Midterm I Report

Team 13

Designing & Testing a Lightweight Heatsink for PV Converter

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ABSTRACT

Three major designs are being considered; an in-line pin fin, a staggered pin fin, and a straight fin heatsink. These designs are weighted and the design that shows the most promising results is selected for testing. Team 13 continues efforts for testing the heatsink with an emulated heat source. A clearer idea for an emulated heat source includes resistors connected to a copper plate with thermal grease and mounted with screws to the heatsink. The heatsink that is currently under testing is the staggered pin fin heatsink. If results are promising, this will be selected as an optimized design for the project. The majority of the background research has been completed and now simulation and testing has begun.

ACKNOWLEDGMENTS

Team 13 would like to express gratitude to Dr. Li for the opportunity to work on the Designing and Testing of Heatsinks for PV Converter. As well as for providing assistance through her graduate students and laboratory space to conduct project proceedings. Team 13 would also like to thank the graduate students, specifically to Thierry Kayiranga for providing feedback and support on this project.

Thank you to the FAMU-FSU College of Engineering, Mechanical Engineering Department, and Electrical Engineering Department for providing the knowledge needed to participate in the Senior Design.

Lastly, Team 13 gives thanks to Dr. Gupta and Dr. Hooker for coordinating the team configuration and providing the guidelines needed for a successful semester ahead.

1. Introduction

This project will focus on creating a lightweight heatsink that is cost effective in order to improve the power density and make future power electronic converters more efficient. The designing and initial manufacturing of this project will be completed by December 2016. The reason for the time-critical nature of this prototype is because of a conference occurring in early 2017 at North Carolina State University, where the prototype will be shared. After the conference, optimization of the prototype will take place from January to April 2017. These results will be achieved by combining the efforts of both electrical and mechanical senior engineering students.

Weekly team meetings on Tuesdays at 2:00pm have been established to help the team move through the planning process, and bi-weekly meetings with the sponsor have begun. The team has established a Google Drive folder for file sharing and will begin working in the lab soon. Project 13 is being sponsored by The Center of Advanced Power Systems (CAPS) under Dr. Hui “Helen” Li. As this project is directly related to the research of a current Ph.D. candidate, multiple graduate students working under Dr. Li will be available for questions regarding the nature of this project. Along with providing expertise and advice, the graduate students will assist with materials needed for the testing and prototyping of this project.

The design and manufacturing plan for the lightweight PV converter and thermal testing will be broken up into four stages in order to achieve the best results possible. Stage one will include all background research into power switches, power converters, switching loss calculations, heatsink configurations, materials, air flow, etc. Stage two will include separate but simultaneous efforts between the electrical engineering students and the mechanical engineering students to begin the simulation process of the project. The electrical engineering students will begin power loss calculations in order to provide these results to the mechanical engineering students who will be designing and configuring the smaller, lightweight heatsink. Stage three will include prototyping the heatsink to meet the specifications determined by stage two along with testing the prototype. The fourth stage will include implementing the final design.

2. Project Definition

The following subsections will address the needs of the customer for the design and any constraints or concerns that will need to be considered when planning and designing. These constraints will include any physical parameters that must be achieved in order to meet requirements set by the customer. Research on power loss calculation and on the design and optimization of heatsinks is summarized to better understand the challenges that have been overcome in the power engineering field and to further develop ideas for this project.

2.1 Problem Statement

In current research and development of power converters, the total weight of the system is a concern due to large, heavy heatsinks. Team 13 will be required to redesign the heatsink component of a PV converter so that the system weight is reduced and the power density is increased. To test the heatsink, an emulated heat source will be created.

2.2 Background Research

2.2.1 Power Loss Calculations

Switching losses in power MOSFETs are the dominant power loss in power electronic converters. Parasitic capacitances in power MOSFET include gate-source capacitance, gate-drain capacitance, and drain source capacitance. To calculate the switching loss for a power MOSFET, a common expression used is $P_{SW} = ½ V_D I_D(t_{OFF}+t_{ON})f + 1/2C_{OSS} V^2_D f$ [1]. C_{OSS} is the output capacitance given by $C_{OSS} = C_{GD} + C_{DS}$ [1] and is thought to introduce the heating of the MOSFET during turn-on through dissipation of energy. This energy was initially stored in the capacitor during the turn-off cycle. While these equations for calculating switching losses are widely accepted and used, they are not as accurate as other methods [1]. C_{OSS}, the term for calculating the switching power loss, overestimates the turn-off switching loss and underestimates the turn-on switching loss [1]. The overestimation and underestimation do not cancel each other out, and in turn they introduce erroneous error. However, since the net power loss contribution from C_{OSS} is minimal, this term can be ignored in power loss calculations.

