Abstract— RF absorbers dissipate the incident electromagnetic wave by converting the RF energy into heat. In many applications, the absorbers can be subjected to high power incident fields. It is imperative to characterize and analyze the thermal behaviors for these high power applications. In this paper, a multi-physics (of EM and thermal) study has been conducted. The absorbers are first simulated in the ANSYS HFSS for electromagnetics. The absorbers are placed under plane wave incident field as well as from a pyramidal horn antenna in the near field. The output of the HFSS model is then imported to the thermal and computational fluid dynamics (CFD) tool, ANSYS ICEPAK. In order to obtain accurate thermal properties of the material, an experimental setup was designed. The simulation results are validated against measured data. Several effects are shown to affect the absorber internal temperatures for the same incident field level at the front of the absorbers, such as the antenna test distance to the absorber, the shape of the pyramid, and the measurement frequency. These simulation data provide greater insights into the heat dissipation and temperature distribution inside the absorbers.

Keywords—Thermal analysis, RF absorber, electromagnetic, conjugate heat transfer.

I. INTRODUCTION

Absorbers under continuous EM field heat up and reach a temperature equilibrium with surroundings. Depending on the substrate material and absorber constructions, maximum temperatures in the material will vary. Certain material structures such as reticulated foams or honeycomb lattice facilitate better heat exchange with the surroundings, thus allowing higher incident field. Different base materials, e.g., polyurethane foam, or expanded polystyrene foams can withstand different maximum temperatures. Absorbers designed for higher power handling almost always come at a higher construction or material cost. It is highly desirable to understand the maximum power limit of different absorbers under different conditions so we do not “over” design for the given applications. In this paper, we focus our study on the power handling of the most common type – the polyurethane (PU) foam absorbers.

The polyurethane foam absorbers are made from impregnating the raw foam with RF lossy carbon solutions. These absorbers, when subjected to the incident fields, convert the electromagnetic wave energy into heat as depicted in Figure 1. The heat is ventilated mainly by radiation and convection, whereas conduction contributes minimally.

Excessive heat can permanently damage the absorbers. Although fire retardant, which are also impregnated in the foams, are very effective at preventing the spread of fire, irreversible damage sometimes not visible from the outside of the absorbers can occur internally. These types of absorbers are rated to their respective power-handling limit based on the temperature ratings of the substrate material. The highest temperature reached in the absorber is in turn a function of the absorbers’ ability to lose heat through radiation and natural convection in the given ambient environment.

Accurate and realistic simulation results depend on establishing the correct model for both EM and thermal behaviors. These modeling efforts rely on accurate material properties. RF material property (permittivity and permeability) measurements are dealt with extensively in the literature, which is not the case for thermal properties of absorber material. An important first step of this study is to acquire thermal conductivity of the material. A test setup, as will be presented later, is constructed for this purpose. The test setup is then validated through an independent test by comparing thermal simulation and measurements.

Temperature distributions in the absorbers are studied under different incident field levels and different frequencies. A previous study [1] discussed the temperature variations within the absorber at Ku band using a measurement based model. This study utilizes the EM (HFSS) and thermal (ICEPAK) numerical tools. The numerical tools provide greater insights in the heat transfer mechanism and more comprehensive view of the temperature distribution in various parts of the absorber. The allow us to investigate several aspects, which would otherwise be difficult or expensive to obtain experimentally. In this study, we specifically investigated effects from near field radiation to the absorbers, temperature difference due to the shape of the pyramids, and frequency dependencies of absorber temperature distribution.
II. SIMULATION AND MEASUREMENT OF THERMAL CONDUCTIVITY

To establish the thermal conductivity of the absorber, a piece of EHP12-PCL (12” pyramidal absorber) is used in an experimental setup. A standard gain horn with a nominal gain of 16 dBi (ETS-Lindgren Model 3160-03) antenna is placed directly in front of the absorber. The measurement is performed at 2 GHz. The RF power to the antenna is monitored through a directional coupler. An electric field intensity level is established without the presence of the absorber first (using a calibrated E field probe). The probe is then replaced with the absorber with its tip aligned with the original probe position. Fig. 2 shows the test setup. The surface temperature is monitored with an infrared camera to ensure safety and avoid overheating, as shown in Fig. 3.

