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Heat Transfer Interface to Graphitic Foam

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HEAT TRANSFER INTERFACE TO GRAPHITIC FOAM

A Thesis

Presented to

The Faculty of the Department of Mechanical Engineering

San José State University

In Partial Fulfillment

of the Requirement for the Degree

Master of Science

by

Fang-Ming Lin

August 2018

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The Designated Thesis Committee Approves the Thesis Titled

HEAT TRANSFER INTERFACE TO GRAPHITIC FOAM

by

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APPROVED FOR THE DEPARTMENT OF MECHANICAL ENGINEERING

SAN JOSÉ STATE UNIVERSITY

August 2018

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ABSTRACT

HEAT TRANSFER INTERFACE TO GRAPHITIC FOAM

by Fang-Ming Lin

The A Toroidal LHC ApparatuS (ATLAS) strip tracking detector is scheduled to be upgraded in 2025. The order of magnitude for the hit densities and the radiation damage are expected to increase. When radiation increases, the leakage current increases and the heat generated at the silicon trackers can lead to thermal runaway. Cooling is critical in these detectors. In this study, a glassy graphitic foam was developed by AllComp Inc. as a precursor to the adhesives (glues). Graphene's highly anisotropic thermal properties result in high thermal conductivity in the planar direction, while it is low in the normal direction. In these conditions, it is interesting to analyze how varying thickness of the thermal interface materials (TIMs) optimizes for effective thermal conductivity. It was hypothesized that the direction where heat enters the graphitic foam and the size of the cross-sectional area normal to the heat flux direction would affect the overall effective thermal conductivity. Furthermore, the overall effective thermal conductivity is likely reduced when a gap is created between ligands and the bonded surface. In this study, a computational approach was adopted, in which a model was developed using the finite element method. From the simulation results, it was found that 0.2 mm thickness of glue provides a better heat transfer at the interface. Using this thickness, the effective thermal conductivity was found to increase by 2.2% to 5.7% depending on the thermal conductivity of the selected filler. The amount of surface area contact between the bonded (titanium) surface and the ligands also alters the required thickness of the glue to reach the heat flux saturation in the graphitic foam. The results demonstrate that the parameters at the interface can be optimized to improve the overall heat transfer via conduction.

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1 INTRODUCTION

1.1 Background

The Large Hadron Collider (LHC), the most powerful and largest particle accelerator, is scheduled to be upgraded by the European Organization for Nuclear Research (CERN). The LHC consists of multiple experiments and each was established for a different detector. There are a total of seven experiments currently run by LHC. The ToTal Elastic and diffractive cross section Measurement (TOTEM) and the Large Hadron Collider forward (LHCf) are the smallest experiments on LHC; they focus on “forward particles” in which protons and heavy ions brush past each other instead of meeting when beams collide. The Monopole and Exotics Detector at the LHC (MOEDAL) is the newest approved experiment which aims to search directly for the magnetic monopole. Experiments for A Large Ion Collider Experiment (ALICE) and the Large Hadron Collider beauty (LHCb) focus on specific phenomena; the former studies the physics of strongly interacting matter at extreme energy densities and the latter investigates the slight differences between matter and antimatter. Lastly, A Toroidal LHC ApparatuS (ATLAS) and The Compact Muon Solenoid (CMS) are categorized as the general—purpose detectors. They share the same scientific goals of investigating a wide range of physics problems with different technical solutions [1].

The ATLAS strip tracking detector is scheduled to be upgraded in 2025. The entire tracking system of the ATLAS experiment will be replaced during the LHC Phase II shutdown. The old tracking system will then be replaced with an all-silicon detector called the Inner Tracker (ITk) [2]. The layout of the ATLAS detector is shown in Figure 1.1. One new layer has been installed in the ITK during the shutdown in 2014, known as the Insertable B-Layer (IBL). The new ITK is designed and built to manage the expected higher radiation and occupancy after the upgrade [3].

Figure 1.1: Components of the ATLAS detector. Image reproduced with open permission from CERN.

Four major components of the ATLAS detector are the inner detector, the calorimeter, the muon spectrometer, and the magnet system. The focus of the study is on the inner detector which consists of three major components, the pixel detector, the semiconductor tracker (SCT), and the transition radiation tracker (TRT).

The IBL layer is a newly added component to the inner detector; the detailed layout of the inner detector can be seen in Figure 1.2 [1]. The particle densities and radiation are expected to increase by a factor of 10 after the upgrade; therefore, the current inner detector (ID) will be replaced with a silicon strip tracking system. This tracking system is also known as the inner tracker (ITk) which is designed to provide an improved radiation resistance [4] [5]. The newly defined design of the ITk will be composed of many layers and silicon pixel sensors will be located at the innermost layers. Outer layers will be composed of short and long strip sensors, with an approximate strip length of 2.5 cm

Figure 1.2: Detailed layout of the inner detector without IBL. Image reproduced with open permission from CERN.

and 5.0 cm, respectively [6]. The ITk is designed to have silicon pixel sensors surrounded by silicon strip sensors to offer higher granularity. As described in Koutoulaki's study, silicon pixel sensors and silicon strip sensors are known as pixel trackers and strip trackers, respectively. They are each arranged in barrels and endcaps. Each tracker has its own local support, known as staves for barrels and petals for endcaps. They both are equipped with a cooling structure being operated with titanium tubes and evaporative CO_2 [5]. Staves (barrels) will be studied in this thesis. The top portion of staves is known as the strip module (Figure 1.3a and Figure 1.3b) and the bottom portion, known as the core, provides mechanical support. At the core, the main components include low density carbon foam for mechanical support as well as highly conductive carbon foam and the titanium tube for cooling and thermal management.

In late 2012, methods developed to reduce the mass of detectors began to affect thermal performance. In order to secure the thermal performance and still meet the expectation for designing a lighter and smaller detector, attention was switched to the

Figure 1.3: (a) Exploded view of a short-strip barrel module. (b) Fully assembled view of a short-strip barrel module. Images reproduced with Creative Common copyright licence.

thermal interface materials (TIMs) with a high thermal conductance. As the degree of hit density is expected to increase, it is important to study high-performance TIMs and methods to characterize them, which allows a high degree of measurement reproducibility [7].

1.2 Motivation

The layout of the stave can be seen in Figure 1.4. The temperature at the silicon strip sensor must be maintained at a value of -5°C [8]. The radiation and hit density are expected to increase after the upgrade. When radiation increases, the leakage current increases and the heat generated at the silicon tracker can lead to thermal runaway. Thermal stability is important to prevent any radiation damage. Thus, cooling at the inner detector becomes extremely important. A thermal path from the silicon strip sensor to a titanium cooling tube is created. Details about the cooling system will be discussed in the later sections. Due to mechanical constraints and the required thermal efficiency at the ITk pixel detector, highly conductive carbon foam with low density is a good candidate for surrounding titanium tubes and for providing sufficient mechanical

stiffness. Carbon foam is believed to provide excellent thermal conductivity due to its high conductivity and highly porous structure.

Figure 1.4: Cross section of the stave. Image reproduced with the Creative Common licence.

The area of interest for this study is the thermal behavior of the components participating at the interface as optimizing material is easier. Thermal behavior is the most critical to optimize at the interface due to the occurrence of high heat flux. To ensure a thermal contact, graphitic foam is hard bonded to the titanium cooling tube by inserting thermally conducting epoxy [9]. Improving effective thermal conductivity at the interface by a factor of 3 to 4 will greatly improve the heat dissipation rate and prevent silicon modules from reaching the critical temperature. This would suffice to meet the expected thermal requirements of the ITk pixel detector.

The focus of this study is to develop methodologies for investigating the interface region of a composite material used at the interface between the highly conductive carbon foam (graphitic carbon foam) and the titanium tube. To join these two materials, a special type of adhesive material is used at the interface. The interface region is where the adhesive material joins the graphitic carbon foam and the titanium tube. The geometry of the carbon foam structure allows the penetration of the adhesive materials.

The cooling system acts as a heat sink and it aims to dissipate heat generated at the strip module. The graphitic carbon foam acts as a mechanical support for the structure and a thermal media from the modules to the cooling tubes [9]. The ligands (foam structure) of the carbon foam do not have a clean cut along the bonded surface, they

simply break. The distance from ligands to the bonded surface would possibly affect the thermal management at the interface. Therefore, the parameters at the interface in microstructural scale are important for analysis. These parameters include the density of the graphitic carbon foam, the size of the pores of the graphitic carbon foam, the distance from ligands to the bonded surface, the type of filler used for the adhesive materials (glues), and the penetration depth of the glue into the graphitic carbon foam used at the interface between the graphitic carbon foam and the titanium cooling tube. Studies for the first two parameters have been attempted by AllComp Inc. [10]. The investigation of the latter three parameters are discussed in this study and the goal is to optimize the effective thermal conductivity at the interface while minimizing overall mass.

As shown in Figure 1.5, the three major components (the bonded surface of the titanium tube, the glue, and the graphitic carbon foam) can be represented by a thermal resistance network. The thickness and the thermal conductivity of the titanium and the graphitic foam (t_{Ti} , t_{foam} , K_{Ti} , K_{foam}) will be fixed. The thickness of the glue (t_{glue}) is varied. By varying the glue thickness, the effective thermal conductivity of the glue, penetrating into the graphitic carbon foam (K_{glue}), is the most interesting observation.

Figure 1.5: Thermal resistance network for the three major components participate at the interface.

The mechanical strength is assumed to be unaffected by the three varying parameters. Finite element analysis is done with ANSYS Mechanical software, where simulations will analyze and verify the approaches. Design of experiments will also be performed to find the cause-and-effect relationships between the defined parameters and the experimental results. Lastly, the results from the analysis will be compared with the preliminary experimental results.

2 INTERFACE MATERIALS

2.1 Introduction to Interface Materials

When individual components are joined together, the interfacial thermal resistance emerges as the interfacial gap created between the two bonded surfaces. For composite materials, this interfacial thermal resistance significantly lowers its effective thermal conductivity/diffusivity as the temperature difference between two layers increases. As the thermal resistance increases, the effectiveness of heat transfer is reduced, greatly affecting the performance in thermal applications or devices where excessive heat is problematic [11] [12] [13].

As mentioned in the previous chapter, high heat flux happens at the inner tracker when discontinuous temperatures become apparent at a thermal junction as a result of undesirable thermal resistance. To deal with this undesirable phenomenon, TIMs are introduced to provide thermal management. A common way to improve effective thermal conductivity is to insert high thermal conductivity materials at the interfaces. Many interface materials are developed as a composite material which consists of matrices (soft base) and fillers (solid particles) [11] [12] [13]. As a result, the interfacial thermal resistance is reduced as the thermal conductivity of interface materials is several orders of magnitude higher than the thermal conductivity of air. Although the interface material helps to close the gap between two surfaces, thermal resistance still exists at the interface. This resistance is called interface resistance and it needs to be reduced to provide optimal heat transfer between two surfaces or layers of composite materials. If a material is composed of layer A and layer B, and R_A and R_B are the respective resistances, then the interface resistance can be calculated as shown in equation 2.1.

$$R_{TIM} = R_A + \frac{t}{kA} + R_B \quad (2.1)$$

t , k , and A are the thickness, the thermal conductivity, and the cross-sectional area of the thermal interface material, respectively [11].

However, the thermal resistance calculated does not include any specific analytic method required for the composite interface material case. A composite material is composed of matrices and filler with different volume fractions.

For this project, the interface material under study is the layers indicated as “Adhesive Material” in Figure 2.1. As shown here, the interface material is between the facesheet (CFRP) and the CVD foam (3D graphitic foam) or between the titanium tube and the CVD foam.

Figure 2.1: Important interfaces in cross-section of the stave (only shows components from silicon module to titanium tube).

