THERMAL DIFFUSIVITY OF STAINLESS STEEL

School of Physics and Astronomy
University of Nottingham

18^{th} of December 2020

The most up to date version of this report can be found at:
`https://www.frost.cx/files/thermal2020.pdf`
The version after this will have fixed citations and references.

Abstract

The thermal diffusivity of a material can be found by observing the rate at which heat propagates though a sample of the material. The flash method of determining thermal diffusivity is one way of using this property, as a pulse of heat energy is put into one side of a plate of material, and the temperature on the other side is measured to give the relationship.

In this experiment the thermal diffusivity of stainless steel was measured using this method and found to be $(2.75 \pm 0.46) \times 10^{-6}$ $\mathrm{m^2s^{-1}}$.

Contents

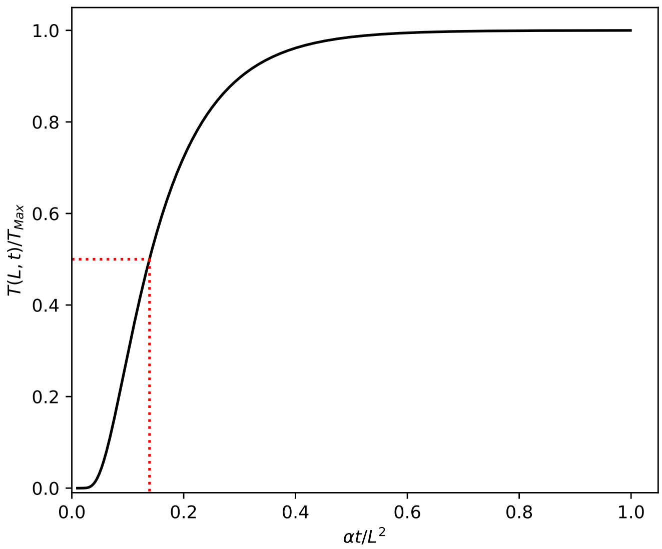

Figure 1: The expected heating curve of the far side of the plate. All units are dimensionless.

1 Introduction

The thermal diffusivity of a material is the property describing the speed at which heat propagates during a change of temperature over time.[?] In this paper the thermal diffusivity of stainless steel will be determined by recreating the flash method of Parker et al.[?] where a pulse of heat generated by a flash gun is used to rapidly heat one side of a thin plate and the rate of heat propagation will be measured using a thermopile.

This method has several advantages compared to alternatives. Due to the very short nature of the flash, the heat is transferred all at once, and the whole measurement takes only a few seconds to take. This not only makes it far quicker that competing methods[?], but also mostly eliminates the effect of cooling of the sample, as the cooling would be negligible in the time taken for the measurement to be taken, and extreme measures such as performing the measurement in a vacuum do not have to be taken. Another benefit is the relative independence of ambient temperature to the measurement, as the heat energy is directly added to the sample, meaning that a consistent rise can be expected so long as the temperature does not cause the sample to change phase.

The expected temperature on the reverse of the sample is a function of the thickness of the sample, and the time from the flash gun firing. The change in temperature is modelled by equation 1, and a dimensionless plot of $T(L,t)/T_{Max}$ against $\alpha t/L^2$ is shown in Figure 1. T_{Max} is the maximum temperature reached by the rear side of the plate, and thus $T_{Max} = \frac{Q}{C\rho L}$.

$$T(L,t) = \frac{Q}{C\rho L}\left[1 + 2\sum_{n=1}^{\infty}(-1)^n \exp\left(-\frac{n^2\pi^2\alpha t}{L^2}\right)\right] \tag{1}$$

By reading Figure 1 at the point where the temperature is half of T_{Max} we find that the relationship between $t_{\frac{1}{2}}$ and α as shown in equation 2, which can be rearranged to find equation 3. This equation can be used to find the thermal diffusivity, α, from the time it takes to reach half the maximum temperature, $t_{\frac{1}{2}}$.

$$t_{\frac{1}{2}} = \frac{\alpha t}{L^2} \tag{2}$$

$$\alpha = 0.139 \frac{L^2}{t_{\frac{1}{2}}} \tag{3}$$

To find $t_{\frac{1}{2}}$,temperature measurements were needed, and they were collected using a thermopile. The thermopile outputs a voltage depending in the temperature, which follows the relationship described in equation 4. This can be simplified to the linear equation 5 using the fact that only a small change of around 1 K occurs on a sample the the region of 300 K. This means that for this experiment voltage can be considered linear to temperature.

$$V \propto T^4 \tag{4}$$

$$V = 4kT^3\delta T \tag{5}$$

The aim for this experiment was to understand the process of thermal diffusion. Specifically we aim to find the thermal diffusivity of stainless steel.

2 Method

The experimental apparatus consisted of a 3D printed plastic base containing a phototransistor and a thermopile, with a depressions to take the plate of the sample. The plate had a slot to let light come through to the phototransistor, as the phototransistor was used to detect when the flash gun fired to allow the data collection to be triggered. The plastic base was opaque and relatively thermally insulating, minimising direct heating of the reverse side of the plate, which was not desired. Figure 2 shows the setup.