To monitor the internal temperatures of the absorber, four thermal couples are inserted into the center of the absorber. They are located at 2”, 4”, 6” and 8” from the tip of the pyramid (denoted as positions 1-4 with position 1 being the closest to the tip). The thermal couples are nonmetallic fiber optic temperature sensors, so they do not affect the electromagnetic field.

In the first measurement setup, the incident E field at the absorber tip is 300 V/m; the measurement distance is 1 m from the aperture of the horn. A maximum temperature is measured to be 53°C inside the absorber (at equilibrium).

The same setup is then simulated using HFSS (for EM simulation with the absorber and a horn antenna). The output from the EM model is the volumetric loss density everywhere in the absorber. The results from the EM model are then imported into ANSYS ICEPAK. The EM losses serve as the heat source to the thermal model (Ohms law). ANSYS ICEPAK is a computational fluid dynamics solver for thermal and fluid flow analyses. For the measurement setup above, the thermal conductivity of the absorber is adjusted to match the measured temperature. The same conductivity is used for the subsequent simulations in the paper.

The temperature contour inside the absorber is shown in Figure 4. Inside the absorber, heat transfer is governed by conduction, and is proportional to the temperature gradient and the thermal conductivity of the material per Fourier’s law [4]. The Polyurethane foam absorber behaves close to an insulator due its low thermal conductivity, thereby resulting in low heat transfer inside the absorber. This explains that the temperature is much higher at the center than near its tip, seen in Figure 4(a).

The heat transfer along the surfaces of the absorber to the ambient environment is governed by radiation and natural convection. In natural convection, the fluid moves due to buoyancy forces. These buoyancy forces are a combination of fluid density gradient and body force (the gravity force in +y direction in this case). The heat generated inside the absorber is transferred to ambient environment due to the high temperature gradient. This increases the temperature of air and leads to a decrease in air density because air density is inversely proportional to temperature [4]. This will raise the lighter and hotter stream of air upward. The absorbers in upper level will have to transfer heat to a hotter ambient air thereby reducing the temperature gradient and slowing the heat transfer rate. Therefore, temperature of absorbers in upper level is higher than lower level. It can be seen in Figure 4(a), the upper absorbers are warmer than the lower ones (even though the horn antenna is aimed at the center cone).

In another study, Gong et al. [5] simulated heat transfer inside a single absorber cone. They assumed a uniform and constant heat transfer coefficient as the boundary condition for all side walls. This implies that heat dissipates from all side walls uniformly to the air at a constant rate regardless of temperature differential and air movement. This conflicts with our observation in Figure 4(b), where heat loss is shown to be dynamically linked to the air movement (heat rise resulting in higher temperature at the top). Assuming a constant heat transfer coefficient is likely too simplistic to capture the physical behavior for heat exchange with surroundings, which in turn may produce inaccurate temperature contours inside the absorber.

Two additional setups are measured and modeled to validate the thermal conductivity value. In the second setup, the distance is changed to 0.5 m; the incident E field is maintained at 300 V/m. The measured maximum temperature is 48 °C, and the simulated result is 49 °C. In the third setup, the distance is maintained at 0.5 m, while the E field is increased to 540 V/m. The measured maximum temperature is 106 °C. The simulated temperature is 101 °C. Note that the temperature values are at equilibrium for the ambient temperature of 25 °C. Based on these comparisons, the simulated maximum temperature matches the measured results. Therefore, the thermal conductivity and simulation model are validated.
III. PRINCIPLES OF THERMAL SIMULATION ANALYSES

In ICEPAK, the three-dimensional equations for conservation of mass, momentum and energy are solved to compute the temperature distribution along the absorbers. Cartesian velocity components $u, v, w$ are used and it is assumed that the flow is steady and laminar, while the fluid is incompressible and Newtonian. No-slip condition was used on all walls. All properties of the materials are constant except for the density of the fluid which changes with temperature. Furthermore, the effect of viscous dissipation is neglected. Equations (1) to (5) are the governing equations for the dependent variables $u, v, w, p$ and $T$.