2.1.1 Carbon Foam

Many applications used for the detectors are in search of materials that can dissipate heat efficiently yet provide a comparably light weight. Carbon foam has very low density, but was found to have improved thermal conductivity with higher density. Carbon foams can be seen as a simpler subset of composite material, since the manufactured solid

acts as the matrix where gap pores are dispersed. When carbon foam is used for thermal management applications, it becomes an exceptionally complex system for analysis of heat and mass transfer. The randomly oriented pores and their irregular geometric formation introduce great difficulty for developing an analytic approach. In previous studies, porous mediums were assumed to have uniform and isotropic characteristics [14]. Many simplifications are needed when developing an analytic method since porous materials rarely behave homogeneously. Different thermal properties can occur for different foam orientations. However, it was observed that carbon foam tends to carry isotropic thermal behaviors when compared to graphite sheet layers. For graphite sheet layers, there is large variation in thermal conductivity, $2000 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ and $6 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$, when the measurements are taken in a planar direction or in a normal direction, respectively. The difference in thermal conductivity between these two directions shows a variation factor of over 300. Carbon foam, on the other hand, only has a maximum factor of two in variation when measurements of thermal conductivity are taken in the planar and normal directions [15]. As indicated in Druma's paper, the bulk conductivity for carbon foam lands in the range of $0.1 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ to $200 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$. Despite the fact that carbon foam is typically more isotropic, its properties are still very sensitive to different microstructural parameters. The density, the number of pores per inch (PPI), and its topology (which represents the connectivity of the porous structure) will all affect the thermal characteristics of the carbon foam [16].

The proposed carbon foam used for this project is supplied and manufactured by Allcomp Inc. The foam is a modified reticulated vitreous carbon (RVC) foam, which is a glass-type carbon with high void volume, low density, and rigid structure [17]. Virgin reticulated vitreous carbon (RVC) foam is a type of open foam, consisting of interconnected pores. Virgin RVC foam is an attractive material option for aerospace and industrial applications due to its light weight and relatively high stiffness. However, some of its

disadvantages include its fragility and thermally insulative property [10]. To use this carbon foam at an interface requiring high thermal conductivity, it must be modified. The process performed by Allcomp Inc. to improve thermal conductivity is based on infiltrating highly oriented carbon throughout the ligament structure via chemical vapor deposition (CVD). The material of this highly oriented carbon is graphite. As pointed out earlier, mass is also a concern for the interface material. Therefore, the effectiveness of this modified RVC foam is determined by the ratio of K_t/ρ where K_t and ρ are the foam thermal conductivity and material density, respectively. Allcomp's manufacturing process was able to achieve a ratio 7 times higher than that achievable with aluminum [10]. This indicates that the graphitic carbon foam developed by Allcomp Inc. can provide better thermal management compared to other choices of materials given the same amount of mass.

The ligament structure of the RVC foam deposited with CVD can be seen from Figure 2.2. The SEM image taken with a magnification of 1000X shows highly-ordered graphitized layers. Graphite is an anisotropic material, and its thermal conductivity is controlled by orientation of the layer planes because heat conducts very fast in the planar direction into the layers but slowly in the perpendicular direction [18]. Therefore, highly-ordered graphitized layers allow for a ligament graphitic conductivity of about 1500 W/mK. The bulk RVC foam processed with CVD used for the cooling system carries the following material properties: 130 ppi, $\rho = 0.23 \text{ g}\cdot\text{cm}^{-3}$, and $k = 30 \text{ W/mK}$. For this study, in order to analyze graphite's anisotropic thermal conductivity, graphitic foam is analyzed with transverse and longitudinal thermal conductivities set to be 3 W/mK and 1800 W/mK, respectively. As mentioned, the thermal study has been done for the graphitic foam by Allcomp Inc., but the interaction between the foam structure and the adhesive material was not covered or discussed.

Figure 2.2: CVD deposited RVC foam, taken with 12X, 50X, 100X, and 1000X. Printed with permission from Allcomp Inc.

2.1.2 Cooling Tube

To design the LHC experiment which enables a long-lifetime performance, a thermal management system becomes crucial to provide stability and reliability. In order to maintain the silicon detector within the range of critical temperatures, the design of the geometries and the selection of the materials become essential to develop a thermal resistance network which can minimize the length of the heat path to the local heat sink [19]. Therefore, much care should be taken when selecting the tube material where the forced convection occurs.

Metals are the most common materials chosen for the on-detector cooling tube, because of their tightness at the connection and formation flexibility [19]. However, nonmetallic materials can be attractive due to their low mass and smaller thermally induced stress. Furthermore, other non-metallic materials such as carbon fiber are not

a favorable material type owing to their poor heat conduction in cross-wall direction and their high stiffness which limits their integration into the detector [20].

Two commonly chosen metallic materials for the tube used for nuclear energy industry are stainless steel (316L) and titanium (commercially pure grade 2 - CP2). Extensive studies have been done by references [19] and [20]. In this section, different material options for cooling tube are discussed.

Stainless steel has been used as the cooling tube material of the inner detector before the phase II upgrade was proposed, owing to its high mechanical strength in combination with very low magnetic permeability at cryogenic temperatures [21]. In order to reduce the mass and still maintain the ability to remove heat generated at the inner detector, titanium is proposed to replace stainless as the selected candidate for the cooling tube. Based on Table 2.1, information obtained from Bates's report shows that titanium's density is around 56% lower than stainless steel. Titanium has other advantageous characteristics such as high corrosion resistance, non-magnetic, and, most importantly, good heat transfer properties with a high melting point succeeding stainless steel [22].

Table 2.1: Properties of tube materials.

	Stainless Steel	Titanium	Aluminum	Cu/Ni	Carbon fibre
Alloy/grade	316L	CP2	5251	70/30	n/a
UNS	S316xx	R50400	A95251	C71500	n/a
Density [g/cm^3]	8	4.51	2.69	8.94	1.6-1.9 (typ.)
Radiation length (X_0) [mm]	18	36	89	14	230-280 (typ.)
Heat conductivity [W/Km]	14.6	21.0	134	29	1 (typ.)
CTE [10^{-6} m/m]	16.5	8.4	25	16	~ 0
Modulus [GPa]	193	103	70	150	High
Yield strength (fully annealed) [MPa]	290	276	80	88	n/a
Yield strength typical (1/3 hard) [MPa]	758	352	190	124	High
Ultimate tensile strength [MPa]	560	345	180	372	High

Note: Data gathered by Bates *et al.*

2.1.3 Adhesive Materials

It is extremely important to optimize heat transfer and removal in large energy devices such as a particle tracking detector. Due to the requirements, the RVC foam used at

the inner detector needs to be integrated with other materials for an effective heat transfer. The RVC foam has an open cell structure and is bonded with the surface of the titanium tube. This type of foam has different properties depending on the manufacturing process. Due to the porous medium, spacing is created at regions of pores where the ligands do not have a direct contact with the surface of the titanium tube. An uneven surface of the RVC foam is seen when joined with the titanium tube. In order to maximize the thermal conductivity, the integration of RVC foam via bonding to metals at an elevated temperature needs to be carefully analyzed [23] [24]. Materials used for bonding, known as the adhesive can be seen in Figure 2.3.

Figure 2.3: BN Epoxy to RVC foam interface, taken with SEM. The bright irregular layer indicates the adhesive. Reprinted from thermal and tensile strength testing of thermally-conductive adhesives and carbon foam, Chertock *et al.*, 12/1, 2017, with permission from Chertock *et al.*

There are many options when selecting an adhesive to be used at the interface for bonding materials. For particle detectors, in particular, some alternatives are Hysol EA9396, Hysol 9390.3 NA, and ACG VTA260 & Amber EF8020. The adhesive selected for the usage at the interface between the titanium tube and the RVC foam is Hysol EA9396 loaded with different fillers; these can come with different volume fractions [25].

The standard filler used for Hysol EA9396 is BN (Boron Nitride). However, other options of fillers are still under investigation for modifying the current adhesive so that better thermal management can be achieved. Based on results shown in Figure 2.4, it is interesting to notice that Hysol EA9396 loaded with graphite results in a significantly high thermal conductivity (data is indicated with the red circle).

Figure 2.4: Thermal Conductivity of Hysol doped with different fillers. Printed with permission from Eric Anderssen.

The adhesive materials containing BN or graphite fillers are each measured independently with different amount of volume fraction ranging from 10% to 20%. Results for both Hysol EA9396 loaded with BN and Hysol EA9396 loaded with graphite can be found in Figure 2.5 [26].

Figure 2.5: Thermal conductivity versus the volume fraction of different types of fillers (BN and graphite).

At approximately 30% volume fraction of graphite powder filler, it can be seen that the adhesive material can reach almost as high as $3.5 \text{ W/m}\cdot\text{K}$. Although there are a few fillers which seem promising for the task of improving thermal conductivity, for this project, Hysol EA9396 is loaded with 30% of BN or graphite. The difference of each is investigated and compared to understand the effects of adhesive material's thermal conductivity on the system's overall thermal management. Thermal resistance for each type of the adhesive material is analyzed to reach an optimal heat transfer for dissipating heat at the interface. In this study, the term “glue” is used for representing the adhesive materials.

2.1.4 Pore Structure

The two main foam structures are open and closed cell. They are produced with different manufacturing processes and raw materials (precursor). Their microstructures can be seen in images taken by the scanning electron microscope (SEM) shown in Figure 2.6.

Figure 2.6: (a) Open-Cell foam structure. (b) Closed-Cell foam structure. Reprinted from polymer foams handbook, NJ Mills, Introduction to polymer foam microstructure, Pages 2, 2007, with permission from Elsevier.

The name of each foam is indicative of its structure, where open-cells (pores) are interconnected with one another in a foam structure and closed cells are isolated from one another in a foam structure. The difference in the structure allows each foam structure to carry different mechanical and thermal properties. For example, open-cell foam structure will have greater air and water vapor permeability.

2.1.5 Porosity

Porosity is widely represented as the void ratio (ε), which is used to represent the volume fraction occupied by the voids (pore volume). The equation for representing ε is shown as follows [27]:

$$\varepsilon = \frac{V_{void}}{V} \quad (2.2)$$

In a study done by Wang [28], there are three typical types of porous structures: (1) porous open-cell foam, (2) fibrous layer in Polymer Electrolyte Membrane (PEM) fuel cells, and (3) cross-section of a graded material as shown in Figure 2.7. The former two types are examples for the two-phase systems of solid and void. Fibrous structure is mostly seen in polymeric and biomaterials, and graded materials are tailored for specific performance requirements by varying its microstructural phases. According to Wang,

metal foam is a type of open-cell foam structure with high porosity. Graphitic foam developed by Allcomp Inc. is one such metal foam and therefore open-cell foam structure is the focus of this study.

Figure 2.7: (a) Porous open-cell foam (b) Fibrous layer in PEM fuel cells (c) cross-section of a graded material. Reprinted from predictions of effective physical properties of complex multiphase materials, 63/1, Moran Wang & Ning Pan, 2008, with permission from Elsevier.

Two common metal foams used for thermal management are made of aluminum and copper. Both are open-cell foams with high void ratio (ranges between 80% to 97%) providing good thermal heat transfer [29]. However, mass is an important factor in designing a thermal device. Thus, the low effective thermal conductivity of aluminum and copper, 54 and 45 W/mK, respectively, are less than ideal. Graphitic foam, developed by Oak Ridge National Laboratory (ORNL) in 1997, emerged with an effective thermal conductivity of more than 150 W/mK [30]. In addition to its high effective thermal conductivity, low density and high specific surface area make it an ideal material in thermal management applications. Using either aluminum or copper, a larger mass is required to achieve a comparable thermal conductivity to graphitic foam.

2.2 Properties of Graphitic Foam

2.2.1 Thermal Conductivity

Based on Fourier's law of conduction, the transfer of energy is due to molecular activity. Heat is transferred due to the temperature gradient in the direction of decreasing temperature. The equation shown below is defined as the heat flow rate per unit surface area (q_x'') normal to x , assuming the surface temperature (T_S) is higher than the ambient temperature (T_∞). This equation is only valid for one directional, steady state heat transfer with a constant thermal conductivity [31].

$$q_x'' = -\kappa \times \frac{A \times (T_S - T_\infty)}{dx} \quad (2.3)$$

As mentioned, the material used for CVD process is graphite. Graphite's anisotropic thermal properties are a result of different photon couplings along a specific crystal axis. Depending on the orientation of the couplings, the crystal can take on different thermal conductivities. Correspondingly, the thermal conductivity factor in equation 2.3 is replaced by a second order tensor shown as [32]:

$$k = \begin{bmatrix} k_{xx} & k_{xy} & k_{xz} \\ k_{yx} & k_{yy} & k_{yz} \\ k_{zx} & k_{zy} & k_{zz} \end{bmatrix} \quad (2.4)$$

The matrix phase derived from a polymer tends to be structureless [33]. Therefore, $k_{xy} = k_{xz} = k_{yz} = 0$ and the second order tensor becomes:

$$k = \begin{bmatrix} k_{xx} & 0 & 0 \\ 0 & k_{yy} & 0 \\ 0 & 0 & k_{zz} \end{bmatrix} \quad (2.5)$$

Graphite is considered as one type of carbon-based fibers. If the x-y plane is the in-plane (transverse) direction, k_{xx} and k_{yy} in equation 2.5 have relatively low thermal conductivity compared to k_{zz} , the longitudinal thermal conductivity [33].

