

Design and Manufacture of Thermal Conductivity Apparatus

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Abstract

Thermal conductivity is a key property in materials engineering, influencing how materials are classified and used. Accurate measurement of this material property is key in many industries, such as construction, electronics, and aerospace, where both thermal insulation and conduction are key properties. This research focused on the design of equipment used to test this material property, specifically using the guarded hot plate method of testing. The project established the underlying theoretical framework behind the measurement process. Although the apparatus was not fully constructed, several important insights were found throughout the testing process. Such as the suitability of certain ceramics, the suitability of temperature cycling hotplates, and the methods of reducing wasted heat generation within the system. These insights provide an insight into the future construction of such equipment as well as the refinement of the system to assure maximum possible accuracy.

Keywords: Thermal Conductivity, Engineering, Materials, Testing, CAD, Guarded Hot Plate

Introduction

During the testing and development of new materials, measuring the thermal conductivity is essential for classifying and describing the material. Thermal conductivity indicates how efficiently a given material transfers heat, and this directly affects how a material can be utilised in engineering. For example, materials with a low thermal conductivity are commonly used as insulators or heat shields in aerospace applications, while those with a high conductivity are used in thermal management systems such as radiators.

Due to the importance of accurately measuring the thermal conductivity, this research aimed to design a piece of apparatus that could reliably provide readings with a low error tolerance and was easy to use. The aim was not only to research how such a device could be constructed, but also to identify the materials and design considerations necessary to minimise errors.

Project Background

My interest in this specific area of materials engineering stems from the space industry, particularly the research and development of rocket engines and spacecraft re-entry, which must withstand extremely high temperatures for prolonged periods. This meant that by researching and designing a piece of equipment that tests materials for this, I would have a better understanding of the materials used and how they are tested in industry.

Whilst there are already existing versions of this equipment, they are often very expensive (around £11,000 for a lab suitable model (SPW Industrial, n.d.)) and require a large amount of setup and training to use. My aim in the design of this equipment was to make it as intuitive and simple as possible while still maintaining as much accuracy as commercially available products.

Literature Review

Much of the literature in this field is either theoretical or very specific and therefore provides little guidance on building test apparatus; instead, many of them explain the application of the measurements. This is likely since there are international standards for the testing of thermal conductivity, specifically ISO 8302:1991 (International Organization for Standardization, 1991). However, in the literature available, it is clear that the method for testing chosen for this study is particularly suited for homogeneous materials undergoing steady-state heating (Dubois, 2015).

In the design of thermal conductivity testing apparatus, it is also important to prevent heat from leaving the system before it has been transferred through the sample (Yang, I, 2018), as this would waste a portion of the energy used to heat the sample and lower the overall efficiency of the apparatus.

For the mathematics required to make this device work, the report produced by Aalborg University (Johra, 2019) on the guarded hotplate method was particularly useful in guiding my understanding of the topic.

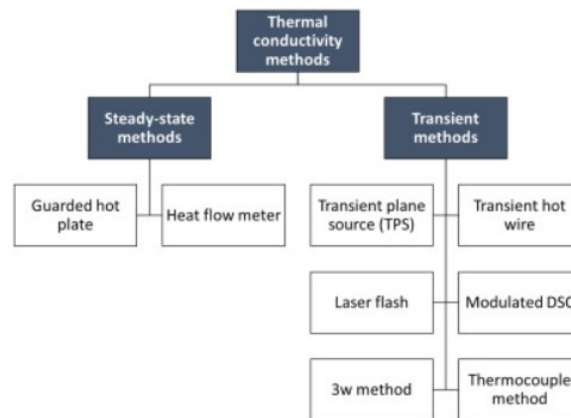


Figure 1 Thermal Conductivity Testing Methods. [4]

Whilst there are multiple methods to test thermal conductivity (Fig. 1), the method chosen for in-depth research and development is the guarded hot plate method (Fig. 2), where the sample is held between a non-heated plate and a heated one. This can be expanded to test two samples at once, as the heating element is surrounded by highly thermal conductive material on all sides. Thermocouples are then added to both the hot plate and the cool plate in order to calculate the thermal conductivity of the sample between them.