Another error introduced in common power loss calculations is when V_{DS} is approximated as a linear waveform, which is introduced by the switching power loss from the equation above. Instead, defining the gate charge Q_{SW} as Q_{SW}^* allows us to neglect the gate charge increment accounting for the gate voltage that was still in the plateau. Using the gate current $I_{GS}^* = V_{gs} – V_P/R_g$ and Q_{SW}^*, the switching power loss can be further estimated in a more accurate model. It is important to note that in this paper, the parasitic inductance loss in power MOSFETs is not explored and this also constitutes a significant loss.

A newer switching device that is being investigated is the Silicon Carbide (SiC) MOSFET. The SiC MOSFET introduces smaller parasitic capacitance while higher switching speed are achieved. Higher switching speeds contribute to the lowering of losses in switching devices by reducing the losses in the switching cycle, which is where most losses occur. A method for calculating power loss is to assume that the gate driver is an ideal voltage source and that the common source stray inductance, L_S, and gate resistance are varied. A model is used to simulate the switching capability of the SiC MOSFET. Due to the fact that the parasitic capacitance is listed in the datasheets as combinations of the MOSFET port capacitances and the fact that these port capacitances play different roles in the switching cycle, these capacitances must be taken into account separately for the model to be as accurate as possible. During the turn-on switching, two things happen: the current rises rapidly through the MOSFET and the voltage drops. The two currents that are observed are the drain current and the channel current. The channel current contributes significantly more than the drain current, specifically in the falling voltage region. This channel current surge is due to the discharging of C_{ds} and C_{gd}, which were charged during turn-off, so that during turn-on voltage fall phase. Channel current = load current + discharge current of C_{ds} + discharge current of C_{gd} [2]. This charging and discharging can be viewed in terms of energy as $E_{on} = E_{on}$(measured) + E_{oss}, where E_{oss} is the energy stored in $C_{oss} = C_{gd} + C_{ds}$. The measured energy is calculated by integrating voltage and current that is measured. These various methods and techniques for calculating power loss offer better insight into possible solution methods for Team 13.

Although these analytical methods provide many calculations to determine the switching loss, another method which can be easier is to use the switching waveform. The switching waveform can show the nonlinear behavior of the switching devices. Through the use of nonlinear approximation methods, the switching waveform can easily determine the total switching loss.

2.2.2 Heatsink Design

The purpose of a heat sink is to transfer heat generated by a source to the environment, so that a device is properly maintained and does not overheat. Creating heat sinks that are smaller in size and weight but that still effectively transfer heat is critical as technology advances. Important factors in the heat sink design that will affect its performance include the overall dimensions of the heat sink, the properties of the material used, and the size, shape, and number of fins used. Conduction, heat transfer through a material, and convection, heat transfer through a moving fluid, are both involved in the thermal analysis of a heat sink. Heat sinks can operate by natural convection or, if fans are used, by forced convection. In order to optimize heat sink performance, various fin types have been developed. A study by Annuar and Ismail compared many different configurations of pin fins including inline, staggered, and randomized [3]. Pin fins were shown to dissipate heat better than plate fins. The inline arrangement resulted in smooth airflow; the staggered arrangement had a little better heat transfer performance but resulted in turbulent airflow. The randomized arrangement combined the effects of inline and staggered and resulted in the best thermal performance. A study by Drofenik, Stupar, and Kolar compared heat sinks made out of different materials in order to optimize heat sink performance [4]. The advanced composite materials with high thermal conductivities were not found to have significantly better cooling results than aluminum and copper. Aluminum was found to be the most reasonable option due to its weight, cost, and manufacturability. The thermal performance of a heat sink design can be analyzed using the finite element method (FEM) through software such as COMSOL Multiphysics.