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$  \hspace{1cm} (1)

$$\frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} + \frac{\partial u}{\partial z} - \frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right)$$  \hspace{1cm} (2)

$$\frac{\partial v}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial v}{\partial z} - \frac{1}{\rho} \frac{\partial p}{\partial y} + \nu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) + g \beta (T - T_0)$$  \hspace{1cm} (3)

$$\frac{\partial w}{\partial x} + \frac{\partial w}{\partial y} + \frac{\partial w}{\partial z} - \frac{1}{\rho} \frac{\partial p}{\partial z} + \nu \left( \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right)$$  \hspace{1cm} (4)

$$\rho C_p \left( \frac{\partial T}{\partial x} + \frac{\partial T}{\partial y} + \frac{\partial T}{\partial z} \right) = k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \dot{q}_r - \dot{q}_s$$  \hspace{1cm} (5)

where, $\dot{q}_r$ and $\dot{q}_s$ are volumetric heat and heat transfer due to radiation, $C_p, \nu$ and $\rho$ are heat capacity, air kinematic viscosity and density, $p$ and $T$ are pressure and temperature.

The second order upwind scheme was chosen for the interpolation of the flow variables. The SIMPLE algorithm is adapted for the pressure velocity coupling [3]. A convergence criterion of $1 \times 10^{-6}$ was used for all variables in all simulations.

IV. FACTORS AFFECTING ABSORBER TEMPERATURES

A. Effect of antenna distance on temperature distribution

Ohmic loss due to the EM field acts as the heat source. Based on the point form Ohm's law, the power loss density $P$ in the absorber is given by

$$P = \sigma |E|^2$$  \hspace{1cm} (6)

where $\sigma$ is the electric conductivity of the material, $E$ is the electric field in the absorber.

Given the electric conductivity is constant at a fixed frequency for the absorber material, the power loss is solely determined by electric field distribution in the absorber.

To study the effect of the antenna distance, EHP24-PCL8 is used for the study. The EHP24PCL8 is a 24" long absorber piece consisting of 64 (8x8) pyramids in a 2'x2' footprint. Figure 5 shows the volumetric loss density for the study case (antenna distance of 36" at 2 GHz, and for incident $E$ field strength of 540 V/m at the tip). It is interesting to observe the curvature of the wave front from the horn antenna. RF energy penetrates deeper into the pyramids near the central area. These cones receive more power, which explains the higher temperature for these cones.

The distance from the antenna affects the power density distribution inside the absorber. In the near field, the electric field falls off as a function of distance. For the same 540 V/m incident field strength at the absorber tip (or 0.5 W/in² if assuming plane wave), if the antenna is closer, the incident field falls off faster along the length of the absorber than if the antenna is farther away. As a result, it is expected when we move the antenna closer, for example to 18" while maintaining the same 540 V/m field strength at the tip, the power dissipated into the absorber is less. The temperature would be lower for the closer distance case. Figure 7 shows this is indeed the case. The temperature scale is kept the same for Figures 6 and 7. The highest temperature is reduced to approximately 48 °C, as compared to 57 °C when the antenna distance is changed from 18" to 36".

The same effect was observed experimentally in section II with EHP12-PCL absorbers. For the same incident field of 300 V/m, the measured maximum temperature is 53 °C for the 1 m antenna distance (from the horn aperture to the tip of the pyramids), as compared to 48 °C for the 0.5 m antenna distance.
B. Effect of pyramid shape on temperature distribution

Temperature in the absorbers is affected by heat exchange rate with the surroundings and conduction inside the absorbers. It has been shown in another study [1] that a more narrow shaped pyramid allows for better heat exchange (because of the larger surface area), and internally less distance to conduct the heat out from inside the pyramids. With the aid of the numerical tools, the contour maps shows this effect clearly. For this, we performed the same simulations using a piece of EHP24PCL3 absorber. The only difference between the EHP24PCL3 and EHP24PCL8 is the pyramid array density. For the same 2’x2’ footprint, EHP24PCL3 consists of 9 cones (3x3 array) vs. 24 cones (8x8 array) for the EHP24PCL8. The EHP24PCL8 consists of much narrower pyramids. The RF reflectivity of the two types of absorber is equivalent.

Same as the previous case, the incident field strength is 540 V/m at the tip; the antenna distance is 36”; and the frequency is 2 GHz. Figure 8 shows the temperature along the center line of the central cone where \( z = 0 \) is located at the tip. The maximum temperature inside EHP24PCL3 exceeds 140 °C. It is considerably higher than the maximum temperature inside the narrower EHP24PCL8 (60 °C). Due to the larger surface area and slender profile, EHP24PCL8 can dissipate heat more efficiently to the ambient air, which helps to keep its internal temperature lower. Note that 140 °C actually exceeds the recommended temperature limit of PU foams of approximately 100 °C. An actual measurement under this condition could potentially damage the absorber.