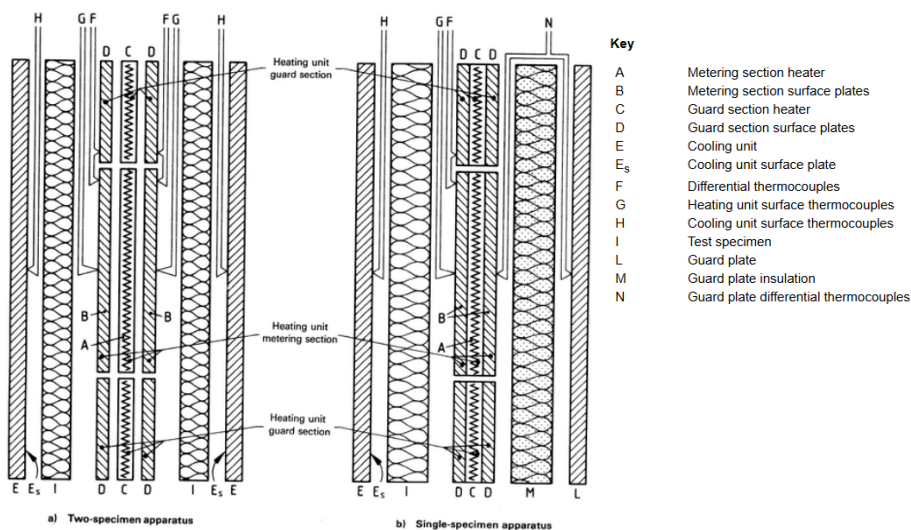


Figure 2 Cross-section design of a guarded hotplate testing apparatus. (International Organization for Standardization, 1991)

Whilst modern research predominantly uses standardised methods of thermal conductivity testing, prior results prove to be unreliable at times (Palacios, et al., 2019), as is the research that is based off of those results. Therefore, it is important to ensure that thermal conductivity testing is based on reliable measurements from standardised equipment, and that the equipment used meets the standard set out in ISO 8302:1991.

Methodology

Using the guarded hot plate method, a hot plate is used to heat a surface onto which the test sample is placed. A second plate (made of the same material as the lower surface) is then placed over the sample, and the temperature is then measured by thermocouples. To automate this process, an Arduino could be used to read the temperature from the thermocouples, the power consumed by the hotplate, and allow the user to input both the thickness and surface area of the sample. This data would then be used in the equation:

$$\lambda = \frac{Q\Delta x}{A\Delta T}$$

Where λ is the thermal conductivity ($\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$), Q is the heat flow through the sample (W), Δx is the thickness of the sample (m), A is the surface area of the sample (m^2), and ΔT is the temperature difference between the hot and cold plates (Johra, 2019). The resulting value for λ would then be displayed on a screen.

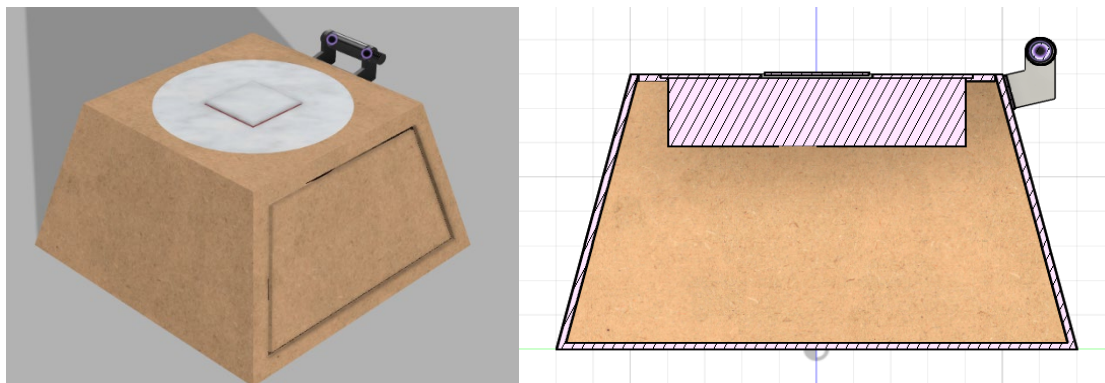


Figure 3 Initial CAD design and cross-section of thermal conductivity testing apparatus.

Once the method of testing was researched, a hotplate was sourced, as well as other base materials used in the initial testing. A ceramic tile was used as the two plates to clamp the sample. At this stage, a design was made in Fusion 360 of what the finished apparatus would look like and how it would work.