For steady-state, the governing energy equation can be represented as:

$$\begin{bmatrix} \frac{\partial}{\partial x} \\ \frac{\partial}{\partial y} \\ \frac{\partial}{\partial z} \end{bmatrix}^T = \begin{bmatrix} k_{xx} & 0 & 0 \\ 0 & k_{yy} & 0 \\ 0 & 0 & k_{zz} \end{bmatrix} \begin{bmatrix} \frac{\partial T}{\partial x} \\ \frac{\partial T}{\partial y} \\ \frac{\partial T}{\partial z} \end{bmatrix} \quad (2.6)$$

As mentioned, graphite has high thermal conductivity in the longitudinal direction and relatively low thermal conductivity in transverse direction. These directions are defined relative to the direction of the center and the axis of the nearest crystal. If the direction of the nearest crystal is aligned with the direction of the global coordinate system's x-axis, then the thermal conductivity matrix for this material property can be represented as [33]:

$$k = \begin{bmatrix} k_{xx} & k_{xy} & k_{xz} \\ 0 & k_y^{high} \cos^2 \theta + k_y^{low} \sin^2 \theta & (k_y^{high} - k_y^{low}) \sin \theta \cos \theta \\ 0 & (k_z^{high} - k_z^{low}) \sin \theta \cos \theta & k_z^{high} \cos^2 \theta + k_z^{low} \sin^2 \theta \end{bmatrix} \quad (2.7)$$

Porous materials have been used for high-energy applications due to their high thermal conductivity and low density. Many studies attempted to obtain the effective thermal conductivity through different analytic methods. This is a complex analysis because the spherical pores in the foam consist of three dimensional networks of ligaments and nodes [34]. A thermal and electrical resistance analogy is widely used to calculate effective thermal conductivity for different models. Furthermore, the unit cell (a tetrakaidecahedron) model is a popular method to analyze the relationship between the pore structure and

the effective thermal conductivity [27]. Further discussion of the tetrakaidecahedron cell is covered in section 3.1. For graphitic foam, effective thermal conductivity is obtained in both planar and normal directions due to its microstructure. Its complex geometry requires an analysis of three-dimensional thermal resistance system.

The directions (normal and planar) where heat enters the composite material are demonstrated in Figure 2.8. Equations for calculating effective k_n (normal direction) and k_p (planar direction) are shown below [11]. Equation 2.10 and equation 2.13 give expressions for k_n and k_p , where t represents the thickness.

For normal direction:

$$R_n = \frac{t_{e,1}}{k_e A} + \frac{t_{e,2}}{k_e A} + \frac{t_{e,3}}{k_e A} + \frac{t_{e,4}}{k_e A} + \frac{t_{c,1}}{k_c A} + \frac{t_{c,2}}{k_c A} + \frac{t_{c,3}}{k_c A} \quad (2.8)$$

$$R_n = \frac{t_e}{k_e A} + \frac{t_c}{k_c A} \quad (2.9)$$

and

$$R_n = \frac{t}{k_n A}$$

the equation for the effective thermal conductivity in normal direction is derived to be:

$$\frac{t_{total}}{k_n} = \sum_{n=i}^{\infty} \frac{t_i}{k_i} \quad (2.10)$$

For planar direction:

$$\frac{1}{R_p} = \frac{k_e t_{e,1} W}{L} + \frac{k_e t_{e,2} W}{L} + \frac{k_e t_{e,3} W}{L} + \frac{k_e t_{e,4} W}{L} + \frac{k_c t_{c,1} W}{L} + \frac{k_c t_{c,2} W}{L} + \frac{k_c t_{c,3} W}{L} \quad (2.11)$$

$$\frac{1}{R_p} = \frac{k_e t_e W + k_c t_c W}{L} \quad (2.12)$$

and

$$R_p = \frac{t}{k_p A}$$

Figure 2.8: Effective thermal conductivities for (a) normal and (b) planar directions.

with $A = t \times W$, the equation for the effective thermal conductivity in the planar direction is derived to be:

$$k_p t_{total} = \sum_{n=1}^{\infty} k_i t_i \quad (2.13)$$

2.2.2 Density

Table 2.2 provides the properties of the graphitic foam. RVC skeleton (structure of the graphitic foam) has extremely low thermal conductivity compared to graphite's. The foam density can, therefore, be computed by subtracting the RVC skeleton from

the CVD processed graphitic foam. The remaining volume fraction is the highly conductive graphite (CVD). This method was illustrated and adopted in the study presented by Allcomp Inc. [10]. This study used the 130 PPI foam with an average density of 0.075 g/cc for the foam skeleton (RVC).

Table 2.2: Properties data for RVC (skeleton) and CVD (Graphite) specified by Allcomp Inc.

Materials	Solid Density (kg/m^3)	Thermal conductivity (W/mK)
Vitreous carbon (RVC)	1500	0.085
Graphite (CVD)	2100	1800

$\rho_{rvc}=0.075$ g/cc

With the properties listed in Table 2.2, the volume-averaging method adopted by Allcomp Inc. is briefly explained.

Notations:

ρ_f = foam density

ρ_{rvc} = RVC density (skeleton)

ρ_{cvd} = CVD density (graphite)

ρ_s = solid density

$$\rho_s = \frac{\rho_{rvc}}{\rho_f} 1.5 + \frac{\rho_f - \rho_{rvc}}{\rho_f} 2.1 \quad (2.14)$$

where coefficients of 1.5 and 2.1 are the densities of RVC and CVD converted to g/cc. The foam density produced by Allcomp Inc ranges from 0.22 g/cc to 0.35 g/cc and the solid density will change accordingly. The relative density (ρ_r) of solid density and foam density can be calculated by equation 2.15.

$$\rho_r = \frac{\rho_f}{\rho_s} \quad (2.15)$$

The ligand's diameter (d_f) is derived with the following equations to obtain the cross-sectional area [35]. It is important to note that the ligand's diameter includes both RVC and CVD regions.

$$a = 1 - \rho_r \quad (2.16)$$

$$G_f = 1 - e^{-\frac{1-\alpha}{0.04}} \quad (2.17)$$

$$a = 2 \cdot \sqrt{\frac{(1-\alpha)}{3\pi}} \quad (2.18)$$

$$d_p = \frac{25.4mm}{(1+a)} \quad (2.19)$$

$$d_f = a \cdot d_p \quad (2.20)$$

Figure 2.9a presents the relationship between thermal conductivity and the foam density (CVD density). As mentioned, this study uses the 130 PPI foam.

Figure 2.9b shows that the cross-sectional area of ligand is a triangular shape where the RVC area could be approximately calculated to be $831.25 \mu m^2$. Furthermore, as shown in Figure 2.9a, a 30 W/mK thermal conductivity corresponds to an approximate 0.2 g/cc foam density. Varying the thickness of the CVD coating also affects the foam density.

After calculating the diameter of the ligand (equation 2.20), the cross-sectional area of one ligand can be computed. Subtracting the RVC area from the cross-sectional area obtains the CVD coating (shown in Figure 2.10b).

The calculated data can be found in appendix A.1. Figure 2.10a shows the plotted relationship between foam density and the area of CVD coating.

(a)

(b)

Figure 2.9: (a) Thermal conductivity vs. foam density. (b) Cross-sectional view of ligand, thermal conductivity was measured to be 41 W/mK. Image printed with permission from Allcomp Inc.

(a)

(b)

Figure 2.10: (a) CVD area vs. foam density. (b) CVD area for one ligand. Image printed with permission from Allcomp Inc.

3 FINITE ELEMENT ANALYSIS

Allcomp Inc. developed a finite element model for simulating the effective thermal conductivity of the graphitic foam. Its model incorporated the density and the isotropic thermal conductivity of the CVD (graphite) but did not include the anisotropic thermal conductivity. A constant heat flux of 0.5 W/cm^2 was applied at the top surface while the bottom surface was set to a constant temperature of 0°C . Knowing the distance and the temperature difference from the top surface to the bottom surface of the foam structure, the effective thermal conductivity can be computed. Although Allcomp's model studied the density and also the size of the graphitic foam, their model did not incorporate other major components of the interface, most importantly the glue layer. And since the area of interest for this study is the interaction between the graphitic carbon foam and the glue, a new model needs to be developed.

For clarity, Figure 3.1 explains the component that Allcomp's model was developed for. The arrays of cells represent the foam structure under magnification. How glue is added to this foam structure will be discussed in section 3.1.

Heat in the foam structure is conducted and released in an optimal path. The graphitic foam has a much larger thermal conductivity when compared to the glue. Therefore, heat escapes the glue through the graphitic foam due to the relative thermal conductivity of the materials. A model was developed to find the required thickness of the glue when an equilibrium of heat flux transfer rate is achieved between the glue and the graphitic foam.

3.1 Geometry For One Cell

Kelvin's tetrakaidecahedral model is widely used to accurately represent the highly porous, open-cell foam structure and describe the geometry among existing studies. [36]

Figure 3.1: Left to right: Graphitic foam, graphitic foam surrounded titanium tube and bounded by adhesive(glue), magnified graphitic foam shows foam structure, closer look of foam structure with layers of CVD. Some images extracted from Allcomp report. Image printed with permission from Allcomp Inc.

[37] [38]. Figure 3.2a shows how Kelvin cells can be represented by a unit cell, where Figure 3.2b shows the cell produced by CAD software which is used for the simulation. The 130PPI foam size ranges from $150\ \mu m$ to $250\ \mu m$. The average of these two values, $200\ \mu m$, is used for the length of geometry, d .

Figure 3.2: (a) Kelvin foam cell. (b) Kelvin cell created using CAD software.

The Kelvin cell was sliced at each node so that anisotropic properties can be applied to ligands with different orientations (Figure 3.3a). The distance from the nodal point to the slice was not kept constant, since the size of the real nodes is random. Nevertheless, the geometry consists of nodes and ligands oriented in different directions. After the Kelvin cell was sliced, it was stacked to form a foam structure with an array of five cells. Two metal, cylindrical plates then sandwiched the foam structure. Afterwards, glue was added to fill the space between the foam structure as shown in Figure 3.3b. The purpose of having two metal plates at two ends was to allow a more realistic simulation, so that heat flux did not enter the foam structure directly. The metal plates also dissipated heat before the heat flux enters the foam structure. The simulation ran with titanium chosen as the material due to its high thermal conductivity; it was also the selected material used for the cooling tube. Furthermore, many experimental setups also include two metal plates at the two ends. Multiple thermal couples placed between these two ends can measure the temperature at a given location. [7] [39] [40].

Figure 3.3: (a) Sliced Kelvin cell with indication of heat direction and separated sections after the slicing. (b) Components for running thermal simulation.

3.2 FEA Setups

3.2.1 Material Properties

The simulation used orthotropic thermal properties in ANSYS to define the anisotropic material properties shown in Figure 3.4a. The schematic shown in Figure 3.4b represents the components participating at the interface. Since RVC has extremely low thermal conductivity (0.085 W/mK), the RVC section of the ligand was removed in this analysis. Table 3.1 shows the material properties used for the FEA model.

Figure 3.4: (a) Anisotropic conductivity of ligand. (b) Schematic depicts the interacting parameters at the interface.

Table 3.1: Properties of materials used for the FEA model.

Materials	Isotropic Thermal Conductivity [W/mK]		
Titanium Alloy	16.4		
Glue (Graphite Filler)	3.5		
Glue (BN Filler)	1.2		
Glue (Low Thermal Conductivity Filler)	0.1		
Nodes	1800		
	Thermal Conductivity X-dir [W/mK]	Thermal Conductivity Y-dir [W/mK]	Thermal Conductivity Z-dir [W/mK]
Ligands	1800	3	3

Note: only one type of Glue is used for each simulation

As shown in Figure 3.5a, there are three different local coordinate systems defined for the horizontal ligands. Six different local coordinate systems were also set for the

vertical ligands (see Figure 3.5b). Ligands across the entire cell array were defined with one selection of the local coordinate system. Although each set of coordinate systems orientate in a different direction, the x-axis for each coordinate system is the direction defined with high thermal conductivity. The metal plates, the glue, and nodes of the cell array follow the global coordinate system due to their isotropic material properties.