C. Effect of frequency on temperature distribution

The E field distribution in the absorber is a function of frequency. It is expected that for lower frequencies, the power loss is more uniformly distributed and spread to a larger volume in the absorber.

To understand how temperature distribution is affected by frequency, we performed simulations using EHP24PCL3 (3x3 layout).

Figures 9 to 11 show the simulation results for plane wave incident wave at 0.5, 2 and 7 GHz. The plane wave power density is 0.154 W/in² (300 V/m). For EM simulations, the plane wave source does not require simulating antennas at
different frequencies, so less computational resources are needed. Thermally, it represents a more severe test condition than the incident field from a near field transmitting antenna, as evidenced by the previous discussions. The RF reflectivity of EHP24PCL absorbers is less than -35 dB (more than 99% absorption) at 0.5 GHz, and is even lower (less reflective) at higher frequencies, so radiated energies are almost entirely dissipated by the absorber at all of the frequencies under study. At 0.5 GHz, EM energy dissipation is spread to a larger volume inside absorber while at 2 GHz EM energy is concentrated in a smaller volume. As a result, the maximum temperature at 2 GHz is significantly larger than 0.5 GHz. At 7 GHz, although the hot spots are even more concentrated, but are located closer to the peaks and valleys of the pyramids, where heat loss is also faster. Temperature distribution along the center line of the center cone is shown in Figure 12 for the three frequencies. The maximum temperature inside EHP24PCL is 69 °C for 500 MHz, 77 °C for 2 GHz, and 52 °C for 7 GHz, all under 300 V/m plane wave incident field (0.154 W/in²). The location of the maximum temperature, i.e. hotspot, moves closer from the base of the absorber for lower frequencies to the tip for higher frequencies (at 7 GHz, a second hotspot appears). As the location of the maximum temperature moves closer to the tip of the absorber with an increase in frequency, the heat is radiated to the ambient air at faster rate due to less thermal resistance. The worst case temperature is dictated by a combination of the power distribution location and the thermal exchange rate nearby. In this case, the 2 GHz represent a worst case scenario in that power loss concentrates in a zone with a slow heat loss rate. On the other hand, at 7 GHz, hotspots occur at the peaks or valleys with easier heat dissipation. This shows that the maximum power handling of absorbers is dependent on the frequency.

Different absorbers (with different shapes and sizes, or material properties) are expected to be affected by frequency differently. To determine the maximum power handling of absorbers for specific applications at different frequencies and test setups, multi-physics numerical studies such as those conducted here can provide crucial insights.
V. CONCLUSION

We have conducted a multi-physics (thermal and EM) study of RF absorber under incident electromagnetic fields to investigate the maximum temperature and power handling of absorbers. An accurate material parameter is the key first step. To this end, the thermal conductivity of the polyurethane foam substrate is solved and the result is validated. The full EM and thermal models are then validated against actual measurement data. The combined ANSYS HFSS and ICEPAK simulations allowed a comprehensive investigation into the different aspects of thermal behavior of polyurethane pyramidal absorbers.

We specifically investigated three aspects of absorber power handleings under incident EM waves, i.e., the influence of the antenna distance to the absorbers under test, the shape of the absorbers (narrow vs. wide pyramids), and the effect of frequency on the maximum temperature. We have shown that the maximum temperature is affected by the antenna distance. For the same incident E field intensity at the front tips of the absorbers, a larger test distance from the antenna will result in higher temperature inside the absorber. Narrowing the pyramidal shape can be an effective way to reduce the temperature. The temperature in the absorber is also significantly impacted by the measurement frequency. A worst case scenario occurs for a frequency where the heat loss (due to the EM field) occurs near volumes with worse heat exchange. For typical 24” inch long pyramidal absorbers (3 x 3 array in a 2’ x 2’ footprint), 2 GHz represents the most severe test case. Understanding absorber thermal behavior under an EM wave involves EM and thermal multi-physics studies. For specific application needs, simulations such as those performed here are indispensable to provide valuable insights.

REFERENCES