This design featured a case around the hotplate, and (although not shown in this design) would feature an arm to hold the cold plate over the top of the sample. Also featured on the device would be a small screen and rotary encoder, used as a control device to enter the thickness and surface area of the sample.

Results

To characterise the hotplate and be able to accurately calculate later data, it was important to know what temperature the hotplate was aiming to reach at each setting, as that can then be used during calibration of the thermocouples used in the final apparatus.

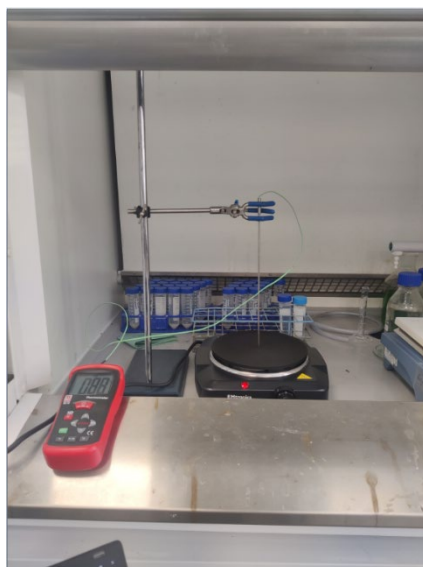
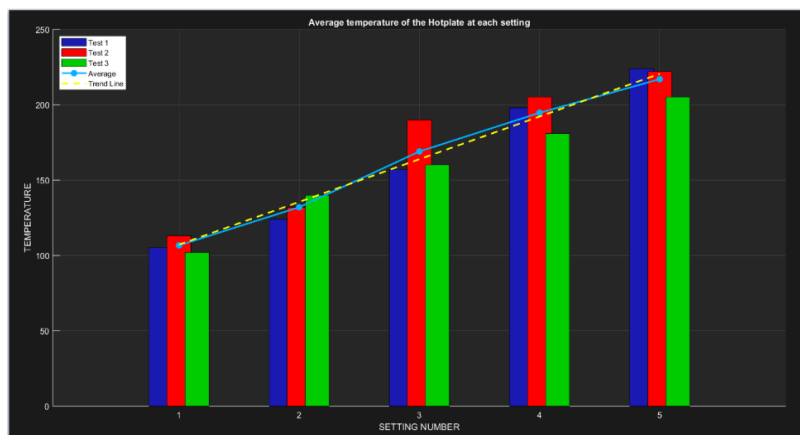


Figure 4 Set up of the experiment for the hotplate test

Setting	1	2	3	4	5
Test 1 (°C)	105	124	157	198	224
Test 2 (°C)	113	132	190	205	222
Test 3 (°C)	102	140	160	181	205
Average (°C)	106.67	132	169	194.67	217

Table 1 Data collected from the hotplate test

To conduct the experiment, the hotplate was placed in a fume hood due to the potential release of smoke and fumes during initial use. A lab stand positioned a thermocouple at the centre of the hotplate (Figure 1), which was then set to its first heating level and allowed to stabilise. As the hotplate uses a bi-metallic strip to cycle the heating element, reaching a steady state took some time. Once stable, the temperature was recorded (Table 1). The thermocouple was then removed until it returned to room temperature before being replaced for another reading. This process was repeated three times per setting across all five settings. The collected data was graphed in MATLAB (Graph 1).



Graph 1 MATLAB graph of the temperatures achieved on each hotplate setting

Shown in Graph 1, the average temperature (indicated by the light blue line) follows a fairly linear trend, which is further supported by the yellow dashed trend line. This linearity is useful for the next stage of testing.

Two sections of a large ceramic tile were cut into octagons with a distance between the sides equal to the circumference of the top of the hot plate (185mm). This was to ensure the hotplate transferred as much heat as possible to the ceramic without much overhanging the edge and radiating the heat away from future test samples.

These were firstly placed onto the hotplate with no sample, this was to establish how evenly the ceramic would transmit heat to a future test sample. This test was conducted using a thermal imaging camera to assess the distribution of heat (Fig. 5), a stopwatch to measure the time it takes for the tile to reach a uniform temperature, and a thermocouple to validate the readings from the thermal imaging camera.