In a study by Ning, Lei, Wang, and Ngo, an analytical model was developed to optimize a heatsink-fan system to reduce the total weight of the cooling apparatus [5]. The heat sink design chosen for analysis was the plate fin heatsink made of aluminum with a cooling fan blowing horizontally along the fins. The design parameters that contribute to the total weight of the system were found to be the heatsink length, fin number, fin height, fin width, channel width and the weight of the fan being used. The MATLAB optimization toolbox was used to optimize the heatsink-fan system based on the parameters previously given. The dimensions and the fan used were then loaded into a thermal analysis tool for thermal resistance verification. The analytical, simulated and experimental model yielded a thermal resistance of 2.5 K/W, 2.47 K/W and 2.44 K/W respectively. This indicates that the procedure of optimization can be implemented as a proven guideline to reduce the weight with optimal heat transfer.

One paper titled "Sub-Optimum Design of Forced Air Cooled Heat Sink for Simple Manufacturing" discusses maximizing the power density of a converter with a focus on minimizing the size of the heat sink. The paper studied a few different fin geometries and compared different configurations for fins and fans. The report also compared testing results for Copper and Aluminum heat sinks. In one case, a Copper heat sink was found to be 15 % more thermally resistant than its Aluminum counterpart, but it was also 4 times the weight. The study concluded that Aluminum proved to be better than Copper in the overall improvement of power density for the 5 different heat sink configurations that were looked at. In this study, Kolar and Drofenik also remarked that the largest constraint in designing heat sinks is the limited manufacturing size of Aluminum and Copper Sheets. The paper suggested that if the fins could be thinner, the power density would improve significantly [6].

2.3 Need Statement

Currently the customer has developed a heat sink for an electrical converter capable of cooling eight power modules operating at a max temperature of 150°C. The current heat sink system uses a fin type design with several cooling fans oriented horizontally along each side. This design once installed into an electrical converter contributes up to 50% of the total weight and takes up a large amount of space. These characteristics reduce the amount of electrical components that can be installed in the converter, which also reduces its efficiency. It is also currently over-designed as the heat sink remains cool throughout all operation.

> "The current heat sink system is over designed and takes up too much space and is too heavy once installed under the electrical converter."

2.4 Project Objectives and Goals

This project will aim towards creating a cost effective lightweight thermal structure for future photovoltaic converters. This will allow for easier and faster installation time of the future PV converters. Figure 1, shown below, shows a high level diagram of the responsibilities for both electrical engineering students and the mechanical engineering students. Each subset of students will be performing their respective research in order to complete their portion of the overall project. After the students of the electrical or mechanical engineering discipline complete their individual tasks and responsibilities, the two teams will combine their work for testing of the final result. Collaboration between the two disciplines will be crucial in the early stages of planning to ensure the team is headed in a cohesive direction.

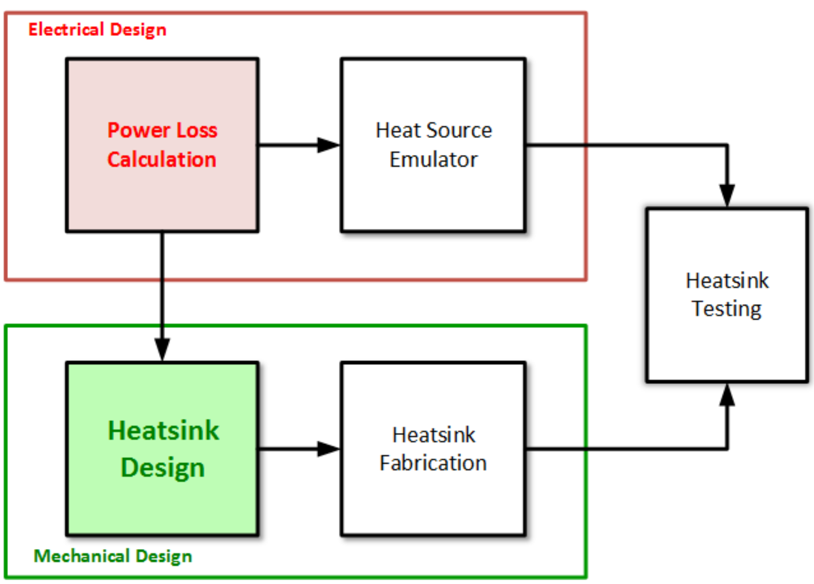

Figure 1 – Responsibilities of EE and ME Students (Image Courtesy of Thierry Kayiranga)

2.5 Project Constraints

These constraints are set by the sponsor and are targeted towards the customer's needs.

- Heatsink must be made of aluminum alloy
- Heatsink must weigh less than 6.5 kg
- Prevent up to eight power modules from exceeding 120°C
- Reduce size of current design.