Figure 3.5: (a) Sliced Kelvin cell with indication of heat direction and separated sections after the slicing. (b) Components for running thermal simulation.

3.2.2 Boundary Conditions

Proper boundary conditions are essential to allow for the calculation of thermal conductivity. This study only analyzes heat conduction with the finite element analysis. Heat transfer via convection and radiation are not within the scope. The simulations used the same boundary conditions applied by Allcomp Inc. to obtain effective thermal conductivity. Figure 3.7 displays the boundary conditions.

The schematic of the silicon module in the pixel detector was used to calculate the required heat flux. The heat flux can be calculated with the area ratio between the silicon module and the surface area at the interface between the graphitic foam and the titanium tube. It is shown in Figure 3.6 that there is heat flux applied to the square shape of the silicon module with 4 cm length. A half-perimeter of the 2.2 mm outer

diameter circle was used to calculate the area ratio. If L is the length of the stove, in the direction normal to the page shown in Figure 3.6, the heat flux at the interface can be calculated as follows:

$$\frac{4 \times L[cm^2]}{0.22 \times \pi \times 0.2 \times L[cm^2]} \times 1W/cm^2 = 11.6[W/cm^2] \quad (3.1)$$

Figure 3.6: Area ratio used to calculate heat flux at the interface.

Figure 3.7: (a) $0^{\circ}C$ applied at top surface of the metal plate. (b) Heat flux applied at the bottom surface of the bottom metal plate.

The calculated heat flux can then be used for the FEA model, as shown in Figure 3.7b. By default, the faces of the geometry without any specified boundary conditions

are adiabatic; therefore, this specific model only requires two boundary conditions. As mentioned, this study assumes that heat transfer only occurs via heat conduction. Convection and radiation are excluded and not discussed in this study.

3.2.3 Setups: the Thickness of the Adhesive Materials

The model was first run without the glue to check the thermal conductivity of the foam. Different thicknesses of the glue can be added to the model as shown in Figure 3.8. When the glue is added, the voided volume between ligands is filled. Three types of fillers for the glue as shown in Table 3.1 are used in different simulations for comparing the results.

Figure 3.8: (a) An array of five cells applied with 0.2 mm thickness of adhesive. (b) An array of five cells applied with 0.6 mm thickness of adhesive.

This setup was also used to run the simulations for obtaining the heat flux of the glue. As the thermal conductivity of the glue is much less than the conductivity of the graphitic foam, most of the heat flux is transferred by the graphitic foam. The remaining heat flux is transferred by the glue gradually entering the graphitic foam from

the transverse direction. An equilibrium is reached between the graphitic foam and the glue at a certain thickness. The density of the graphitic foam, the number of the pores of the graphitic foam, and also the thermal conductivity of the filler used for the glue can potentially alter the thickness. Simulations were run to verify the results for these variables.

3.2.4 Setups: the Amount of the Contact Surface of the Ligands at the Interface

There are six ligands orienting vertically with a tilted angle at the interface where the foam structure bonds to the titanium tube. One Kelvin cell was divided into three levels; the ligands of the first level were connected with nodes with the ligands at the second level as is shown in Figure 3.9. The six ligands at the first level are numbered.

Figure 3.9: One Kelvin cell is divided into three levels.

In actuality, ligands will not necessarily be directly in contact with the bonded surface. Multiple simulations were also run to observe the effect. Using the Kelvin cell to represent the amount of contact area of ligands at the interface, the number of disconnected ligands can range from one to six.

The case with only one disconnected ligand at the interface is used as a verification that the ligands contact surface does not affect the overall effective thermal conductivity.

When six ligands are disconnected at the interface, a gap is simply created between the graphitic foam and the bonded aluminum surface. An interesting observation was found when there were two or more ligands that were disconnected at the interface. To explain this, the first and the second levels of the three-dimensional Kelvin cell shown in Figure 3.9 were flattened and represented by the thermal resistance network. The thermal resistance network can be found in Figure 3.10.

Figure 3.10: The first two levels of the Kelvin cell are represented by the thermal resistance network.

From Figure 3.9 and Figure 3.10, it can be observed that ligand 1 and ligand 2 from the first level are connected with the two ligands at the second level with a horizontal ligand. On the other hand, there are no horizontal ligands connecting ligand 2 and ligand 3 from the first level with the other two ligands at the second level. The former case is identified as the adjacent case and the latter case is identified as the separate case. The reason these two cases are created can be explained by Figure 3.11 and Figure 3.12.

As shown in Figure 3.11, ligand 1 and ligand 2 were removed to represent the two disconnected ligands. Heat could only go through four out of the six ligands at the second level when the two ligands mentioned above were disconnected at the interface. For the separate case shown in Figure 3.12, heat could still go through all six ligands at the second level when ligand 1 and ligand 2 were disconnected at the interface. Therefore,

Figure 3.11: Adjacent case with two disconnected ligands.

Figure 3.12: Separate case with two disconnected ligands.

the assumption is that there is a larger drop in overall effective thermal conductivity when more adjacent cases of disconnected ligands existed at the interface.

These six ligands were connected with the nodes where their locations from the top view of a cell were represented with a two-dimensional drawing; this can be found in Figure 3.13. This two-dimensional drawing was used to represent different combinations of the ligand simulations.

Considering the six vertically orientated ligands, the first simulation sets consisted of removing one vertically orientated ligand at the first level (at the interface). As mentioned

Figure 3.13: Top view of six ligands of the Kelvin cell.

earlier, this simulation was run as a validation step. To compare the difference between the adjacent case and the separate case, different simulations were run with varying numbers of disconnected interface ligands. Table 3.2 lists the runs of the disconnected ligands when one separate case was included.

Table 3.2: The combinations of the disconnected ligands with one separate case.

Runs	(A_{1s})	(B_{1s})
Number of the disconnected ligands	2	3
Combinations of the ligands	2&3	2&3&5

Using the two-dimensional drawing shown in Figure 3.13 to represent the disconnected ligands; the two runs tabulated above can be represented and seen in Figure 3.14a and Figure 3.14b.

Figure 3.14: Two-dimensional drawings represent for (a) run (A_{1s}) and (b) run (B_{1s}) of Table 3.2; each has one separate case. The colored numbers indicate the disconnected ligands.

Three different combinations of ligands were simulated using an adjacent case. These three simulation runs are shown in Table 3.3. The two-dimensional drawings of these three runs are seen in Figure 3.15a, Figure 3.15b, and Figure 3.15c.

Table 3.3: The combinations of the disconnected ligands with one adjacent case.

Runs	(A_{1a})	(B_{1a})	(C_{1a})
Number of the disconnected ligands	2	3	4
Combinations of the ligands	1&2	1&2&4	1&2&4&5

Figure 3.15: Two-dimensional drawings represent for (a) run (A_{1a}) , (b) run (B_{1a}) , and (c) run (C_{1a}) of Table 3.3; each has one adjacent case. The colored numbers indicate the disconnected ligands.

It was determined that the adjacent cases were expected to have a larger impact on the drop in the overall thermal conductivity. Different combinations of the ligands can be found to have two adjacent cases. The two combinations are shown in Table 3.4. The two-dimensional drawings for the two adjacent combination cases can be found in Figure 3.16a and Figure 3.16b.

Table 3.4: The combinations of the disconnected ligands with two adjacent cases.

Runs	(A_{2a})	(B_{2a})
Number of the disconnected ligands	4	5
Combinations of the ligands	1&2&3&4	1&2&3&4&5

Besides the combinations shown in Figure 3.14, Figure 3.15, and Figure 3.16, there are other different combinations with one separate case, one adjacent case, or two adjacent

Figure 3.16: Two-dimensional drawings represent for (a) run (A_{2a}) and (b) run (B_{2a}) of Talbe 3.4; each has two adjacent cases. The colored numbers indicate the disconnected ligands.

cases, respectively. The runs tabulated in Table 3.2, Table 3.3, and Table 3.4 demonstrate only some of the combinations for each case.

3.3 FEA Results and Analysis

3.3.1 Results: the Total Heat Flux in the Graphitic Foam and the Glue

The resulting heat flux of the graphitic foam and the glue, from the simulation, changed depending on the variables set for the foam structure or the glue. As calculated in section 3.2.2, the heat flux from the silicon modules was calculated to be 11.6 W/cm^2 . The sum of the heat flux from the graphitic foam and the glue equals the calculated value. The first variable changed for the simulation was the type of filler used for the glue. Figure 3.17 shows the results for these sets of the simulation, where the thickness required for the heat flux to reach a saturation increases when using a filler with higher conductivity for the glue. Although the glue with higher thermal conductivity improves the overall effective thermal conductivity at the interface, results show that a thicker glue is required to reach the saturation.

The density of the graphitic foam structure was also changed for the model. When the density increases, the thickness of the graphene coating increases accordingly. The results for these sets of simulation are shown in Figure 3.18. 0.21 g/cc and 0.23 g/cc

Figure 3.17: The total heat flux in the graphitic foam and the glue for the cases with different types of filler added to the glue. The first y-axis (left) is for the heat flux in the glu. The second y-axis (right) is for the heat flux in the graphitic foam; the values are normalized respect to the total applied heat flux (0.116 W/m^2).

graphitic foams have the cross-sectional area of approximately $179 \mu\text{m}^2$ and $241 \mu\text{m}^2$, respectively. These two numbers agree closely with the calculation shown in appendix A.1. The required glue thickness to reach the saturation is barely different for the two cases with different graphene coating thicknesses. However, more heat flux enters the graphitic foam in the thicker graphene coating case. The result is reasonable since thicker graphene layers can carry more heat. Nevertheless, when choosing the thickness of the glue to be applied at the interface, the thickness of the graphene layers has a negligible effect.

The third variable changed for these sets of simulation was the PPI, also known as the pores per inch. When the graphitic foam has a smaller PPI, the size of the foam cell gets larger. On the other hand, the cross-sectional area of the graphene layers stays the same. With the same unit volume, the occupied glue volume is larger for a smaller

Figure 3.18: The total heat flux in the graphitic foam and the glue for the cases with different graphitic foam densities. The first y-axis (left) is for the heat flux in the glu. The second y-axis (right) is for the heat flux in the graphitic foam; the values are normalized respect to the total applied heat flux (0.116 W/m^2).

PPI. For a smaller pore cell, the surface area per unit volume where heat enters from the glue to the graphitic foam also gets smaller. Figure 3.19 shows the results for the graphitic foam with different PPIs. As shown, the saturation points for the heat flux locate differently for the graphitic foam with different PPIs. A smaller PPI requires a thicker glue to reach the saturation.

The simulated results have been shown when one of the variables was adjusted: the density of the graphitic foam, the size of the graphitic foam (PPI), or the type of filler used for the glue. Regardless of what variable, the results all show a greater dependency of heat flux when the glue thickness is less than 0.15 mm. This number is critical to determine the glue thickness needed to ensure an equilibrated heat transfer rate to improve thermal dissipation at the interface rather than adding extra weight.

To obtain the effective thermal conductivity of the infiltrated glue region in the

Figure 3.19: The total heat flux in the graphitic foam and the glue for the cases with different PPI (pores per inch). The first y-axis (left) is for the heat flux in the glu. The second y-axis (right) is for the heat flux in the graphitic foam; the values are normalized respect to the total applied heat flux (0.116 W/m^2).

graphitic foam, temperature drops and glue layer thicknesses need to be determined from the simulation. These data are shown in Table 3.5.

Table 3.5: Temperature drop data are obtained from the analysis.

Sample	ΔT Non-saturation [C]	Length of the glue layer [mm]	ΔT Saturation [C]	Length of the glue layer [m]
Glue(Graphite)w/.6	2.40	0.6	1.08	0.15
Glue(BN)w/.6	2.81	0.6	1.28	0.15
Glue(Graphite)w/.2	1.09	0.2	1.09	0.125
Glue(BN)w/.2	1.41	0.2	2.55	0.125

As shown in equation 2.3, the effective thermal conductivity can be calculated as:

$$\kappa = \frac{Q}{A} \times \frac{L}{\Delta T} \quad (3.2)$$

Since the glue layer is very thin, it is better to quantify the heat conduction by calculating how much heat per unit area it conducts, for a given T rise across the layer.

