Paper ID #45746

An independent study on designing and building of an ASTM D5470 standard apparatus for testing thermal performance of various materials

Hammad Afzal Quddus, Mercer University

Hammad Quddus is an undergraduate student pursuing a B.S. in Mechanical Engineering at Mercer University expecting to graduate in May 2025. He has spent the past two years as an undergraduate research assistant under Dr. Chandan Roy, where he has worked on building and designing a cost-effective thermal interface material testing apparatus.

Landon James Yarbrough, Mercer University
Miss Megan Elizabeth Batchelor, Mercer University

I am a sophomore studying mechanical engineering at Mercer University.

Dr. Chandan Roy, Mercer University

Dr. Chandan Roy is an assistant professor in Mechanical Engineering in the School of Engineering at Mercer University in Macon, GA. He received his Ph.D. in Mechanical Engineering from Auburn University in Auburn, AL. Dr. Roy published many peer-reviewed articles. His research interests include engineering education, heat transfer, thermal management of electronics, thin film analysis, and thermal barrier coatings.

An independent study on designing and building an ASTM D5470 standard apparatus for testing thermal performance of various materials

Abstract

The goal of this independent study is to design a thermal test setup for future research and to provide students with hands-on learning experience. A steady-state thermal test setup has been outlined in ASTM D5470 standard. The apparatus consists of two metered bars (hot & cold). Electrical heat is supplied through one bar as the other bar is cooled. The sample is placed between the two metered bars. Each meter bar is equipped with several temperature sensors to measure the drop across the sample. This setup can measure the thermal resistance and thermal conductivity of various thermal interface materials (TIMs). The function of the TIM is to enhance the heat transfer between two solid surfaces by displacing the air gaps from the interfaces. An ideal TIM should have high thermal conductivity, low thermal resistance, high compliance, and excellent reliability. This paper describes the design and building of the setup. After building the setup, a series of tests were conducted to assess the thermal performance of various TIMs, which are discussed.

Introduction

Research and development for new technologies are developing very fast and this requires tremendous amounts of computing power and advanced electronics. As power processing per unit area increases, heat dissipation also increases. And when the processor is in contact with the heat sink, only a small percentage of the surface is actually touching. Most of the remaining space consists of air, which has a very low thermal conductivity of 0.024 $W \cdot m^{-1} \cdot K^{-1}$ [1], and thus prevents an efficient heat transfer from the processor to the heat sink. Imperfect surface contact between the processor and the heat sink is a major limiting factor for creating new electronics. Thermal Interface Materials (TIMs) are thermally conductive materials used to improve surface contact with a thermally conductive material, displacing the air and increasing interfacial heat transfer between the heat sink and processor and this prevents overheating of the system.

The objective was to produce repeatable and reliable results using a setup, which costs significantly less than commercial testers. This would make TIM testing more accessible to high school laboratories and developing nations. The goal of this project was to improve the design of a cost-effective TIM (thermal interface material) testing device to be more similar to commercially available testing units. The TIM testing device design follows ASTM standard D5470-12 for testing the thermal properties of different mediums of TIMs such as thermal impedance and thermal conductivity. To test the specified thermal properties of the TIM, it was placed between a hot and cold meter bar. Temperature gradients were measured in each meter bar to determine its thermal impedance by using heat transfer analysis. The final deliverables of this project include an upgraded, cost-effective TIM testing device, test results validating the machine's accuracy, and a user guide.

Problem Definition

Modern-day advanced electronics dissipate excess heat, and this creates a high demand for effective thermal interface materials. That makes the research and development of advanced thermal interface materials crucial. However, TIM testing devices, which are used to test for the material's thermodynamic properties can cost more than $50,000. This makes TIM testing inaccessible to various talented scientists and engineers across the world, especially in high school laboratories and developing nations.

Problem Solution

Addressing the problem of extremely expensive TIM testers in the market, a senior design team at Mercer University decided to build their own TIM testing device, which would cost significantly less than commercially available units. The research team has been working on modifying this setup to replicate the results in terms of accuracy and repeatability of the TIM testers that are found in the market.