3. Deliverables

In order to keep its members on task and to manage different elements of the project effectively, Team 13 developed work breakdown structure for the project. The major components of the project were laid out in Figure 1. To reiterate, they include power loss calculations, heat source emulators, heatsink design and fabrication, and finally heatsink testing, or optimization. The elaborate work breakdown structure which assigns subtasks to the main components for this project is provided in Figure 2 below.

Table 1 – Work Breakdown Structure

Designing & Testing a Lightweight Heatsink for a PV Converter	Power Loss Calculations	Review Documents
		Optain Specifications
		Determine Procedure for Solving
		Perform Calculations
	Heat Source Emulation	Research Comparable Heat Sources
		Decide Materials
		Design Emulator
		Procure Materials
	Heatsink Design	Review Documents
		Collect Current Heatsink Parameters
		Comparative Heatsink Testing
		Decide Fin Type
		Perform Simulation Analysis
		Find Best Fan Configurations
		Determine Fan Attachment Methods
	Heatsink Fabrication	Finalize CAD Design
		Decide Heatsink Materials
		Procure Material
		Machine Parts
	Optimization	Test Heatsink
		Compare Results to Simulations
		Iterate Design Process

Following assigning subtasks to the major components, Team 13 went ahead to organize them into a Gantt chart for this semester which established approximately how much time must be dedicated to each element, as well as when those tasks should begin and end. The Gantt chart also establishes precedence to necessary tasks, which is indicated by arrows. The colors on the chart indicate the different groups of team members that will be mainly responsible for each task. It should be noted that these deadlines are tentative, as unexpected circumstances can arise. Currently, the mechanical engineering students and the electrical engineering students in Team 13 are working on discipline specific tasks, but towards the end of the semester the team will be collaborating more as a whole. The most important goals are to have a heat source emulator and a finalized heat sink design by mid-November. Once these aspects are complete, the team will be coming together more to fabricate and begin testing the heatsink. However, one will notice that the testing/optimization section (which was included in the work breakdown structure on the previous page) is not included in the Gantt chart. This is because that aspect is planned to take place primarily during the spring semester. If time allows, Team 13 will begin testing this semester.

