model at 1 m/s and 5 m/s
Justin Chen	4/8/2024	5	Refamiliarized with Starccm, looked into use of k-omega solver as compared to k-epsilon solver (used previously), looked into use of wake refinement (opted to not use as not interested in studying wake for purpose of competition, instead went with changing prism layer number and total thickness)
Justin Chen	4/9/2024	4	Set up mesh, continua, regions, and scenes for Revision 2. Need to remesh for negative volume cells
Justin Chen	4/9/2024	6	CEAS Expo
Owen Koch	4/9/2024	7	CEAS Expo
Owen Koch	4/11/2024	4	Modeled lattice heat sink alternative
Justin Chen	4/11/2024	4	Assisted Nick and Owen with modeling lattice design/revolve and extrude designs
Justin Chen	4/12/2024	2	Went over lattice design with Owen, discovered use of sheet bodies, tasked Owen with remedying issue. Lattice model is now without sheet bodies, made request to increase amplitude of arches. Started and finished nTop 101 course, started 102 course for meshing. Attempting to use nTop meshing procedure to create meshes to reimport back into Starccm
Owen Koch	4/12/2024	4.5	Created new lattice design with solid bodies and improved horizontal arch pattern, re-installed test setup, fixed* thermocouple and heater pad wiring
Justin Chen	4/13/2024	3	Diagnosed thermocouple and arduino issues with physical test setup, finished 102 meshing course on NTop, attempted to mesh Revision 2. Running into intersecting mesh errors. Split work for final presentation

Owen Koch	4/13/2024	4	Increased amplitude of horizontal fins in lattice design, aided Justin in diagnosing thermocouple issues, collected experimental results
Owen Koch	4/14/2024	4	Made significant changes to final presentation powerpoint, collected experimental results again (11 hours, checking intermittently)
Justin Chen	4/14/2024	5	Completed designated sections for slides, reattempted to mesh in NTop to no avail, continued looking for resources to solve negative volume mesh issues
Owen Koch	4/17/2024	5	Did not complete, but wrote large swaths of introduction and test setup sections in the final report. Also submitted new models for printing at makerspace so their experimental FOM's can be compared to reference models and our competition design.
Justin Chen	4/20/2024	4	Wrote Engineering Standards and Codes, Time Schedule, and Comparison to Exist Work sections for Final Report
Justin Chen	4/21/2024	5.5	Continued and finished Time Schedule deviation sections, started Summary and Conclusions section, redid calculations for 3W power input, wrote sample calculations and discussion for white paper results. Will continue with Straight Fin model later today
Justin Chen	4/22/2024	1.5	Finished running simulations for 1 and 5 m/s straight fin and put results in final report, finished simulation portion of results section
Justin Chen	4/23/2024	1	Finished writing simulation constraints in final report
Owen Koch	4/18/2024	5	Created drawings and assembly explosions of every non-electrical component in the test setup. Added them to the final report and created numerous cross references throughout the document
Owen Koch	4/20/2024	3	Collected new experimental data for straight fin and white paper submission designs. Finalized majority of test setup section in white paper.
Owen Koch	4/23/2024	4	Wrote executive summary section, wrote half of conclusion, added experimentally determined data and FOM calculations to results section. Fixed cross referencing errors.

Total Hours

Justin Chen		Amelia Bernard		Nick Tucci		Owen Koch
199.75		101.75		68.75		156.5

Weekly To Do List (2/19 – 4/1)

Week Starting	Justin	Owen	Nick	Amelia
19-Feb	Come up with 1 new heat sink design. Continue working on starccm simulations (straight fin, tapered fin, see notes) Work on progress report sections (gant chart)	Progress report, 1819 orientation, PO, 1 new heat sink design	Progress Report, 1819 orientation, PO, 1 new heat sink design	Progress Report, Look into Victory Parkway 3D-Printer Feasibility (Talk to Dr. Jog), Continue working on NTop simulation, Come up with 1 new heat sink design
26-Feb	Using starccm, mesh gyrodial model/ run simulation. Look into NTop file for correcting contour plot	Orientation on Friday, look into 1819 classes. Submit amazon PO, start building table/ design ducting	Orientation on Friday, look into 1819 classes. Submit amazon PO, start building table/ design ducting	Research potential metal 3D printing companies to get heat sinks printed at (binder jet). NTop simulation, help Nick/ Owen with 3D printing set up parts
4-Mar	Run simulation of gyroidal model, Look into NTop file for correcting contour plot, come up with several other designs, edit competition design according to GE requirements	Schedule general project consultation, CNC Wood Routing consultation (table), make overall assembly, pick up PO materials, get started building enclosure if possible	3D Model Table, Get correct 3D model of fan, make overall assembly, Pick up PO materials, get started building enclosure if possible	3D Print Ducting, Request quote for heat sink designs (3) print
11-Mar	GE seminar, revise model for printing optimization	Arduino Code, Purchase insulation, purchase enclosure sheet metal (wasn't delivered in initial PO)	Arduino Code, Project Consultation, 3D print POM bracket, 3D print fan->enclosure ducting, form enclosure + subassembly, mill heater block	GE seminar, revise model for printing optimization

18-Mar	Start planning for trifold, simulation (improved model, baseline models, gyrodial, develop new model)	Arduino Code, Project Consultation, 3D print POM bracket, 3D print fan-->enclosure ducting, form enclosure + subassembly, mill heater block	Arduino Code, Project Consultation, 3D print POM bracket, 3D print fan-->enclosure ducting, form enclosure + subassembly, mill heater block	Printing all models in pla, NTop Trifold
25-Mar	Posterboard, video, continue working on simulations	Build test setup (Table, heater block subassembly, enclosure+cover and brackets for honeycomb, anemometer, and thermocouples)	Build test setup (Table, heater block subassembly, enclosure+cover and brackets for honeycomb, anemometer, and thermocouples)	Printing all models in pla, NTop Trifold
1-Apr	Posterboard, video, continue working on simulations	Finish building test setup, connect heating pad to DC power supply, record first measurements	Finish building test setup, connect heating pad to DC power supply, record first measurements	NX additive manufacturing model checks, printing all models in PLA for expo, posterboard