Setup Description

The ASTM D5470 setup consists of two meter bars (hold and cold) and heat flow was made one dimensional using proper insulation. The temperature gradients in each meter bar, heat flow, and the TIM's thickness were measured to determine its thermal resistance and conductivity through fundamental heat transfer analysis. For the thermocouples, there were four holes on the top meter bar and two holes are in the bottom meter bar. A cooling plate, connected to a chiller, was located on the bottom to keep the temperature constant. There were two pipes through which water flows and keeps the bottom plate isothermal. A heater, which was connected to a power supply, was inserted into the top meter bar. Two cylindrical columns were on the sides to provide support. A rectangular aluminum plate was then placed on the top heater, which was bolted down on the columns. On top of the aluminum plate, the pressure was applied using a compressed air cylinder. The pressure was provided by an air hose and could go up to 100 psi. Lastly, another aluminum flat plate was bolted on the columns to provide stability, especially after pressure was applied. Once pressure was applied, the desired insulation could be wrapped around the meter bar. Pressure was supplied by a compressed air cylinder and could be adjusted through the pressure gauge.

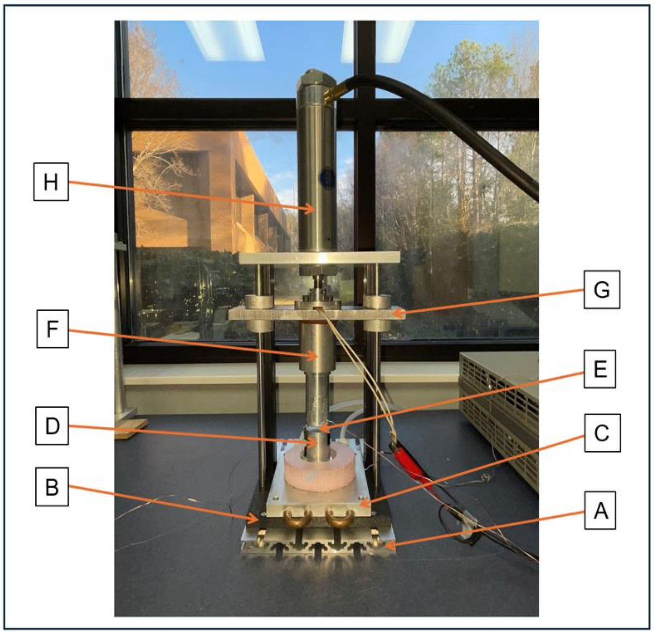

Figure 1: The current setup without insulation

A. Aluminum base plate
B. 3-D printed plate
C. Aluminum cold plate
D. Bottom half of meter bar
E. TIM insertion space
F. Top half of meter bar
G. Vertically sliding plate
H. Compressed air cylinder

Testing Method

The thermal interface material was inserted in between the two meter bars and then the top meter bar was pressed against the bottom meter bar. Any excess material was removed from the surface. Pressure was applied and then insulation was wrapped around the meter bars. Power was supplied to the heater which heats the top meter bar. Heat travels one-dimensionally to the bottom meter bar and in the meantime, the cooling plate keeps the bottom meter bar's temperature constant. Data was taken once a steady state was reached. For batch tests, the pressure was increased once the data for the desired pressure value had been taken.

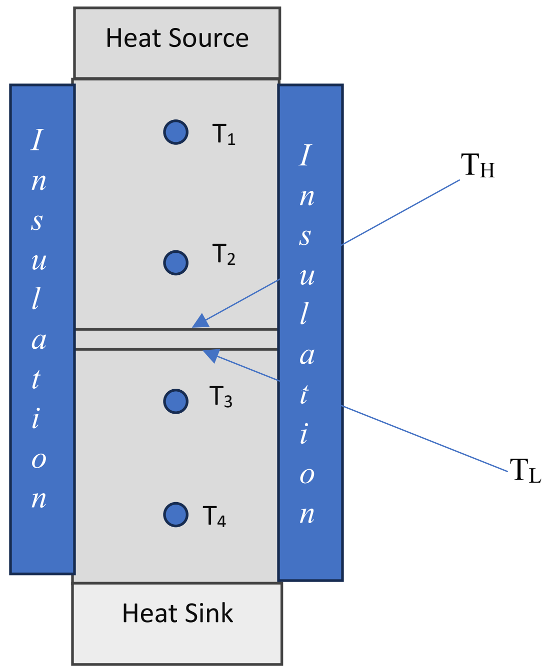

Figure 2: Simplified schematic of a typical TIM tester setup

Calculating Thermal Impedance & Apparent Thermal Conductivity

Thermal Impedance was calculated to analyze the performance of the materials and ASTM Standard D5470 [2] method was used to perform the calculations.