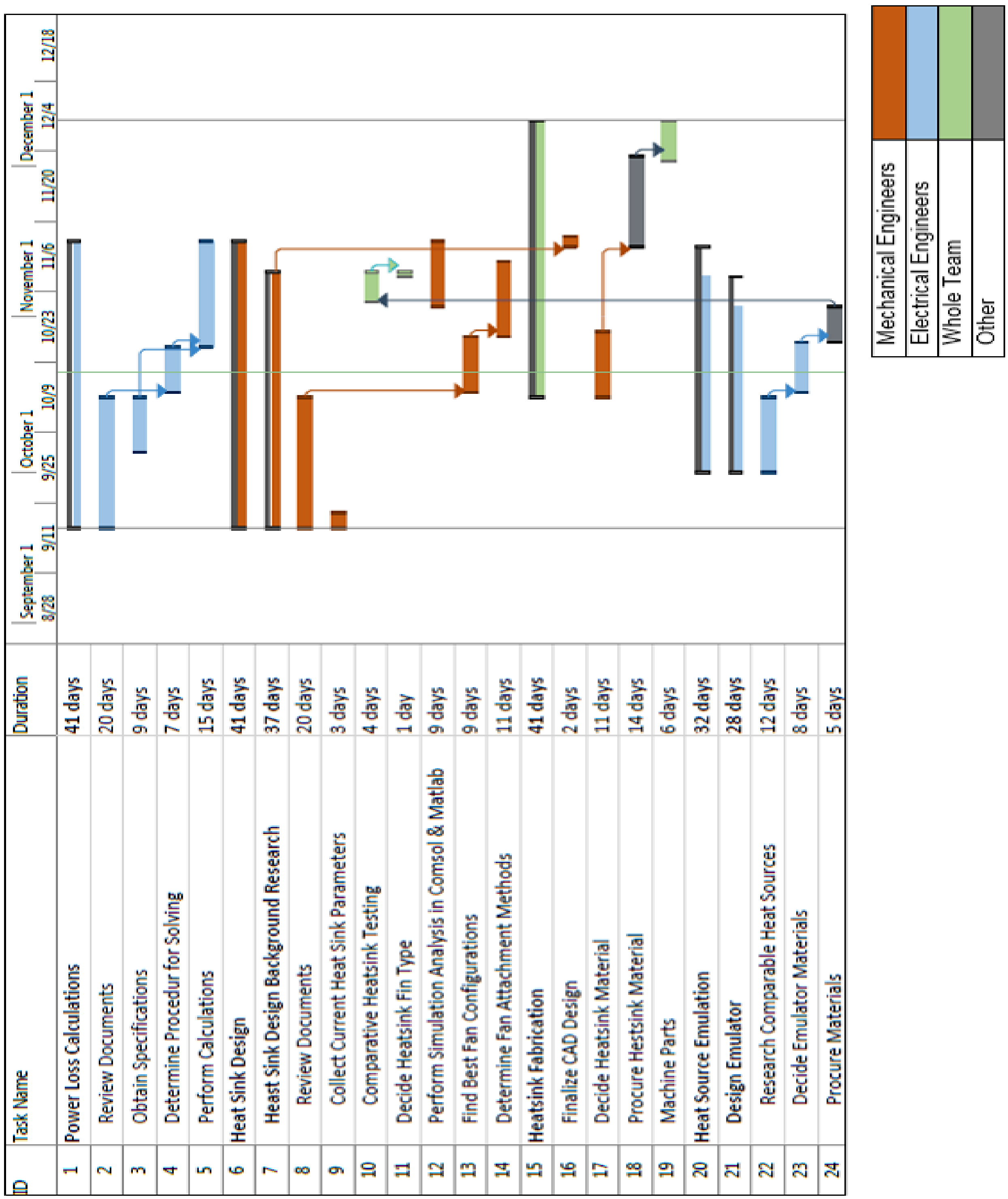

Figure 2 – Gantt Chart

4. Resource Allocation

Team 13 is led by Melanie Gonzalez. She is responsible for managing the team as a whole. This includes delegating tasks among the rest of the team members, finalizing all documents, planning and organizing team meetings with and without the sponsor, and overall project plans and progress. As well as being team leader, Melanie is also the lead electrical engineer and is responsible for the electrical design in support of the project. During the course of the project, Melanie will be responsible for the design of the heat source emulator that will be used to test the heatsink designed by the mechanical team.

Colleen Kidder, lead mechanical engineer, is responsible for the mechanical design in support of the project. She will be responsible for the simulation of the heatsink designs and the heat transfers analysis of the different heatsink designs using COMSOL. She will also oversee all testing done with the heatsink in the lab.

The financial advisor, Tianna Lentino, is responsible for managing the budget, maintaining a record of all credits and debits to the project account, and reviewing and analysis of expenditure requests. Tianna will also be responsible for calculating the power loss of the power modules.

Leslie Dunn is the webmaster and visual expert. She is responsible for developing and maintaining a website that follows the team's progress throughout the project. She will also be responsible for compiling any presentations and visual charts. Leslie will complete the calculations needed for the heatsink, along with determining the resistances of the plate fin heatsink if it is chosen as the final design.

Project 13 is a design project that will utilize computer aided design (CAD) software to create the heatsink designs. James Hutchinson is the lead CAD designer of this project. He is responsible for overseeing and finalizing all CAD designs related to the project. During the course of the project, James will also be responsible for calculating the pressure drop of the heatsink.

5. Product Specification

5.1 Design Specification

The general design currently being considered is sized to hold two power modules. The power modules have dimensions of 108mm by 48mm. The baseplate of the heat sink will have a length of 137mm, width of 128mm, and thickness of 5mm. These dimensions were chosen so that two modules fit on the baseplate with at least a 10mm clearance from the modules to the heat sink edges and so that the modules are spaced 15mm apart. A 12Vdc fan was selected for the design in order to generate forced convection through the heat sink. The fan has a diameter of 80mm, a weight of 170.1 g, and a volumetric flow rate of 1.94m^3/min. The aluminum alloy, Al T5-6063, was chosen as the heat sink material due to its light weight, low cost, and manufacturability.

The heat sink weight is a very important aspect of the design of this project. The weight of the current heat sink created by CAPS researchers, shown in Figure 4, is 6.45 kg. To increase the power density, the weight of the heat sink must be lowered. Therefore, optimizing the weight is largely the focus of the heat sink design process. The current heat sink, which is a plate-fin design, has a size of 279.4 mm by 374.65 mm, 24 fins evenly spaced, and 8 fans. The fans are arranged with 4 on each side of the heat sink. Because Team 13 is still in the conceptual design phase, characteristics such as the exact number of fins or the arrangement of the fins have not been finalized.