This can be represented by the heat transfer coefficient (HTC). Dividing the effective thermal conductivity with the length of the sample (the thickness of the glue in this case) results in the HTC. Table 3.6 shows the effective thermal conductivity and the calculated HTCs. The required glue thicknesses to reach the heat flux saturation in the foam have been obtained; they are also used for the calculation.

Table 3.6: Calculated effective thermal conductivity and HTC for non-saturation (non-sat.) cases and saturation (sat.) cases.

Sample	k_{eff} (Non-sat.) [W/m°C]	HTC (Non-sat.) [W/m ² °C]	k_{eff} (Sat.) [W/m°C]	HTC (Sat.) [W/m ² °C]
Glue(Graphite)w/.6	28.89	48.15	16.12	107.47
Glue(BN)w/.6	24.68	41.13	11.28	90.24
Glue(Graphite)w/.2	21.22	106.10	15.89	105.93
Glue(BN)w/.2	16.44	82.20	11.42	91.36

For comparison, Figure 3.20 also shows the results of the HTCs for glues with different fillers and thicknesses. As shown, the saturation cases perform better for the 0.6 mm thickness cases. These results correspond to the saturation points of the heat flux in the graphitic foam. Based on the results, 0.2 mm is the ideal glue thickness for optimal thermal performance at the interface.

Figure 3.20: Plotted results of the HTC for both the saturation and non-saturation cases.

3.3.2 Results: the Effective Thermal Conductivity with the Addition of the Glue

Knowing the required glue thickness for obtaining the optimal thermal conduction at the interface, simulations were run to see how the overall effective thermal conductivity varies with the participation of the glue layer. Figure 3.21 shows the temperature difference across the graphitic foam with different glue fillers. The overall effective thermal conductivity is calculated, the results are shown in Table 3.7.

Figure 3.21: Temperature results for a) 0.2 mm thickness of adhesive with BN filler
(b) 0.6 mm thickness of adhesive with BN filler.

Table 3.7: Overall effective thermal conductivity for the graphitic foam.

	No Glue	Glue w/BN Filler	Glue w/Graphite Filler
Effective Thermal Conductivity [$W/m^{\circ}C$]	28.74	29.37	30.38
Percent of Improvement %	NA	2.2	5.7

3.3.3 Results: The Ligands' Contact Surface vs. the Effective Thermal Conductivity

The simulations were run for different cases discussed in section 3.2.4. The results include the runs for one separate case, one adjacent case, and two adjacent cases; they are shown in Table 3.8, Table 3.9, and Table 3.10, respectively. As expected, the effective thermal conductivity drops as more ligands were removed at the interface.

Table 3.8: Effective thermal conductivities for the runs with one separate case.

Runs	(A_{1s})	(B_{1s})
Combinations of the ligands	2&3	2&3&5
Effective Thermal Conductivity [W/m°C]	29.28	31

Table 3.9: Effective thermal conductivities for the runs with one adjacent case.

Runs	(A_{1a})	(B_{1a})	(C_{1a})
Combinations of the ligands	1&2	1&2&4	1&2&4&5
Effective Thermal Conductivity [W/m°C]	28.93	27.37	25.96

Table 3.10: Effective thermal conductivities for the runs with two adjacent cases.

Runs	(A_{2a})	(B_{2a})
Combinations of the ligands	1&2&3&4	1&2&3&4&5
Effective Thermal Conductivity [W/m°C]	25.49	14.19

Different sets of simulation were also run without the addition of the glue. The two simulation sets (with and without the infiltration of the glue into the graphitic foam) can be compared to verify the improvement in the overall effective thermal conductivity.

Figure 3.22 shows the results of six simulation sets; three sets are the models with the glue infiltrated and the others are the model without it. From the results, the overall effective thermal conductivity is improved with the participation of the glues. Furthermore, the vertical displacement of the plots (the drop in the effective thermal conductivity) also varies. The variations in the slope and drop in the effective thermal conductivity indicate that the results are not trivial. More analysis and perhaps comprehensive three-dimensional

Figure 3.22: Plotted results of the effective thermal conductivity for all runs include the one separate cases, the one adjacent cases, and two adjacent cases.

measurements of the ligands' distribution are needed to obtain a more accurate prediction. A statistical approach such as a development of the stochastic distribution to analyze the distance between the bonded surface to the ligands should also be adopted.

The same heat flux simulations were run to determine how the amount of contact area between the ligands and the bonded surface alters the required glue thickness to reach the saturation point. As mentioned earlier, there are six ligands in contact with the bonded surface. Simulations were run with different numbers of ligand removed at the interface. Figure 3.23 presents the resultant plots. As shown, the required thickness of the glue to reach the saturation increases when more interface ligands were removed. The ligands break when manufacturing the graphitic foam. Thus, it is unlikely that all ligands at the interface are in perfect contact with the bonded surface. When choosing the glue thickness, it is imperative to consider the amount of contact area between the ligands and the bonded surface.

Figure 3.23: The total heat flux in the graphitic foam and the glue for the cases with different number of missing ligands at the interface. The values are normalized respect to the total applied heat flux (0.11575 W/m^2).

3.4 Analytical Approach

In this section, a back-of-envelope calculation with some assumptions were adopted to verify the simulated results.

Another simulation was run to simplify the calculation. This simulation had all horizontally orientated ligands removed. As shown in Figure 3.24a, the effective thermal conductivity without those ligands was calculated to be approximately 28.33 W/mK. Compared to the calculated effective thermal conductivity without any ligands removed (28.74 W/mK, shown in Figure 3.22), the comparison shows an approximate difference of 1.42 %. With this small % difference, the back-of-envelope calculation was adopted with the assumption that no horizontal ligands were present. Furthermore, Figure 3.24b supports the assumption that most of the heat transfer through the vertically orientated ligands. Thus, neglecting the horizontally oriented ligands' effect can give a relatively close result.

The ligand section was assumed to have an isotropic thermal conductivity of 1800 W/mK. A thermal resistance network was developed to represent all ligands from the top surface of the bottom metal plate to the bottom surface of the top metal plate.

Figure 3.25 shows the thermal resistance network. The six thermal resistances (R_l), each represents one set of vertically orientated ligands and are in parallel arrangement.

Notations:

T_c = Cold temperature [$^{\circ}C$]

T_h = Hot temperature [$^{\circ}C$]

R_l = Thermal resistance of one set of vertically orientated ligands [W/m $^{\circ}C$]

R_m = Thermal resistance of metal plate [W/m $^{\circ}C$]

Recall the relationship between thermal resistance and thermal conductivity, $R = L/kA$. Table 3.11 contains all of the associated parameters for the calculation.

Figure 3.24: (a) Simulated results for when all horizontally orientated ligands were removed. (b) Simulated results for total heat flux without glue.

Table 3.11: Data for calculating thermal resistance.

Sections	Thermal Conductivity [W/mK]	Length [m]	Cross-sectional area [m²]
Titanium Foil	16.4	0.1×10^{-3}	3.4636×10^{-8}
Ligands	1800	Direct Vertical: 7.2925×10^{-4} Along Ligands: 8.8845×10^{-4}	1.79×10^{-10}

Table 3.11 includes two different lengths for the thermal resistance of ligands; the difference is illustrated in Figure 3.26. The length obtained for the "along ligands" case is the sum of first, second, and third lengths.

The calculation was done with $Q = (\text{heat flux}) \times (\text{cross-sectional area of metal})$. Fetching the cold temperature from the simulated data, the hot temperature can be computed with the heat conduction equation discussed in section 2.2.1. The detailed computation was done with MATLAB (found in appendix A.2). Table 3.12 concludes the results.

Figure 3.25: Developed thermal resistance network for the back-of-envelope calculation.

Figure 3.26: Data for thermal resistance of ligands section.

Table 3.12: Results for back-of-envelope calculation. Percent difference compares the simulated and the calculated results.

Cases	Hot Temperature [$^{\circ}C$]	Percent Difference [%]
Direct Vertical	3.9	0.5
Along Ligands	4.2	8.0

The computed results were found to be close to the simulated outcomes when the length of the ligands section was set to be “direct vertical”. With the percent error found to be less than 10 %, this concludes that this back-of-envelope calculation is reasonable for result verification.

4 THERMAL RESISTANCE MEASUREMENT

As mentioned in previous chapters, RVC foam is deposited with CVD to improve its thermal conductivity. The adhesive joins the RVC foam with the cooling tube. The interface where the adhesive penetrates into the graphitic foam is the area of interest. The interaction between the graphitic foam and the glue helps to improve conduction at the interface. When observing the interface at the microscale, the anisotropic characteristics of graphite coating allow heat to enter either in a transverse or longitudinal direction. The adhesive material and RVC foam (without graphitization via CVD process) are assumed to have isotropic thermal properties, meaning that the same thermal conductivity is applied from glue to graphite layers and from graphite layers to the RVC skeleton. The same amount of heat conduction occurs in any direction heat travels. As mentioned, graphite has much higher thermal conductivity when heat enters into the graphite layers in the longitudinal direction. However, the cross-sectional area of graphite layers where heat enters in the longitudinal direction is much smaller than when heat enters in the transverse direction. In addition, heat flux also enters from the glue to the graphite layers in the transverse direction. Therefore, it is important to know how the glue thickness layer affects the overall thermal behavior due to divergent thermal conductivity.

4.1 Design of Experiments

In order to measure the thermal resistance for the interface, the meter bar approach (shown in Figure 4.1) will be adopted. The parameters required are: the heat flow through the sample ($\dot{Q}$), temperature difference between the upper bar/sample interface ($T_{s,u}$) and the sample/lower bar interface ($T_{s,l}$), and the contact area between the sample and the bars (A_c). The heat flux is assumed to enter the specimen in one direction [41].

$$R_{th} = \frac{T_{s,u} - T_{s,l}}{\dot{Q}} A_c \quad (4.1)$$

Figure 4.1: Meter bar approach for taking measurements of thermal resistance for the interface material.

It is challenging to measure the thermal resistance of the interface layer since it is extremely thin. As is shown in equation 4.1, it is necessary to obtain the temperature drop across the sample layer ($T_{s,u} - T_{s,l}$). The thin layers result in small temperature drops. However, alternating layers of composite material allow for measurable thermal resistance.

4.2 Development of the Composite Material

The area of interest for improving thermal management is the interface material between the titanium tube and the RVC foam as shown in Figures 1.4 and 2.1. An analytic method is needed to calculate the effective thermal resistance at the interface layer where the carbon foam is infiltrated with the glue layer. It suffices to use titanium foil to represent the bonded surface of the titanium tube that is adhered to the graphitic foam. As mentioned in the previous section, the interface layer is very thin with high

thermal conductivity; therefore, obtaining the resistance for one single layer might be challenging. In order to perform the measurement of the thermal resistance of the interface material, multiple alternating layers of composite material are stacked together. The specimen is produced by cutting layers in half, placing one half on top of the other. This ensures that each layer of the interface material has a constant thickness throughout the entire stack. The same steps will be taken until the desired number of alternating layers is obtained. The illustration of the process is shown in Figure 4.2. Due to the constant alternating layer thickness, the total specimen thickness is calculated by multiplying the thickness of one layer with the number of the alternating layers.

Figure 4.2: Process of creating test specimen for measuring the effective thermal resistance of the interface layer.

Here, the study is analyzed as a 1-D steady-state heat conduction. The thermal resistance is calculated in the direction normal to the stacked layers. Since the alternating layers are stacked, the effective resistance can be analyzed with the electrical resistance analogy, where each layer is aligned in series. For layered composite materials, the effective

resistance for the joined materials is calculated as $R_{eff} = \sum \Delta x_i / K_i A$, where Δx_i and K_i are the thickness and thermal conductivity of the i^{th} layer of a material, respectively. A is the cross-sectional area, assumed to be uniform for each layer. The interface material to be analyzed is composed of layers of titanium foil, carbon foam with infiltrated glue (Hysol EA9396 + BN), and non-infiltrated carbon foam. The effective thermal resistance term can be found to be [23]:

$$R_{eff} = \frac{1}{A} \left(\left(\frac{\Delta x_{Ti}}{K_{Ti}} \right) + \left(\frac{\Delta x_{glue}}{K_{glue}} \right) + \left(\frac{\Delta x_{glue+foam}}{K_{glue+foam}} \right) + \left(\frac{\Delta x_{foam,noglu e}}{K_{foam,noglu e}} \right) \right) \quad (4.2)$$

where Δx_{glue} represents the thickness of excessive glue which does not infiltrate the carbon foam and $\Delta x_{glue+foam}$ is the thickness of foam infiltrated with glue.