The temperatures at the tip of the hot meter bar and on the surface of the cold meter bar would be required to calculate the thermal impedance. Linear interpolation was used to find both these temperatures.

$$T_H = T_2 - \frac{d_B}{d_A} \times [T_1 - T_2] \qquad (1)$$

T_H= temperature of the hot meter bar surface in contact with the specimen, K,

T_1 = warmer temperature of the hot meter bar, K,

T_2= cooler temperature of the hot meter bar, K,

d_A = distance between T1 and T2, m,

d_B = distance from T2 to the surface of the hot meter bar in contact with the specimen, m

$$T_L = T_3 + \frac{d_C}{d_D} \times [T_3 - T_4] \qquad (2)$$

T_L= temperature of the cold meter bar surface in contact with the specimen, K,

T_3= warmer temperature of the cold meter bar, K,

T_4 = cooler temperature of the cold meter bar, K,

d_C = distance between T3 and T4, m,

d_D = distance from T3 to the surface of the cold meter bar in contact with the specimen, m.

T_H and T_L are calculated using the temperature values measured by the four thermocouples and the distance between each of the thermocouples.

$$Q = V \times I \quad (3)$$

The power supplied is calculated using the voltage and current and can be seen in equation (3).

$$\theta = \frac{A}{Q} \times [T_H - T_L] \quad (4)$$

The final step was to calculate the thermal impedance T_H and T_L are calculated using equations (1) and (2) and the Q is calculated using equation (3). The area of the sample is measured.

Insulation

In the original setup, closed-foam insulation was used. This proved to be a big disadvantage since it covered the whole setup. It was crucial for the two meter bars to be perfectly aligned as there needs to be one-dimensional heat flow throughout the whole apparatus. With closed-foam insulation, there was no way to ensure this condition. It was possible that once pressure was applied, there might have been a slight misalignment, and even a minor misalignment could bring air gaps into the system, making the data inaccurate.

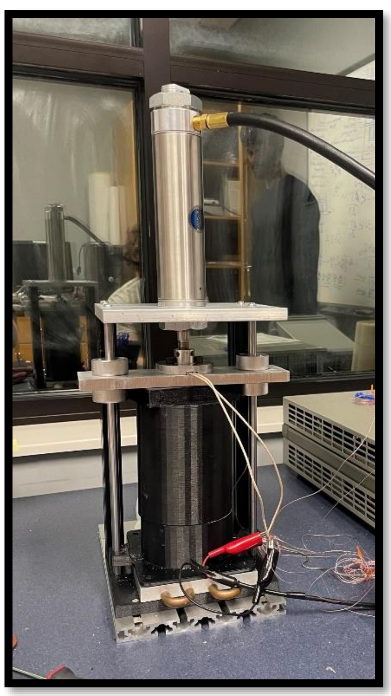

Figure 3: Previous Design with Closed-Foam Insulation

The team decided to switch from closed-foam insulation to fiberglass insulation. For this particular insulation, there was an opportunity to wrap it around once pressure had been applied and proper alignment was ensured. Once the pressure would be applied, and proper alignment would be ensured, and any material that was sticking outside or on the edges of the testing location would be cleared, the insulation would be wrapped. The same procedure was followed for a batch test, where tests would be conducted on multiple pressures. As pressure would increase incrementally, it was crucial to ensure that proper alignment was still maintained.

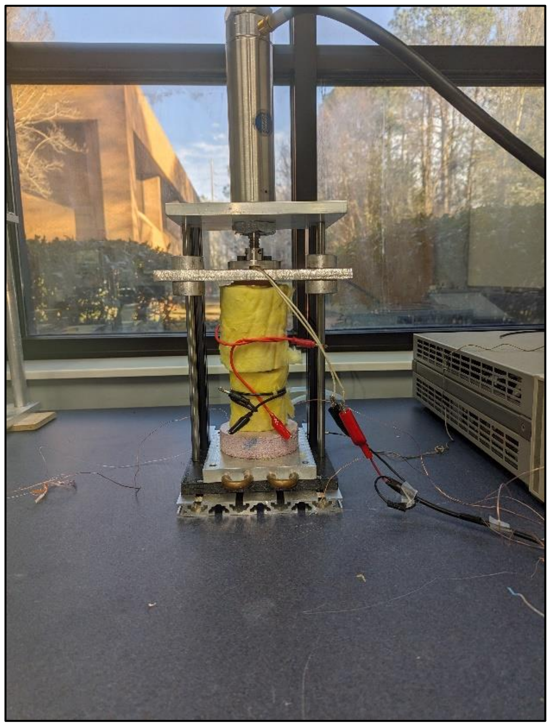

Figure 4: Current Design with Fiberglass Insulation

Data Collection

The objective was to calculate the thermal impedance in different pressure values during the TIM testing process. The first step was to wait until a steady state is reached. It took about 30-45 minutes to reach steady-state (the temperature of the thermocouples stopped changing). According to the standard, all tests were performed at an average interface temperature of 50^{o}C. This was done by monitoring the average temperature between T2 and T3 (figure 2) to be approximately 50^{o}C. The four temperature values were recorded by thermocouples and displayed by a data acquisition system. Pressure values were measured using the pressure gauge.