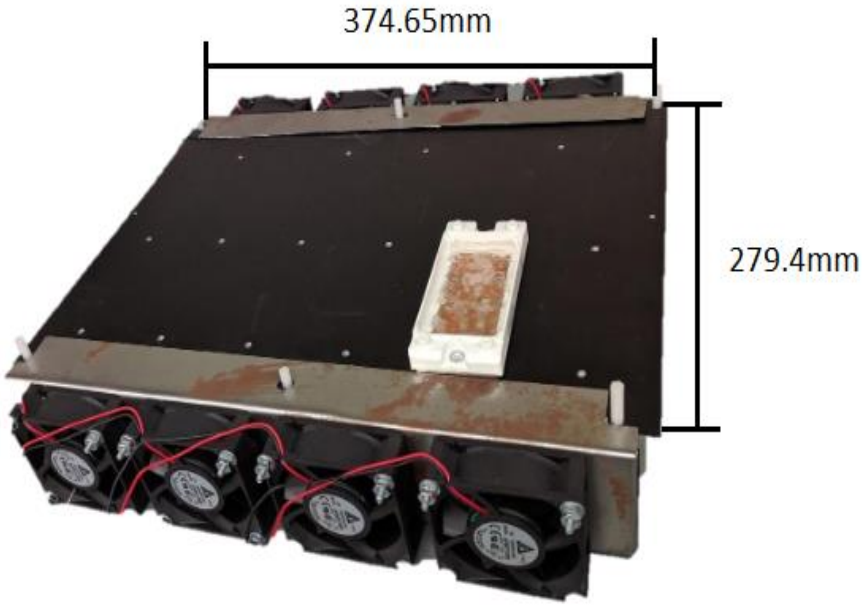

Figure 3 – Heat Sink designed by CAPS researchers

5.2 Performance Specification

The current heat sink is over-designed, which can be observed when the power modules are in operation and the bottom of the heat sink is cool to the touch. The heat sink system that CAPS has developed has a power density of 2.5 kW/kg. Team 13 aims to design an improved heat sink that will have a power density of 5kW/kg or double that of the current design. The current design has two stages of power modules. Stage 1 consists of 2 modules laid horizontally along and these modules obtain an efficiency of 98.5%. Stage 2 has 6 modules laid vertically under stage 1 and have an efficiency of 97.0%. The modules each have a power loss of approximately 100W. The maximum allowable junction temperature for the power modules is 150°C. As a factor of safety, the operating temperature for Team 13's design will be 120°C to ensure the power modules do not overheat. Team 13 will soon begin testing using an emulated heat source and a commercial pin-fin heat sink.

6. Conceptual Design

6.1 Emulated Heat Source

The heat source will be emulated through the use of resistors resting on a copper plate. The temperature threshold of the resistor will be taken into account to ensure they will operate at 150˚C. Resistors will be mounted to the aluminum plate via thermal grease to ensure maximum thermal conductivity is achieved. To mimic the power module as closely as possible, the emulated heat source will be attached to the heatsink in the same manner – resting directly on the heatsink and bolted with screws. The heat dissipation of these resistors will be measured with a thermal imaging camera. The data will be recorded to determine the trend of power versus heat. Once this trend is established, the proper resistors will be determined via Ohm's Law and purchased.

6.2 Heatsink Design

For the overall design concepts, Team 13 group members came to a consensus that a bi-modular concept was the best choice in reducing the weight and increasing the overall heat transfer. In the original heat sink, the length and width was 279.4mm x 374.65mm and the surface area of the top was 0.1046m^2. This area, while housing all of the necessary power modules, included unused material that accounted for extra weight on the system. By implementing a bi-modular design, this unnecessary spacing can be eliminated and thus remove unnecessary weight.

Another important aspect of the bi-modular design would also be its potential for an increase in overall heat transfer. Since smaller dimensions allow for smaller channels for airflow, this will ensure that a constant flow of cool air supplied by the fans which will quickly enter and exit through the system. Larger heat sink dimensions have the potential for increased air temperature as it travels throughout the heat sink which can have negative effects on air flow characteristics and heat transfer. By choosing a bi-modular design, Team 13 can ensure that unnecessary weight and undesired air flow can be kept to a minimum. All design concepts will be made from Aluminum T-5 6063 due to its high thermal conductivity and low density.