Test No.	1	2	3	4	5
Average Time Taken (s)	60	120	150	240	N/A
Highest Recorded Temperature (°C)	89.2	147	194	268	N/A

Table 2 Recordings from Ceramic testing

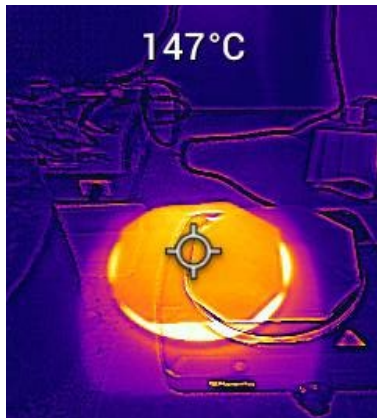


Figure 5 Thermal image of setting two with the tile on the hotplate

During testing, the rapid temperature changes caused the tile to fracture into large chunks. This failure likely stemmed from one or more factors: structural inconsistencies within the ceramic (e.g. pores, voids, or pre-existing microfractures) that acted as crack initiation sites; uneven heating due to the patterned surface on one side of the tile, which created localised hot spots and stress concentrations; and the heating method of the hotplate itself, which cycles and can lead to the tile surface reaching significantly higher temperatures than the exposed metal plate.

Together, these effects created large thermal gradients within the tile, generating stresses that exceeded the material's strength. Although the tile was effective at absorbing heat, it proved unsuitable for rapid thermal testing, as its low thermal shock resistance and poor heat conduction make failure at elevated temperatures likely.

At this stage in the research, other materials were considered for the guard plates, such as iron (or other conductive metals) or heat-resistant mats to assure an even spread of heat through the test sample.

Importantly, the time it would take to complete the project was greater than the time available, and therefore, testing was halted at this point. However, from the research conducted, it is clear that this system would work effectively to test the thermal conductivity of various materials. Based on the data gathered, a more conductive pair of clamping plates would be the best choice, as this would allow for a more rapid test of the sample between the plates.

The construction of the external components of the apparatus should be made from heat-proof mats and include plenty of ventilation so as not to overheat the electronics (such as the microcontroller and hotplate) inside. As for the coding of the microcontroller, it would likely just be a simple circuit, connecting the thermocouples to a relevant controller board, which is then connected to the microcontroller. The code for which would simply be to log the temperatures of both the hot and cold plates once they reach a steady state, and then utilise the equation for λ , which is then displayed on the screen.

UROS Experience

My experience of the UROS project has been entirely positive. I have greatly enjoyed taking the lead in a research project, and although the project didn't advance as far as I would have liked, I still learned many valuable lessons. Not only did I refine my research skills and ability to pick out relevant information quickly, but I also learned a

lot about the design of equipment within the engineering field. Especially that it will always take longer than you think.

The only thing more that I'd want from the UROS project is time, as that would allow me to fully complete the construction of the apparatus, as well as testing and calibrating it so that it works as intended.

Conclusion

This project aimed to explore the design of a testing apparatus for measuring the thermal conductivity of materials using the guarded hot plate method. Through this, the theoretical basis for determining the thermal conductivity was established, and initial designs were completed with considerations for accurate measurement and ease of use.

Whilst the apparatus wasn't constructed, a lot has been learnt about the materials and procedures required for constructing this equipment in the future. Firstly, the ceramic originally selected to act as the clamping plates is not appropriate for this application. When used in the completed apparatus, the ceramic would experience a lot of temperature cycling, and whilst the potential for failure from this could be mitigated through only using the lowest settings on the hot plate, this would result in the tests taking much longer, especially if testing a material with a low thermal conductivity. Secondly, if this apparatus is later constructed, a hotplate that regulates its temperature differently would be recommended, as the cycling nature of the one used in these experiments likely contributed heavily to the failure of the tile.

However, beyond the practical challenges, the project provided valuable insight into the importance of controlling heat losses, ensuring good thermal contact between components, and how the design of equipment affects the accuracy of measurements.

The guarded hot plate method remains the correct choice for this application, and the work completed here is a good starting point for a fully operational piece of testing equipment. Future refinement could involve building the system until completion, calibrating it with reference materials and applying it to test insulators and composites. Such research would be directly relevant to aerospace and the space sector, where low-conductivity materials are critical for spacecraft re-entry.

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