Test Results

The tests were performed without any sample (called Bare test) and using two types of thermal pads: Silicone thermal pad and non-silicone thermal pad. The results of all tests are discussed below.

Bare Test

To ensure the functionality of the apparatus, tests were performed without any sample between the meter bars. The thermal impedance was measured on different pressure values to ensure that the setup was working. As expected, the thermal impedance decreased as pressure increased. Another objective of performing this experiment was to check the thermal impedance if there were no sample and air gaps were filling the space between the meter bars. The thermal impedance calculated for the different pressures are shown in table 1 below and are very high. Compared to the thermal impedance values using silicone and non-silicone thermal pads, as is mentioned in the next sections, the values are higher by almost one order of magnitude.

Table 1: Change in Thermal Impedance with an Increase in Pressure for Bare tests

Pressure (psi)	Thermal Impedance ($^oC*in^2/W$)
30	1.49
50	1.21

Silicone Thermal Pad

The first material tested was the silicone thermal pad. According to the manufacturer, it has a thermal conductivity of 11.0 W/m*K, which is relatively high, and it has extremely low thermal resistance under minimal force. Figure 5 below displays the data from tests conducted at 4 different pressures on a single sample of silicone pad, ranging from 20 psi to 50 psi. Both the manufacturer’s data [3] and the tested results have been plotted on the same graph as a comparison. The experimental results are very close to the manufacturer's data for pressures of 30, 40, and 50 psi. The experimental value for 20 psi, however, is slightly lower than the reported value.

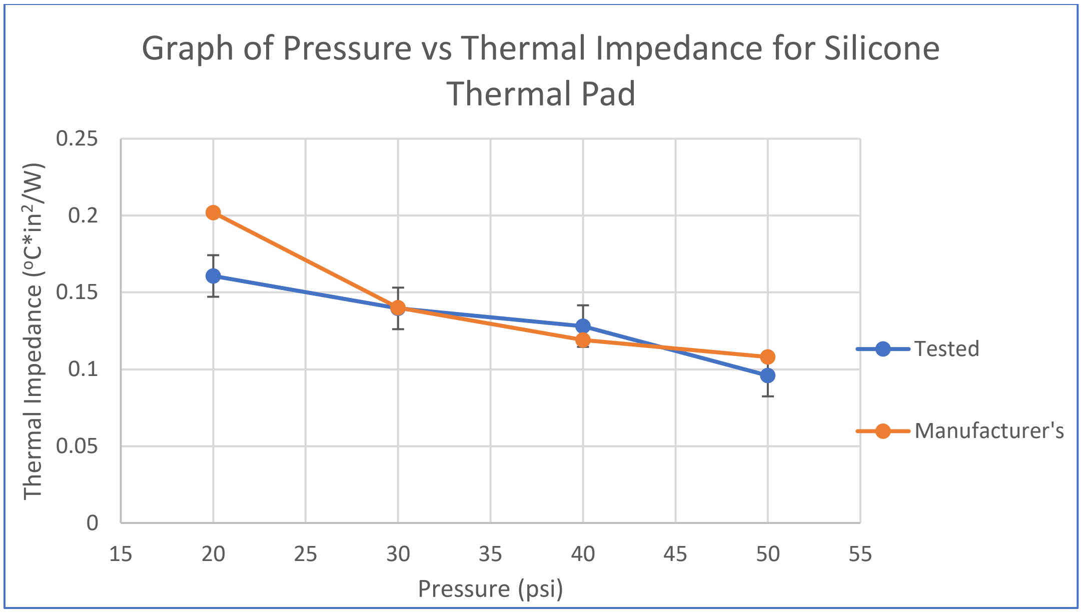

Figure 5: The graph represents how the thermal impedance changes with a change in the pressure applied to the silicone pad of 1 mm thick.

Non-silicone Thermal Conductive Pad

The Non-Silicone Thermal Pad sample is made of non-silicon resin material. It is flexible and has great thermal conduction, low compressive stress, and high compressive characteristics can effectively reduce the stress load of components, so that the equipment only needs to bear less mechanical stress, and at the same time, it can have low thermal resistance and high thermal conductivity [4].

