Microwave Calorimeters
For Traceable Power Measurements

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Executive Summary

Measurement standardization is crucial to technological advancement as it helps ensure that components work together correctly, both nationally and internationally. The National Institute of Standards and Technology (NIST) standardizes certain measurement techniques by maintaining traceability for these measurements. A traceable measurement can be compared to international standards (ultimately, the definitions of the SI units) with an unbroken chain of calibrations, each with well-defined uncertainties. NIST Boulder’s RF Technology Division characterizes power sensors so that they measure microwave power in a way that is consistent with the basic definition of the milliwatt. They do this using a process called traceability. By making precise, traceable measurements, all uncertainties in those measurements can be related back to a reference point.¹

Our job for this project was to assist our client’s understanding of this device and then enhance its design. We used finite element analysis to determine the correction factor in the microcalorimeter and more fully understand the sources of uncertainty. Then, we redesigned and manufactured a new microcalorimeter model which aimed to reduce uncertainty in the design. Our new design is expected to improve connection repeatability while reducing the manufacturing cost by 85%.

Background

In order to characterize power sensors to accurately measure microwave power, NIST uses a device called a microcalorimeter. Unlike a typical calorimeter which measures energy in Joules, a microcalorimeter instead measures microwave power in milliwatts. Despite this distinction, we will be referring to the microcalorimeter as a ‘calorimeter’ for brevity. There are several types of microcalorimeters that vary based on their overall design and the microwave frequency they can handle. During our project, we worked with the twin-load type calorimeter.

Functionality

The twin-load type calorimeter core has two nearly identical halves. One half contains the device under test (DUT) and the other half contains the reference sensor. The only differences between the two sides are that the clamping mechanism that connects them is not symmetrical and one side receives power while in operation. During operation, microwave power is sent into the DUT, while no power is sent to the reference side. The DUT absorbs microwave power via the thermistor and heats up the sensor. The reference side receives no power and remains cool. Therefore, heat flows from the DUT, through the thermopile, and to the reference side, thus creating a temperature difference across the thermopile. The thermopile measures the temperature difference between the DUT and reference side which NIST uses to calculate the microwave power.
Project Goals

Thermal Simulation
The thermistor’s resistance depends on temperature. When the thermistor absorbs microwave power, it heats up. In this way, microwave power can be detected through DC resistance measurements. Not all of the microwave is absorbed in the thermistor bead; some is reflected back through the waveguide, and some is absorbed through the walls of the calorimeter. One of our clients’ biggest challenges was determining where heat dissipates inside the calorimeter. We used the COMSOL Multiphysics FEA program to obtain a more accurate understanding of the heat dissipation and its relationship to the correction factor. Initially, this was our clients’ original goal for the project. Since we were able to complete a thermal simulation that satisfied NIST’s needs in the first semester, we moved on to manufacturing in the second semester.

We simplified the calorimeter’s original geometry, removing features that were inconsequential to the thermal analysis.

Design and Manufacture
After completing our clients’ initial project request, we addressed some of the shortcomings in the current calorimeter design by redesigning it to be more modular.

Our clients expressed that one major area of concern in the old calorimeter design is connection repeatability, which we had not considered in our thermal simulation. Frequently reassembling the calorimeter causes wear between the precision components, meaning experimental results can deviate between tests based on the conditions of the pieces. Therefore, it is important to replace the components as they become worn. However, the original calorimeter consists of many expensive parts that are custom-made and difficult to replace. Thus, one of our goals for the second semester was to design a calorimeter with more commercially available components.

Our redesigned calorimeter featured more commercial parts which are easier to replace.
Thermal Simulations

Building the Model
Our first task was to create a thermal simulation of the microcalorimeter under load to determine where heat loss and uncertainty were occurring. We started by simplifying the geometry in SolidWorks, which made the thermal model more manageable. We then began learning the basics of COMSOL. Once we understood the correct file types and the basics of meshing, we continued by modeling one half of the calorimeter core. We applied the corresponding material properties and boundary conditions.

Next, we imported a more complex model and determined more realistic boundary conditions. We modeled the full twin assembly which included both the dummy and the DUT, as well as the thermopile in between the two halves. Finally, we applied constant heat flux boundary conditions, with which we could then determine the temperature gradient across the thermopile. This is one of the crucial measurements for determining microwave power.

Electromagnetic Boundary Conditions
We advanced our model further by replacing the constant heat flux in the waveguide with a variable heat flux that more closely represented the microwave's behavior. We modeled the propagation of microwaves in the waveguide to determine where heat was dissipated.

We again measured the temperature difference across the thermopile which allowed us to determine its correction coefficient value of 0.0041, which is realistic based on measurements of similar calorimeters. We ran tests on our simulation by changing factors such as geometric dimensions and boundary conditions to see how they affected the correction factor and thus optimized the design of the calorimeter to reduce the uncertainty. This new geometry became the starting point for our redesign during the spring semester.
Manufacturing

At the start of the spring semester, we transitioned from working on the thermal simulations to designing and manufacturing an improved WR-15 calorimeter. We went through six major design iterations before deciding to move forward with manufacturing the final version.

Our first design was similar to the previous calorimeter model. The main improvement was fitting a bulkhead adapter into the interface plate. Originally, the interface plate had a waveguide slot through the center, which required inside right angles and are difficult and expensive to manufacture. Our new design instead fits the bulkhead adapter, a commercially available part, into the interface plate. This accomplishes the thermal role of the interface plate, eliminates the need to custom-machine inside corners in the interface plate, and reduces the total number of connection points, improving connection repeatability.

Our later iterations modified the geometry to create more precise connections with the waveguides. Unfortunately, these changes required excessive precision manufacturing. Thus, our final design incorporated custom bulkhead adapters and numerous commercial components thereby improving manufacturability and hopefully connection repeatability.