6.2.1 Bi-modular Pin Fin

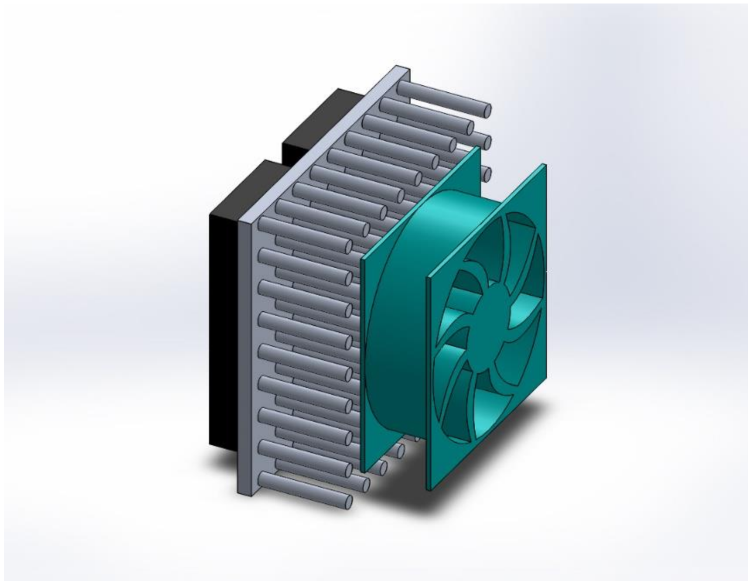

Figure 4 – Bi-modular Pin Fin Design

The bi-modular pin fin design is composed of a base that is 5mm thick with dimensions 128mm x 131mm. On the underside of the base, circular pins of constant cross section and constant spacing are evenly distributed along the entire bottom area of the base. The fan, which is used for forced convection cooling, is placed axially along the bottom of the pins. Approximately two power modules will be placed along the topside of design entailing that a total of 4 of these heat sinks will need to be fabricated. From analyzing this design, a clear advantage would be a rise in heat transfer. Due to the pins circular design, air flow introduced into the heat sink will enter the turbulent regime, driving an increase in mixing of the air which will remove heat at a quicker rate.

Disadvantages of the design is the need of a bigger cooling fan. Due to the fan being mounted axially along the base, a larger dimensioned fan will be needed to cover a larger amount of area for air flow. This has the potential for increasing the weight of the fan and making it an important issue when trying to remain inside the weight constraint. Mounting the fan will also be a challenge as well. The fan will need to be mounted in a manner where any fasteners, screws or bolts do not impinge on the pins and without changing the overall geometry of the heat sink as well. Currently, Team 13 is brainstorming ideas to overcome this problem. Another disadvantage will be the analytical modeling of the heat sink. Since the air flow going through the heat sink is in the turbulent regime, highly complicated equations are needed to determine the pressure drop and overall thermal resistance of the system. Due to the unpredictability of the turbulent regime, calculated values could differ significantly from actual experimental values. This could lead to an undesirable model for fabrication.