The thermopile was connected to the analog input on a data acquisition card, while the phototransistor was attached to the trigger on the same card.

The plates of stainless steel had their thickness measured with a micrometre screw gauge in three different places, and the mean of this measurement was used for further calculations. Five plates were used, ranging from 1.48 ± 0.005 mm to 0.52 ± 0.005 mm in mean thickness. The plates were coated in camphor black to increase the amount of energy absorbed from the flash, as a greater temperature gradient will minimise the effects of random noise.

When collecting the flash data there are several important points to pay attention to. The thermopile should be calibrated such that the cold baseline temperature (likely the ambient temperature) is set as the zero point, as this makes analysis easier, while also potentially limiting the size of the noise floor. The flash gun only fires for a small fraction of a second, but it is important to collect enough data to be ensure the half-time is accurately known. It was found that 1.5 seconds collected plenty of data. The final point to pay attention to is letting the sample cool sufficiently between runs. It was found that

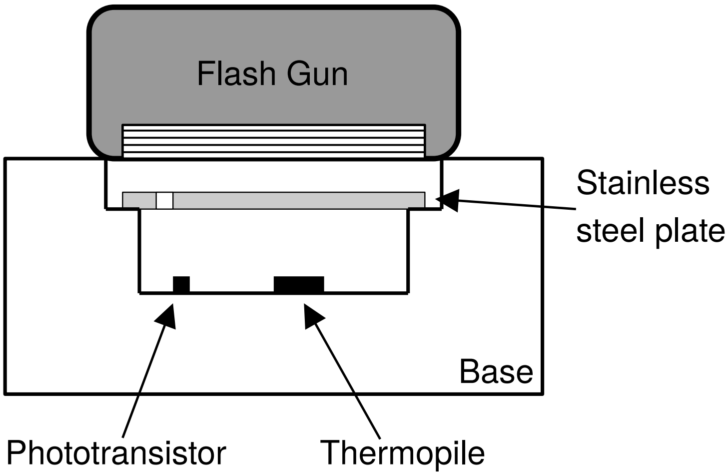

Figure 2: Experimental setup for measuring the thermal diffusivity

a minimum of 30 seconds should pass between samplings, but this could vary significantly depending on the thickness of the sample and energy output of the flash gun.

Data collection was simple enough, with each sample placed into the base before a collection program was run on the computer to which the thermopile and phototransistor were connected. The flash gun was placed on top of the plate, and manually fired. The collection program took a reading of the thermopile many times a second (250,000Hz in this case) and saved it to a file for further processing. For each of the five plates tested, three readings were taken.

The data was analysed to find the half time, the time taken for the temperature to rise halfway from its baseline "cold" temperature to the "hot" temperature that is the maximum it reaches after the flash gun is fired. As the magnitude of the temperature is not important in of itself, the voltage could be directly plotted to find $t_{\frac{1}{2}}$, as per equation 5.

The challenge in this analysis was removing the large spike that was generated when the flash gun fired. This spike came about because of the large amount of electrical noise generated by the flash gun when fired. It could have been manually removed from the data, but to speed up analysis a rolling average was taken instead, which lowered the spike to below the half time, preventing it from causing issues. This rolling average also helped by removing noise from the data, aiding in identifying the half time. Once the half time was identified, equation 3 could be used to find the thermal diffusivity.

3 Results

The thickness of the plates was determined to the accuracy of a micrometer screw gauge, which was ±0.005mm. The accuracy of the thermopile was much harder to quantify. The data from the thermopile was quite noisy, and contained a big spike from the EMF pulse generated by the flash gun firing, as seen in Figure 3. The data was smoothed with a rolling mean to produce Figure 3, and this also removed the noise in the data, though it does not quantify it. As many readings of the data were taken it should have minimal random error.

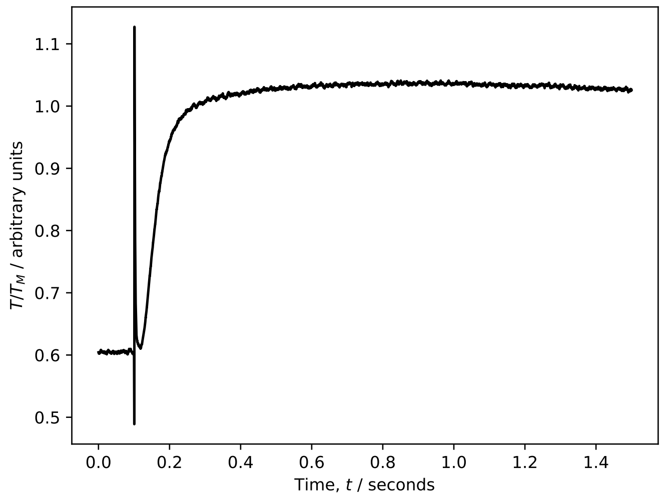

Figure 3: Graph of temperature against time. The spike early on is electrical noise from the flash gun.