A final point of design iteration involved improving the isolation section, which plays a key role in creating a thermal boundary between the upper measurement section of the calorimeter and the lower waveguide section. A thicker isolation section prevents unwanted thermal dissipation but also gives a higher correction factor.

Eventually, we decided to reduce the isolation section thickness from 0.25” to 0.125” and change the material from ABS to acrylic. The geometric change in thickness was made due to dimensional constraints of the overall calorimeter, and the material change was made because we decided to laser cut the isolation section instead of 3D print it. Our simulations concluded that making the isolation section smaller results in the added benefit of a lower correction factor, but also reduces the difference in voltage across the thermopile, possibly making the system more susceptible to noise. Laser cutting the part results in tighter tolerances and faster production than 3D printing.

Key design changes between the original design and our final design which we manufactured. We eliminated many inside corners, which are difficult and expensive to machine. We also included more commercial parts which are easier to replace when they become worn.
Assembly

Three important aspects of the physical calorimeter are that it can be easily assembled, easily replicated, and robust. Since the entire microwave calorimeter is only about 3 inches wide and 4 inches tall while consisting of 135 components, assembly was sure to be challenging. To ease the assembly process, we made sure that all screw lengths would be easily identifiable and share consistently sized hex sockets. In order to reduce the risk of applying too much torque on the screws, a specialized break-over torque wrench fastens all screws.

This wrench will fold in once the appropriate torque is applied.

Another assembly consideration is the usage of a granite inspection slab as a flat surface in order to gently align components. Custom and commercial parts are held together with screws, guide pins, and thermal paste which all provide precise alignment in the horizontal directions. Additionally, the inspection slab provides less than 1 thousandth of an inch of tolerance in the vertical direction, reducing the possibility of misalignment and a poor fit.

A flat lay of our microcalorimeter components with a quarter (bottom-left) for scale. Some of these parts had not arrived at the time this photo was taken. The bulkhead adapters and waveguides are substituted for their 3D printed versions and the isolation sections shown have not been gold-plated. Our timeline was shifted because of the first semester spent thermal modeling.
Conclusion

Overall, this project was a great success. Our thermal simulations allowed us to determine the correction coefficient of NIST's previous microcalorimeter design. Additionally, these simulations served as a convenient and accurate way for NIST and future senior design teams to continue testing the theoretical heat distributions in their calorimeter designs. Our clients have also received our improved physical microcalorimeter to be used for testing, and a parts brochure in case they want to order new parts. Future senior design teams who continue this project will have the opportunity to test our physical calorimeter and compare the experimental correction coefficient to the one from our thermal simulations. They can also alter our simulations to reflect the new design.

One of the design challenges of our project was our $2,000 department budget. Therefore, we strived to maximize the number of commercial parts and minimize custom manufacturing since the microcalorimeter's high precision tolerances would have exponentially raised the total cost of the project had we sourced more custom components. By carefully redesigning certain custom parts, we were able to refine the calorimeter assembly and utilize commercial part interfacing, aiming to reduce error in part-to-part mating.

Our clients estimated that the original calorimeter with its many custom components would have cost upward of $50,000 to manufacture. With our new calorimeter design, using off-the-shelf components and only a couple of custom parts, the total cost with additional replacement parts came out to $7,500. This new design is not only cheaper than the original, but has advantages over the initial design. Our calorimeter is more modular than the original design; therefore, if one piece wears out over time, it can be re-ordered from an established supplier of microwave components instead of remanufactured. While we didn't have time to test the physical calorimeter since we used the first semester to create the thermal simulation, we expect this will allow for increased longevity and better connection repeatability over time. This is ultimately our clients' goal for the new design as they believe a major source of the error in their experiments is lack of connection repeatability due to wear.
Meet the Team

Ryan Brink is the team’s Project Manager, and will receive his BS in Mechanical Engineering this spring, and MS the following year. He is currently in the final stages of the NUPOC program application process where after college he will be a nuclear engineer with the US Navy.

Megan Borfitz is the team's logistics manager whose responsibilities included documentation, communication, and planning. She will be graduating with a BS in mechanical engineering and a minor in computer science. She looks forward to using her skills to contribute to sustainability.

Paul DiTomas is the test engineer for the team, whose main responsibilities included analyzing the simulation results and applying them to the new design. He is graduating with a BS in mechanical engineering and a minor in music, and is looking forward to career opportunities in research, management and design.

Chase is the team’s Systems Engineer, and will graduate with a BS in Mechanical Engineering. Afterwards he will be pursuing a job as a professional engineer at a defense and aerospace company and will continue his pursuit of design challenges and problem solving.

Paris Buedel is the team’s CAD Engineer, and will graduate with a BS in Mechanical Engineering and minors in Energy Engineering, Leadership Studies, and Chinese. Paris will continue to study thermal design as a mechanical engineer at the Laboratory for Atmospheric and Space Physics.

Sophia Henze is the team's Financial Manager, and will graduate with a BS in Engineering Plus with an emphasis in mechanical engineering and a concentration in Creative Design and Technology. She has accepted a position at Deloitte Consulting and is looking forward to continuing combining her passions of engineering and design.

Austin Hegemann is the team’s Manufacturing Engineer, and will receive his BS this coming spring and MS the following spring of 2022, both in Mechanical Engineering. Austin is looking forward to pursuing his passion of design and manufacturing for his professional career.

Dr. Longji Cui is an Assistant Professor in the Department of Mechanical Engineering and acted as the Director for this project. His lab focuses on experimental and theoretical research of micro and nanoscale heat transport and energy conversion. His experience assisted the team greatly with the micro-scale and theoretical nature of the project.