The foam is optimally manufactured to be in contact with the titanium foils from the previous and the next layers. The glue layers also infiltrate the carbon foam and wet both the titanium foil and carbon foam (shown in Figure 4.3). For these reasons, the term for $\left(\frac{\Delta x_{glue}}{K_{glue}} \right)$ is voided and $\Delta x_{foam,noglu e} = \Delta x_{foam} - \Delta x_{glue+foam}$. The effective thermal resistance term will then be:

$$R_{eff} = \frac{1}{A} \left(\left(\frac{\Delta x_{Ti}}{K_{Ti}} \right) + \left(\frac{\Delta x_{glue+foam}}{K_{glue+foam}} \right) + \left(\frac{\Delta x_{foam} - \Delta x_{glue+foam}}{K_{foam}} \right) \right) \quad (4.3)$$

Assuming that there are n layers of the alternating layered composites and the completed interface material is closed with one extra layer of titanium foil, the effective thermal resistance term becomes:

$$R_{eff} = \frac{n}{A} \left(\left(\frac{\Delta x_{Ti}}{K_{Ti}} \right) + \left(\frac{\Delta x_{glue+foam}}{K_{glue+foam}} \right) + \left(\frac{\Delta x_{foam} - \Delta x_{glue+foam}}{K_{foam}} \right) \right) + \left(\frac{\Delta x_{Ti}}{K_{Ti}} \right) \quad (4.4)$$

Given the uniform cross-sectional area A , the effective thermal conductivity is inversely proportional to the bulk thermal resistance of the interface material. The effective thermal conductivity can be calculated as shown in equation 4.5. It is important to point out

Figure 4.3: Configuration of the Ti-Glue-Foam composite layers.

that the overall thermal conductivity depends only on the number of alternating layers and is independent of the size of uniform cross-sectional area.

$$K_{eff} = \frac{t_{total}}{R_{eff}A} \quad (4.5)$$

Considering $K_{glue+foam}$ in equation 4.3 to be the effective thermal conductivity of matrices with dilute volume fractions, an extra step is required to obtain the approximated value for $K_{glue+foam}$ which incorporates both K_{foam} and K_{glue} . The Maxwell Garnett approximation can be used to calculate the effective thermal conductivity for which particles (glue) are well-bonded and dispersed in the matrix (carbon foam) [42].

The Maxwell Garnett approximation is formulated as:

$$\mu = \mu_1 \frac{2\mu_1 + \mu_2 + 2k(\mu_2 - \mu_1)}{2\mu_1 + \mu_2 - k(\mu_2 - \mu_1)} \quad (4.6)$$

where k represents the volume fraction of elements in a unit volume of the substance. μ_1 and μ_2 represent the conductivity of the substance and the elements, respectively.

Using the analogy from equation 4.6, the effective thermal conductivity for $K_{glue+foam}$ can be calculated by the following equation.

$$K_{glue+foam} = K_{foam} \frac{2 \left(\frac{K_{glue}}{K_{foam}} - 1 \right) V_{glue} + \frac{K_{glue}}{K_{foam}} + 2}{\left(1 - \frac{K_{glue}}{K_{foam}} \right) V_{glue} + \frac{K_{glue}}{K_{foam}} + 2} \quad (4.7)$$

where V_{glue} represents the volume fraction of glue (Hysol 9396 + BN). This derivation can be used for obtaining a term to represent the effective thermal conductivity of the composites. However, another model was developed to include both transverse and longitudinal thermal conductivity of the graphite coating on the RVC foam. The derivation for including these anisotropic characteristics is discussed and presented in chapter 5.

5 THE EFFECTIVE THERMAL RESISTANCE OF THE GRAPHITIC FOAM

Many studies on the effective thermal conductivity used a unit cell model in high-porosity metal foams, showing the effective thermal conductivity increases as the porosity decreases. Recent studies done by Yang *et al.* observed the pore size effects when heat transfers with convection and radiation at temperatures higher than 400K [43]. In order to account for the pore size, Yang *et al.* developed another analytic method to obtain a new function for porosity by calibrating the experimental data [44].

The analogy between thermal and electrical resistance was adopted as the analytic method in this study. Fu *et al.* also adopted this analogy to predict the thermal conductivity of metal foam. One of the developed models was based on a body-centered cubic unit cell where the effective thermal conductivity was calculated by equation 5.1 (assuming the unit cell scale is equal to unity, $2b = 1$) [45]:

$$k_{eff} = 1/(AR_{total}) = \left(\int_0^b \frac{1}{(A_s/A)k_s + (A_g/A)k_g} \frac{dx}{b} \right)^{-1} \quad (5.1)$$

In this equation, the integral does not incorporate the varying cross sectional surface of the solid phase as a function of position in the foam. Druma also developed a model having pores distributed in a body-centered cubic unit cell. This model related the total surface area and thermal conductivity of carbon foams. The effective thermal conductivity in Druma's model took into account the pore size; this is under the assumption that the specific surface area of the foam per unit volume depends on the porosity, the pore size, and the distribution in the foam [34]. The equation developed for Druma's model is the same as Fu's equation, but areas for porous and solid sections vary and depend on the cross-section perpendicular to the axis of interest. Examples of the cross-sections can be found in Table 2 of Druma's paper [34].

Another approach was adopted by Bauer who calculated the effective thermal conductivity

based on the density of the solid portion of the foam [15]. Bauer's study assumed that the mass of voids in the foam is negligible [46]. The following equations were obtained:

$$k_{eff} = \frac{k_b}{k_s} \quad (5.2)$$

and

$$\frac{k_b - k_p}{k_s - k_p} \left(\frac{k_s}{k_b} \right)^{1-n} = 1 - \left(\frac{P}{100} \right) \quad (5.3)$$

where k_{eff} , k_b , k_p , k_s , P , and n are the effective thermal conductivity of the porous medium, the bulk thermal conductivity, the thermal conductivity of pore material, the solid (intrinsic) thermal conductivity, the porosity, and the pore conduction factor, respectively.

With the assumed bulk thermal conductivity being much higher than the pore thermal conductivity, the equation was expressed as shown below [46]:

$$k_{eff} = \frac{k_b}{k_s} = 1 - \left(\frac{P}{100} \right)^{1/n} \quad (5.4)$$

Furthermore, a tetrakaidecahedron unit cell was developed by Yang to analyze the effective thermal conductivity of high porosity, open-cell metal foams [47]. Leong also developed a unit cell and separated it into three sections to calculate the effective thermal conductivity of a graphite foam with the advantage of allowing variation of pore structure. Leong adopted the electrical and thermal resistance analogy to analyze the effective thermal conductivity when heat enters the cell in the transverse or longitudinal direction [27]. The unit cell model developed by Tee (shown in Figure 5.1) incorporated the anisotropic thermal conductivity of graphite layers [48]. The model was also developed by adapting the electrical and thermal resistance network analogy. In Tee's study, the unidirectional thermal conductivity of the graphite foam was obtained to be:

$$k^* = k_g(1-t)^2 + \frac{k_{sl}k_{sj}t^2}{k_{sl}t + k_{sj}(1-t)} + \frac{2k_{st}k_gt(1-t)}{k_gt + k_{st}(1-t)} \quad (5.5)$$

where k_g , k_{sj} , k_{sl} , and k_{st} represent the thermal conductivity for: the gas portion, the solid portion at the junctions (nodes), the ligands (struts) in the longitudinal direction, and the ligands in the transverse direction. t in equation 5.5 is a normalized thickness related to the porosity of the graphite foam.

Figure 5.1: Cubical unit cell for deriving a term to calculate the effective thermal conductivity .

5.1 Unit Cell

This study develops a unit cell to calculate the effective thermal conductivity for the interface in which RVC foam is coated with graphite and the adhesive is penetrated into the foam structure. One cell represents approximately one pore. Ligands are solid RVC foam coated with graphine layers. Glue is assumed to fully occupy the voided volume of the unit cell, and it carries an isotropic thermal conductivity. This unit cell differs from the previous models, by including the anisotropic thermal conductivity characteristics of the graphene coating. The heat enters graphene layers in either the transverse or the longitudinal direction. On the other hand, the thermal conductivity of glue penetration

is isotropic. After obtaining the effective thermal conductivity of the interface region, it is used in equation 4.4 as discussed in chapter 4.2. Equation 4.4 controls the adhesive penetration thickness.

By modifying the unit cell developed in Figure 5.1, the resulting unit cell shown in Figure 5.2 is obtained. This unit cell includes ligands with RVC foam and graphite layers. The length of the simplified unit cell represents the diameter of the pore, determined by the volume fraction (density) of the carbon foam after applying the graphitic coating (CVD). Applying similar derivation methods used in Leong's approach, the unit cell can be separated into three sections: top, middle, and bottom [27]. Derivations for obtaining the effective thermal conductivity term utilize equations 2.10 and 2.13 introduced in section 2.2.

Figure 5.2: (a) One unit cell represents one pore. (b) Section view of the unit cell shows graphite layers, RVC foam, and nodes. (c) One ligand shows cross-sectional area of RVC foam and graphite layers.

As shown in Figure 5.3, the upper and bottom portions share the same geometry; they will have the same derived equation for the effective thermal conductivity. A detailed derivation is shown in section 5.2 where equations 5.6 and 5.7 represent the effective thermal conductivity term for the upper and middle portions, respectively. Since three portions of the unit cell are parallel to each other with respect to the heat direction

Figure 5.3: Separate the unit cell into three portions: upper, middle, bottom.

(assuming one-dimension, steady-state thermal), equations 5.6 and 5.7 are substituted into equation 2.13. Equation 5.8 was derived to represent the overall effective thermal conductivity for the entire unit cell.

$$k_{eu} = \frac{2k_{eu1}G + k_{eu2}(L - 2G)}{L} \quad (5.6)$$

$$k_{em} = \frac{2k_{em1}G + k_{em2}(L - 2G)}{L} \quad (5.7)$$

$$k_e = \frac{k_{eu}G + k_{em}(L - 2G) + k_{eb}G}{L} \quad (5.8)$$

k_{eu} , k_{em} , and k_{eb} represent the effective thermal conductivity for the upper, middle, and bottom portions, respectively. k_{eu1} , k_{eu2} , k_{em1} , and k_{em2} represent different sections in the upper and middle portions. The upper and bottom portions have the same derivation.

5.2 Derivation of the effective thermal conductivity for a cell

A thermal resistance network was utilized to obtain the desired term for all the participating components. As shown in Figure 5.4a, heat enters the unit cell in one direction. An assumption was made that this analysis runs in steady-state thermal; thus, there is no diffusion of any participating fluid. Prior to the derivation, the notations for different components in the unit cell are established. The length of the unit cell is noted as L , and it is the same for all edges. The corners of the unit cell are colored black and referred to as *nodes*. Figure 5.4b provides dimensions for the RVC foam and the graphite layers; they are denoted as VC and G , respectively. It is important to reiterate that although heat only enters the unit cell in one direction, it can enter the ligand in either the longitudinal or the transverse direction. Table 5.1 summarizes all components with their notations.

Figure 5.4: (a) Assuming heat only enters the unit cell in one direction. (b) Heat enters ligands in either the longitudinal or the transverse direction with different values of thermal conductivity and cross-sectional area.

Table 5.1: Notation for all components of the unit cell.

Notation	Component
L	Length of the unit cell
G	Thickness of graphite layers
VC	Length of reticulated vitreous carbon foam (including G)
$node$	Eight corners of the unit cell
$glue$	Voided volume: adhesive material with the selected filler
$graphite, l$	Graphite layers in longitudinal direction with respect to heat
$graphite, t$	Graphite layers in transverse direction with respect to heat

When a multilayered composite material has orthotropic heat transfer properties, it results in different thermal conductivity when heat enters in different directions such as the transverse or longitudinal direction. The heat transfer path for both directions are shown in Figure 5.5. The same concept can be applied to our unit cell — heat enters different components in different directions depending on the orientation of the portion to be analyzed. It is worth introducing the equation for each direction once more since they will be the primary two used throughout the derivation.