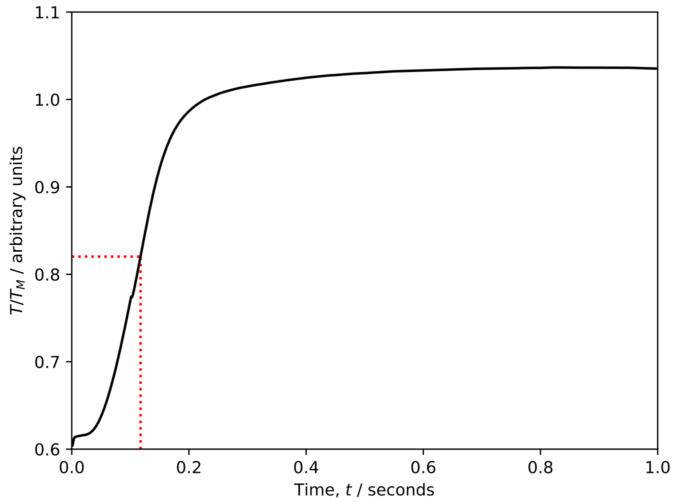

Figure 4: Graph of temperature against time. The graph has been smoothed with a rolling mean to remove the spike. The dotted lines mark the middle temperature, and thus $t_{\frac{1}{2}}$.

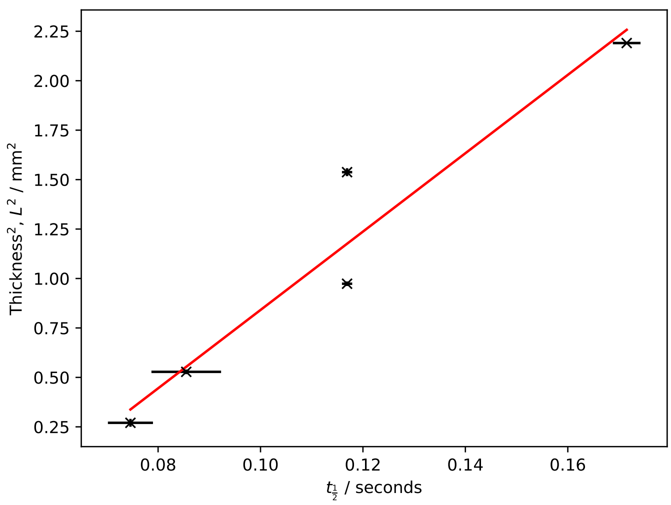

Figure 5: Graph of L^2 against $t_{\frac{1}{2}}$. The gradient is 19.8 ± 3.3 mm^{2}s^{-1} and the Y-intercept is -1.14 mm^2

Figure 3 shows the relationship between plate thickness and half time that was detailed in equation 3, and the gradient, which was found through the least squares method, can simply be used to work out the thermal diffusivity. The thermal diffusivity for stainless steel thus comes out as $(2.75 \pm 0.46) \times 10^{-6}$ m^{2}s^{-1}.

4 Discussion of Results

The expected value for thermal diffusivity for 403 stainless steel is 3.68×10^{-6} m^{2}s^{-1}[?]. The type of steel that the plates were made of was not specified, but 403 stainless steel is a good guess, as it is by far the most common type of stainless steel. The value obtained in this paper's measurement was $(2.75 \pm 0.46) \times 10^{-6}$ m^{2}s^{-1}, which is two standard deviations away from the expected value. This indicates that some errors were unaccounted for, which is also reflected in the least squared line of regression on Figure 3 not passing through the error bars of everything. It does at least fall within the right ball park, so supports the flash method being an effective way of determining thermal diffusivity.

Much of the random error in this experiment stemmed from the EMF noise produced by the flash gun. In particular the main source of noise in the curve was probably the electrical field generated while the gun was recharging itself. This could have been mitigated by either getting a flash gun that does not automatically recharge, though this would no longer be an off the shelf component, or by using a more powerful flashgun such that the temperature rise itself is an even stronger signal. Another way of mitigating it would be to have the base be EMF shielding for the thermopile, but this would still leave the issue of the sample not necessarily shielding. There was also a reasonable amount of variation in the plate thickness, especially in the thinner plates, and this may have been where they were not perfectly flat. This could be minimised by making the plates all a bit thicker, as the absolute thickness doesn't really matter for this experiment, so long as the temperature change travels fast enough to prevent any cooling from occurring.

Systematic error came from a couple of sources. The thermopile had a slow drift in the voltage it would produce, This was mitigated by regularly recalibrating the thermopile, and was quite small in magnitude compared to the voltage produced by the temperature change, but still occasionally made the graphs of raw data such as Figure 3 to go slightly negative. As we are interested in the temperature difference this should not have caused any major issues. Another issue that was not quantified was the uniformity, or lack there of of the flash gun. The method described in this paper makes the assumption that the heat energy is evenly applied to the entire surface of the sample, which is highly unlikely to be the case.

5 Conclusions

The flash method of Parker et al. was used to determine the thermal diffusivity of stainless steel, producing the value $(2.75 \pm 0.46) \times 10^{-6}$ m^{2}s^{-1}, which is two standard deviations away from the expected value. This method was a quick way to find the value of the thermal diffusivity, using off-the-shelf components, and only requiring a small sample of the material.