The manufacturer only provided data for 10, 20, and 30 psi [4] and the reported thermal conductivity is 11 W/m*K. The team decided to perform a test on 30 psi as well as 70 and 100 psi to check how much the thermal impedance decreases with pressure increment. The trend that was observed is shown in Figure 6.

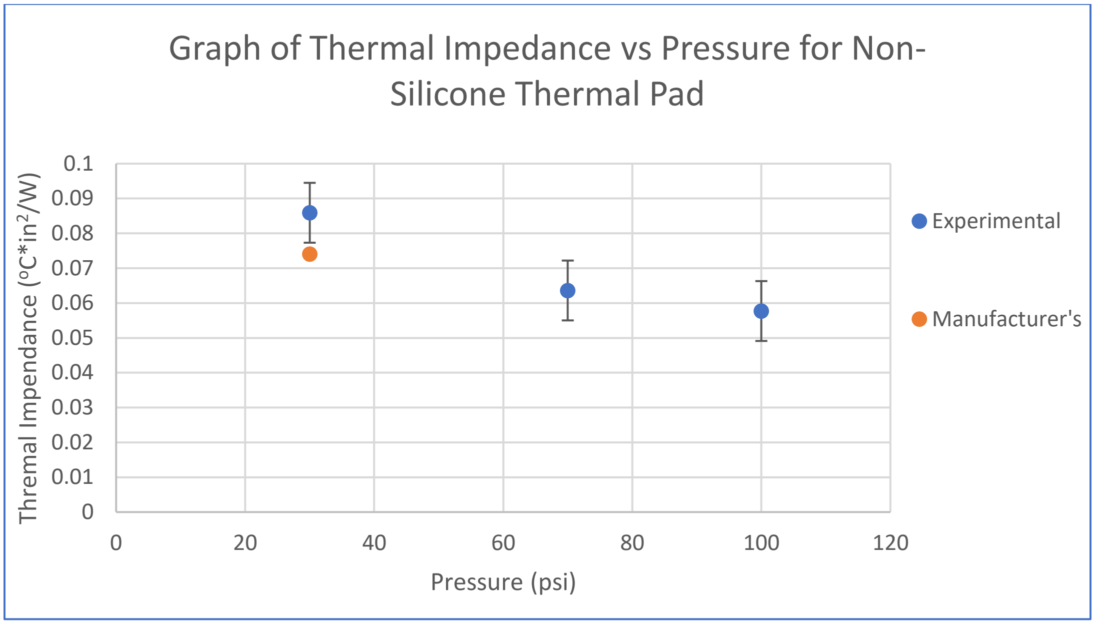

Figure 6: The graph represents how the thermal impedance changes with a change in the pressure applied to the non-silicone thermal pad of 1 mm thick.

Conclusion

In conclusion, the team has successfully designed, built, and tested a TIM testing apparatus, which can be used for conducting further research. The total cost of the TIM tester, including raw materials, parts, instruments, and the chiller pump, was $8,327, which was less than 20% of the cost of a commercial TIM tester. The objective of building this apparatus was so that TIM testing can become accessible to high-school laboratories and developing nations across the world. The team has proven that repeatable tests can be conducted using the design. In addition, this independent study course required the students to use their in-depth knowledge of heat transfer and thermodynamics in a practical setting. Through this independent study course, the students gained exposure to a variety of experimental tools, learned how to design and build, tackled practical challenges, and developed essential skills that will be crucial for building a successful engineering career after graduation.

References

[1] W. Xing, Y. Xu, C. Song, and T. Deng, "Recent Advances in Thermal Interface Materials for Thermal Management of High-Power Electronics," *Nanomaterials*, vol. 12, no. 19, p. 3365, Jan. 2022, doi: https://doi.org/10.3390/nano12193365.
[2] "Test Method for Thermal Transmission Properties of Thermally Conductive Electrical Insulation Materials," doi: https://doi.org/10.1520/d5470-12.

[3] "Silicone Thermal Gap Pad | LiPOLY® Gap Filler," *LiPOLY® Thermal Interface Materials (TIMs)*, Oct. 03, 2024 https://lipolytim.com/wp-content/uploads/2023/10/T-work7000.pdf (accessed Nov. 18, 2024).
[4] "Non-Silicone Thermal Pad | LiPOLY® Gap Filler," *LiPOLY® Thermal Interface Materials (TIMs)*, Sep. 25, 2024. https://lipolytim.com/wp-content/uploads/2023/09/N800B-s.pdf (accessed Nov. 18, 2024).