Figure 5.5: Path of heat enters composite materials in normal and planar directions.

In the case that heat enters in the normal (transverse) direction:

$$R_n = \frac{t_a}{k_a A} + \frac{t_b}{k_b A} \rightarrow \frac{t_{total}}{k_n A} = \frac{t_a}{k_a A} + \frac{t_b}{k_b A} \quad (5.9)$$

where $A = WL$. Since the value for A is the same for each layer, the effective thermal conductivity (when the heat enters in the normal direction) can be shown as:

$$\frac{t_{total}}{k_n} = \frac{t_a}{k_a} + \frac{t_b}{k_b} \longrightarrow k_n = \frac{t_{total}k_a k_b}{k_a t_a + k_b t_b} \quad (5.10)$$

When heat enters in the planar (longitudinal) direction:

$$\frac{1}{R_p} = \frac{L}{k_a t_a W + k_b t_b W} \rightarrow \frac{L}{k_p t_{total} W} = \frac{L}{k_a t_a W + k_b t_b W} \quad (5.11)$$

where values of W and L are the same for each layer, the effective thermal conductivity (when heat enters in the planar direction) can be shown as:

$$k_p t_{total} = k_a t_a + k_b t_b \longrightarrow k_p = \frac{k_a t_a + k_b t_b}{t_{total}} \quad (5.12)$$

As mentioned in section 5.1, the unit cell is separated into three portions as shown in Figure 5.3, and the heat enters these three portions in the planar direction. Therefore, the overall effective thermal conductivity of the unit cell can be presented as:

$$k_{eff}L = k_{eu}G + k_{em}(L - 2G) + k_{eb}G, k_{eu} = k_{eb} \quad (5.13)$$

where the notation for k_{eu} and k_{em} are summarized in Table 5.2.

Table 5.2: The notations for portions to be analyzed.

Notation	Portion for the analysis
k_{eff}	The overall effective thermal conductivity of the unit cell
k_{eu}	The effective thermal conductivity of the upper portion
k_{em}	The effective thermal conductivity of the middle portion
k_{eb}	The effective thermal conductivity of the bottom portion
k_{node}	The effective thermal conductivity of the node
$k_{ligand,l}$	The effective thermal conductivity of ligands in longitudinal direction
$k_{ligand,t}$	The effective thermal conductivity of ligands in transverse direction

As is shown in Figure 5.6a and Figure 5.6b, the upper and middle portions are each separated into three different sections. Each section either has an isotropic thermal

conductivity value or a derived effective thermal conductivity value. Either the normal or planar effective thermal conductivity is adopted depending on each section's orientation with respect to the heat source direction. For the upper portion, heat enters the three sections in the planar direction, hence the equation becomes:

$$k_{eu} \cdot L = k_{eu1} \cdot G + k_{eu2} \cdot (L - 2G) + k_{eu3} \cdot G \quad (5.14)$$

where $k_{eu1} = k_{eu3}$. k_{eu1} , k_{eu2} , and k_{eu3} denote the first, second, and the third section of the upper portion, respectively.

Figure 5.6: (a) Separating upper portion into three sections. (b) Separating middle portion into three sections.

To start, the first section of the upper portion, $eu1$, is analyzed. As shown in Figure 5.7a, heat enters the unit cell in the normal direction with the following sequence: the node on the left, the graphitic carbon foam in the center, and the node on the right. Therefore, equation 5.15 is derived for the first section of the upper portion:

$$\frac{L}{k_{eu1}} = \frac{2G}{k_{node}} + \frac{L - 2G}{k_{ligand,l}} \quad (5.15)$$

Another equation is developed for $k_{ligand,l}$. Since the heat enters the graphite layers and RVC foam in the planar direction, the following equation is derived:

$$k_{ligand,l} \cdot G^2 = k_{graphite,l} \cdot (G^2 - VC^2) + k_{VC} \cdot VC^2 \quad (5.16)$$

At the second section of the upper portion, $eu2$, heat also enters in normal direction, as is shown in Figure 5.7b. The voided volume of this unit cell is assumed to be filled with the adhesive material; hence the conductivity depends on the filler type. The heat also enters the second section of the upper portion in the normal direction. Although heat enters the ligands in the transverse direction, the equation is essentially the same as equation 5.15 with different notations. The equation for the second section of the upper portion becomes:

$$\frac{L}{k_{eu2}} = \frac{2G}{k_{ligand,t}} + \frac{L - 2G}{k_{glue}} \quad (5.17)$$

Figure 5.7: (a) First section of the upper portion: heat enters the nodes and ligand in a normal direction. (b) Second section of the upper portion and first section of the middle section: heat enters ligands and voided volume in the normal direction.

Another term is developed for $k_{ligand,t}$, but this derivation is more complex since heat enters the graphite layers and RVC foam in the normal direction. In addition, the middle section of the ligands, k_{mix} , has another term since heat enters it in the planar

direction. $k_{ligand,t}$ is derived in two steps:

$$k_{ligand,t} \cdot G = k_{graphite,t} \cdot (G - VC) + k_{mix} \cdot VC \quad (5.18)$$

where

$$\frac{G}{k_{mix}} = \frac{(G - VC)}{k_{graphite,t}} + \frac{VC}{k_{VC}} \quad (5.19)$$

To obtain the effective thermal conductivity term for the upper portion, equations 5.15 and 5.17 are substituted back to equation 5.14.

Similar steps are taken for deriving the effective thermal conductivity term for the middle portion shown in Figure 5.6b. Since heat enters this portion in the planar direction, the equation is derived as follows:

$$k_{em}L = k_{em1}G + k_{em2}(L - 2G) + k_{em3}G \quad (5.20)$$

where $k_{em1} = k_{em3}$. k_{em1} , k_{em2} , and k_{em3} denote the first, the second, and the third section of the middle portion, respectively.

The second section of the middle portion is simply the voided volume which carries the thermal conductivity of the selected adhesive material. Furthermore, the geometry of the first and third sections are the same; only one derivation is needed for either section. The first section of the middle portion is essentially the same as the second section of the upper portion shown in Figure 5.7b. The equation is therefore derived to be:

$$\frac{L}{k_{em1}} = \frac{2G}{k_{ligand,t}} + \frac{L - 2G}{k_{glue}} \quad (5.21)$$

where k_{em1} denotes the effective thermal conductivity for the first section of the middle portion. Equation 5.18 contains the derivation for $k_{ligand,t}$.

6 SENSITIVITY STUDY

A sensitivity study is needed since the accuracy of the outcome will be strongly influenced by the precision of parameter estimation. Error from the experiments can be negligible if the measured parameter sensitivity is high. The effective thermal resistance at the interface, which is a thin carbon foam layer penetrated with the glue, is the value of interest. The sensitivity for the glue thickness layer and the filler thermal conductivity will be observed. The dominant term of the two determines the effective measurement.

6.1 Methodology

Measuring a quantity coming from one or more different measured variables requires obtaining the uncertainties for their experimental measurements. With those uncertainties, errors in the measured quantity can be carried over to ensure an accurate result [49].

If a dependent variable R is a function of x_1 , x_2 , and x_3 , the variable R can be linearly approximated with the Taylor-series expansion shown as [49]:

$$R \cong R_o + \Delta x_1 \left(\frac{\partial R}{\partial x_1} \right) + \Delta x_2 \left(\frac{\partial R}{\partial x_2} \right) + \Delta x_3 \left(\frac{\partial R}{\partial x_3} \right) \quad (6.1)$$

where Δx_1 , Δx_2 , and Δx_3 represent the uncertainties of each parameter.

The resistance of the interface material is the value of interest. Experimentation can be carried out and used for verifying the estimated values after an error propagation analysis is conducted. In this case, the resistance R is the dependent variable which requires a function with respect to the parameters of the experiment. From equation 6.1, the partial derivative terms also represent the sensitivity of each independent variable. The results of the calculation are plotted; the slope of each plot indicates the sensitivity of each dependent variable with respect to the independent variable. The derived equation is used to ensure the accuracy of a particular measurement.

6.2 Results

In accordance with the results obtained, the measurements to be completed in future studies will use the same parameters as shown in the FEA simulations. The parameters include different adhesive material thicknesses and different filler types in the adhesive material.

Based on the derived effective thermal conductivity term from section 5.1, the effective thermal resistance for the composite material covered in section 4.2 is calculated. MATLAB is used to perform the calculation; reference code can be found in Appendix A.3. The thickness of the adhesive material is varied. Figure 6.1 shows the results for when the filler is chosen to be BN or Graphite..

Figure 6.1: Results showing the sensitivity for different filler options and different thicknesses of the adhesive material.

When comparing different filler types in the adhesive material, BN has a steeper slope compared to graphite. When comparing different numbers of the alternating composite

layers (the total adhesive material thickness), more layers result in a steeper slope. Therefore, taking measurements becomes more effective when additional alternating composite layers are applied.

In conclusion, when taking measurements, choosing BN as the type of filler and selecting eight layers of composite materials results in greater sensitivity. The effective thermal resistance can be measured more efficiently with this combination. Increasing the number of layers of adhesive materials will most likely increase the sensitivity; the trade-off in doing so is the increase in the price of the materials as well as the overall mass.

7 PRELIMINARY TESTING RESULTS

Figure 7.1 shows a summarized sample fabrication process. Section 4.2 has discussed the steps. The fabrication process involves slicing the sample in half and placing one half onto another until reaching the desired number of layers.

Figure 7.1: Summarized sample fabrication process.

Section 6.2 showed that the combination of eight alternating layers with the BN filler has the highest sensitivity. For comparison, four different samples were made: 0.2 mm glue layers with the BN filler, 0.2 mm glue layers with the graphite filler, 0.6 mm glue layers with the BN filler, and 0.6 mm glue layers with the graphite filler.

As discussed in section 4.1, the meter bar approach was adopted to complete the measurements. The TIM device used for completing the measurements is shown in Figure 7.2a. The sample was placed between two lead pillars; RS (high temperature) grease was applied connecting the sample and the pillars.

An infrared camera (FLIR A40M with 320 pixels wide) was used to capture the

Figure 7.2: (a) TIM device, the sample is placed between two lead pillars. (b) Thermal image shown with temperature gradients and IR pixels. Figure printed with permission from Graham Beck (QMUL).

temperature drop across the sample. The thermal image is shown in Figure 7.2b; using the color gradients and the pixels can determine temperature drop and the height of the sample. The ruler shown in Figure 7.2a was used temporarily to calibrate IR pixels versus mm.

The calibration was performed for the two lead pillars as illustrated by the red and blue lines in Figure 7.3. Data in the top and bottom lead pillars were fitted with a quadratic function to examine the temperature drop and thermal flux at the top and the bottom of the sample. The rough line segment between the two parallel straight lines represents the thermal resistance of the sample if the heat flux is assumed to be constant. The heat conduction equation is used again:

$$Q = -kA \frac{\Delta T}{\Delta x} \quad (7.1)$$

Neglecting the negative sign and rearranging, the equation becomes:

$$\frac{A_c}{\dot{Q}} \times \Delta T = \Delta x \cdot R_{th} \quad (7.2)$$

where $\frac{A_c}{\dot{Q}}$ is the inverse of the heat flux. Plotting T against x (height) from equation 7.2, the slope represents the thermal resistance of the sample.

Figure 7.3: Temperature vs. height of the sample, after the calibration. Figure printed with permission from Graham Beck (QMUL).

7.1 Preliminary Testing Data

Each sample has two measurements performed, listed in Table 7.1. Heat is the input and the total ΔT is used to calculate the thermal resistance and the thermal impedance. The heat is applied onto the samples with a cross-sectional surface of 4 cm^2 . Thermal impedance can be calculated by multiplying the thermal resistance by the cross-sectional area where the heat enters the sample. The heat transfer coefficient is evaluated because the thickness of each layer is exceedingly thin and the effect of heat

spread laterally (in the planar direction of the layer) is negligible. Therefore, it is better to quantify the effect by showing how much heat per unit area the heat conducts for a given temperature drop across the layer.

Table 7.1: Preliminary testing data for different sets of samples with graphite and boron nitride fillers.