6.2.2 Bi-modular Plate Fin

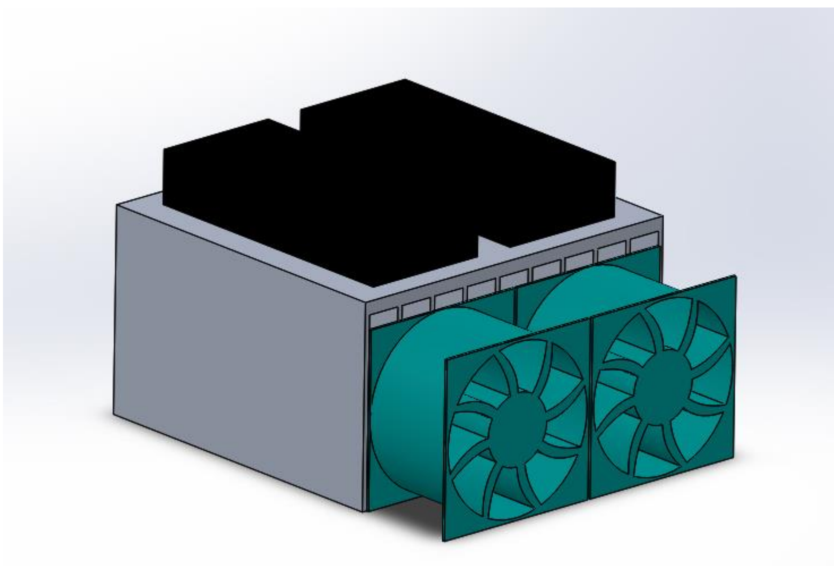

Figure 5 – Bi-modular Plate Fin Design

The bi-modular plate fins design, though similar to design 1, contains different geometry in the type extruded fins used. This design is composed of the same 5mm thick 128mm x 131mm base however thin rectangular fins are extruded through underside of the base. Each of these fins has a constant thickness and spacing along the along the base of the heat sink. Two cooling fans will be placed laterally along the side of the heat sink to allow for forced convection through the fin channels. Two power modules, just like the first design, will be placed on top on the heat sink entailing 4 will need to be fabricated.

This design contains two main advantages, one being that due to the chosen fin type it is possible that the analytical process will be will be less complicated. This is primarily due to the incoming air flow acting in the laminar regime. Another advantage would be the manufacturability of the design. Typically, plate fin heat sinks are cheaper and more customizable as compared to their pin fin counterparts. This advantage will help Team 13 significantly as the more customizations will result in more possible configurations for reducing the weight of the heat sink, and the low cost will help maintain Team 13 within the budget. However, one disadvantage of this design will be the possible decrease in heat transfer. Since the air flow will be operating in the laminar regime, less mixing will occur inside the heat sink's channels decreasing the heat transfer.

7. Conclusion

Through meetings with the team sponsor and graduate students, the scope and needs of the project have been identified and taken into consideration for generating design ideas. The constraints and specifications of the project gave the team guidance to conduct extensive research towards developing heatsink design ideas. With this research, the mechanical team has selected two possible heatsink designs to conduct further research and testing. These designs include a bi-bi-modular pin fin design, staggered and aligned, and a bi-bi-modular plate fin heatsink design. In order to further narrow down the concepts for the heatsink design and to allow the team to make the best possible decision, Team 13 has acquired a staggered pin fin heatsink that will be tested.

While the mechanical team is working towards a heatsink design, the electrical team is conducting tests to determine the relationship between power input and heat output. With this relationship defined, a heat source emulator can then be designed. The heat source will be composed of resistors attached to an aluminum plate and used to test the heatsinks. The heat source emulator will act as the power modules when the heatsink is being tested.

The next steps of this project will include finalizing the heatsink design and testing. Materials will be ordered upon the results of the tests that will be conducted on the staggered pin fin heatsink. This may include ordering more of the same type of heatsink or a different design (i.e. in-line pin fin).

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Biography

Melanie Gonzalez is a fifth-year senior engineering student studying electrical engineering. Her interests include control systems and embedded microprocessor design. She previously worked as an undergraduate research assistant at the Center for Advanced Power Systems. After graduation, she plans to work while obtaining a Master’s in Electrical Engineering.

Tianna Lentino is a fourth year senior electrical engineering student. Her interests include systems engineering and power systems engineering. She has spent the past two summers working as an intern with Northrop Grumman. After she graduates, Tianna plans on working with aircraft systems.

James Hutchinson is a fifth year senior attending Florida State University, studying mechanical engineering. He is a member of the National Society of Black Engineers, Golden Key Honor Society and the Foundations Chair of the Society of Engineering Entrepreneurs. His interests include CAD design, thermal fluids, and robotics. After graduation he plans on working in either the energy or aerospace industry.

Colleen Kidder is pursuing a bachelor's degree in mechanical engineering and will graduate in May 2017. She is most interested in mechanics & materials and thermal fluids. Through internship experience at Crane Aerospace & Electronics, Colleen has developed engineering skills in a business environment. Upon graduation, she plans to take the Fundamentals of Engineering exam and begin her career at a preeminent company.

Leslie Dunn is a fifth year senior at Florida State University pursuing her B.S. in mechanical engineering. She works part-time at the FSU Central Utilities Plant where she’s been conducting engineering work for a back-up fuel conversion. She has also held chair positions with the FAMU/FSU Society of Women Engineers for 3 years and is their current Vice President. Her main interests are in renewable energy, materials science, and robotics. After graduation, she wants to work with a company that focuses on sustainability.