Sample	Heat Input [W/m · K]	Total ΔT [K]	Thermal Resistance [K/W]	Thermal Impedance [K · cm ² /W]	Heat Transfer Coefficient [kW/m ² · K]
G6.1	2.11	10.77	5.10	20.42	19.8
G6.2	2.06	11.56	5.61	22.45	15.8
B6.1	2.10	13.22	6.30	25.18	12.5
B6.2	1.95	13.97	7.16	28.66	9.8
G2.1	2.07	12.28	5.93	23.72	14.2
G2.2	2.10	10.97	5.22	20.90	18.7
B2.1	2.05	12.06	5.88	23.53	14.3
B2.2	2.08	11.86	5.70	22.81	15.4

Note: G represents graphite filler and B represents boron nitride.

6.1 and 6.2 represent the first and the second tests with 600 micron meter of the glue layers; and 2.1 and 2.2 represent the first and the second tests with 200 micron meter of the glue layers. Measurement data are provided by Graham Beck (QMUL).

The samples with thicker layers of glue are expected to perform better than the samples with thinner layers of glue; it is also expected that glue with the higher thermal conductivity filler (graphite) would also perform better. When comparing G6 cases with B6 cases, the glue with the graphite filler did indeed perform better (lower thermal resistance) than the BN filler. However, when comparing the glue thicknesses, the difference of the thermal resistance was not as prominent. Noticeably, the glue with BN filler performed better with thinner layers, which differs from what was predicted. These uncertain results might be due to the noise or edges of the samples damaged during the fabrication process. Additionally, these are preliminary experimental results and further testing is needed. To ensure discernible data are presented, a statistical approach with more testing data is required. This will help determine if the discrepancies are due to damage in the samples and/or noise; this may also verify if the results are repeatable. This approach will be taken in future studies.

8 DISCUSSION AND CONCLUSIONS

The simulated results from this study were first validated using methodologies from Allcomp Inc's original report [10]. The effective thermal conductivity for the 0.205 g/cc graphitic foam was measured to be approximately 28.7 W/mK. Another FEA model was developed in this study to incorporate the anisotropic thermal conductivity for the graphene coating, as well as the interaction between the graphitic foam and the glue layer. The cross-sectional area of ligands for the new model was found to be approximately $179 \mu m^2$, which corresponds to a density of approximately 0.21 g/cc (shown in appendix A.1).

Using this new model, the heat flux in the graphitic foam reached saturation when the glue thickness was in the range of 0.125 mm to 0.21 mm. This thickness variance depends on the filler type used for the glue, the cell size, and the amount of contact area between the ligands and bonded titanium surface. The heat transfer coefficients obtained were indistinguishable when a glue saturation thickness of 0.2 mm or 0.6 mm was applied. This implies that the performance, when applying either of these glue thicknesses, is the same. This is an important finding since minimizing weight is one of the goals of this study.

Using a thickness of 0.2 mm, the effective thermal conductivity of graphitic foam with the glue was improved from 28.7 [W/mK] to 29.4 [W/mK] and 30.4 [W/mK]; this is equivalent to a 2.2% and 5.8% improvement for BN filler and graphite filler, respectively.

This study has shown that parameters at the interface alter the thermal behavior at the interface. Although the variation is not substantial, it is important to control the thickness of the glue layer to provide an optimal thermal performance at the interface.

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A APPENDICES

A.1 Foam Density vs. CVD Coating Area

Table for calculated results of CVD coating area corresponds to foam densities will be shown in this section.

Foam Density	Solid Density	Relative Density	α	Gf	a	dp [mm]	df [mm]	foam area [μm^2]	RVC_area [μm^2]	CVD area [μm^2]
0.09	1.6	0.05625	0.94375	0.75493946	0.17782758	0.16569315	0.02946481	681.863183	831.25	-149.3868166
0.103	1.6631068	0.06193228	0.93806772	0.7873924	0.1827077	0.16500502	0.03014769	713.835135	831.25	-117.4148648
0.116	1.71206897	0.06775428	0.93224572	0.8161908	0.18770094	0.16430683	0.03084055	747.023085	831.25	-84.22691514
0.129	1.75116279	0.07366534	0.92633466	0.84144179	0.19275847	0.16360565	0.03153638	781.112252	831.25	-50.13774755
0.142	1.78309859	0.07963665	0.92036335	0.86342977	0.19785039	0.16290572	0.03223096	815.898977	831.25	-15.35102316
0.155	1.80967742	0.08565062	0.91434938	0.88249397	0.20295666	0.16220981	0.03292156	851.237504	831.25	19.98750377
0.168	1.83214286	0.09169591	0.90830409	0.89897605	0.20806299	0.16151981	0.03360629	887.015378	831.25	55.76537761
0.181	1.85138122	0.09776485	0.90223515	0.91319761	0.21315862	0.16083708	0.03428381	923.141043	831.25	91.89104268
0.194	1.86804124	0.1038521	0.8961479	0.92545128	0.21823519	0.16016262	0.03495312	959.537149	831.25	128.2871488
0.207	1.8826087	0.10995381	0.89004619	0.93599828	0.22328602	0.15949718	0.03561349	996.136738	831.25	164.8867382
0.22	1.89545455	0.11606715	0.88393285	0.94506907	0.22830573	0.15884128	0.03626437	1032.88095	831.25	201.6309463
0.233	1.90686695	0.12218996	0.87781004	0.95286545	0.23328988	0.15819535	0.03690537	1069.71755	831.25	238.4675522
0.246	1.91707317	0.12832061	0.87167939	0.95956321	0.23823488	0.15755967	0.03753621	1106.60001	831.25	275.3500112
0.259	1.92625483	0.13445781	0.86554219	0.9653149	0.24313777	0.15693442	0.03815668	1143.48677	831.25	312.2367699
0.272	1.93455882	0.14060053	0.85939947	0.97025259	0.24799619	0.15631972	0.03876669	1180.34075	831.25	349.0907484
0.285	1.94210526	0.14674797	0.85325203	0.97449037	0.25280822	0.15571561	0.03936619	1217.12893	831.25	385.8789285
0.298	1.94899329	0.15289945	0.84710055	0.97812665	0.25757241	0.1551221	0.03995517	1253.82201	831.25	422.5720053
0.311	1.95530547	0.15905443	0.84094557	0.98124624	0.26228763	0.15453912	0.0405337	1290.39408	831.25	459.1440799
0.324	1.96111111	0.16521246	0.83478754	0.98392213	0.2669531	0.15396659	0.04110186	1326.82238	831.25	495.5723811
0.337	1.96646884	0.17137317	0.82862683	0.98621714	0.2715683	0.15340439	0.04165977	1363.08701	831.25	531.8370073
0.35	1.97142857	0.17753623	0.82246377	0.98818524	0.27613296	0.15285237	0.04220758	1399.17068	831.25	567.9206807

Figure A.1: Foam Density vs. CVD Coating Area

A.2 MATLAB Codes for Back-of-Envelope Calculation

MATLAB codes written for completing the back-of-envelope calculation will be shown in this section.

```
1 %%%%%%%%% Metal %%%%%%%%%
2 metal_area = 3.4636*10^-8;           %[m^2]
3 metal_k = 16.4;
4 metal_length = 0.1*10^-3;           %[m]
5 R_metal = metal_length/(metal_area*metal_k);
6 Q = metal_area*115749;               %[W]
7
8 %%%%%%%%% Ligands %%%%%%%%%
9 ligand_area = 1.79*10^(-10)          ;           %[m^2]
10 ligand_k=1800;                       %assume isotropic thermal
11                                     %conductivity
12
13 ligand_length1 = 0.00005611;         %[m]
14 ligand_length2 = 0.00006547;         %[m]
15 ligand_length3 = 0.00005611;         %[m]
16 length = 5*(ligand_length1+ligand_length2+ligand_length3);
17 vertical_length = 5*0.00014585;      %[m]
18
19 %%%%%%%%% Resistance %%%%%%%%%
20 ligand_R = length/(ligand_area*ligand_k);
21 vertical_R = vertical_length/(ligand_area*ligand_k);
22 ligand_R_eff = ligand_R/6;
23 vertical_R_eff = vertical_R/6;
24
25 %%%%%%%%% Total Thermal Resistance %%%%%%%%%
26 R_total = R_metal+ligand_R_eff+R_metal;
27 vertical_R_total = R_metal+vertical_R_eff+R_metal;
28
29 T_c = 0.94761;
30 T_h = T_c + Q*R_total
31 T_h_vertical = T_c + Q*vertical_R_total
32
33 %%%%%%%%% Percent Error %%%%%%%%%
34 simulated_T_h = 3.8892;
35 Error_length = abs((T_h - simulated_T_h))/simulated_T_h*100
36 Error_vertical = abs((T_h_vertical - simulated_T_h))/simulated_T_h*100
```

A.3 MATLAB Codes for Sensitivity Study

MATLAB code written for the sensitivity study will be shown in this section.

```
1 clear
2 clc
3
4 cell_size = 200*10^(-6); % m approximately 200 micro meter.
5 % Approximate cell size is
6 % 150 to 250 micro
7 VC = 35*10^(-6); % m 34 micro meter for vitreous carbon diameter
8 % , it's a fixed number
9 foam_density = 0.4; % <— user can input it
10 v_cell = cell_size^3;
11 ligand = (cell_size - ((cell_size^3 - foam_density * ...
12 cell_size^3)/6)^(1/3))/2;
13 G = (ligand - VC)/2;
14
15
16 k_glue = 3.5; % conductiivity of glue
17 k_glue_graphite = 3.5;
18 k_gra_t = 3; % conductivity of graphite in transverse direction
19 k_gra_l = 1800; % (1500+1800)/2;
20 % conductivity of graphite
21 % in longitudinal direction
22 k_VC = 0.085; % conductivity of vitreous carbon
23 k_node = 1800; % assume to be conductivity of bulk graphite
24
25 %%%%%%%%% Top Section %%%%%%%%%
26
27 k_ligand_mix = (G*k_gra_t*k_VC) / ...
28 ((G-VC)*k_VC+VC*k_gra_t);
29 k_ligand_t = (G-VC)*k_gra_t/G + VC*k_ligand_mix/G;
30 k_ligand_l = k_gra_l*(G^2-VC^2)/G^2 + k_VC*VC^2/G^2;
31 k_eu2 = cell_size*k_ligand_t*k_glue / ...
32 (2*G*k_glue+k_ligand_t*(cell_size-2*G));
33 k_eu1 = cell_size*k_node / ...
34 (2*G*k_ligand_l+(cell_size-2*G)*k_node);
35 k_eu3 = k_eu1;
36
37 k_eu = k_eu1*G+k_eu2*(cell_size-2*G)+k_eu3*G;
38 k_eb = k_eu;
39
40 %%%%%%%%% Middle Section %%%%%%%%%
41
42 k_em1 = cell_size*k_ligand_t*k_glue / ...
43 (VC*k_gra_t+(cell_size-VC)*k_VC);
44 k_em2 = k_glue;
45 k_em3 = k_em1;
46
47 k_em = (k_em1*G+k_em2*(cell_size-2*G)+k_em3*G) / ...
```

```

48         cell_size;
49
50 %%%%%%%%% Overall Foam Region conductivity %%%%%%%%%
51
52 k_int = (k_eu*G + k_em*(cell_size-2*G) + k_eb*G) / ...
53         cell_size;
54 k_gra_t=1.5;
55
56 %%%%%%%%% Stacked Comosite %%%%%%%%%
57
58 t_Titanium = 0.1*10^(-3); % 0.1 micro
59 k_Titanium = 16.4 ;
60 t_Foam = 3*10^(-3);
61 k_Foam = 30;
62 R_Titanium = t_Titanium/k_Titanium;
63 R_Foam = t_Foam/k_Foam;
64 n_4=4;
65 n_8=8;
66 n_16=16;
67
68
69 %syms A
70 t = 0.1*10^(-3):0.05*10^(-3):0.5*10^(-3); % varying thickness
71                                         % of glue layer
72 R_eff_int = t/k_int;
73 R_eff_4 = n_4*(R_Titanium+t/k_int+R_Foam);
74 R_eff_8 = n_8*(R_Titanium+t/k_int+R_Foam);
75 R_eff_16 = n_16*(R_Titanium+t/k_int+R_Foam);

```