THERMAL DIFFUSIVITY OF STAINLESS STEEL

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`https://www.frost.cx/files/thermal2020.pdf`

Abstract

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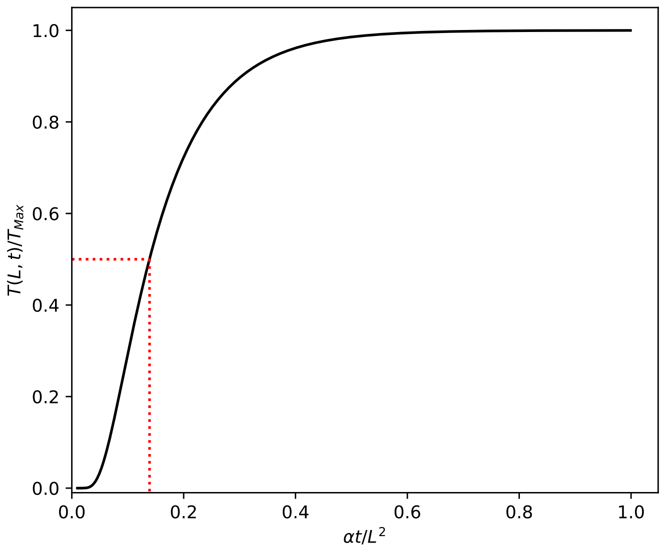

Figure 1: The expected heating curve of the far side of the plate. All units are dimentionless.

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 compaired to alternitives. Due to the very short nature of the flash, the heat is transfered 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 neglegable in the time taken for the measurement to be taken, and extreme measures such as performing the measurment in a vacume do not have to be taken. Another benifit is the relative independance of ambient temperature to the measurement, as the heat energy is directly added to the sample, meaning that a consistant rise can be expected so long as the temerature 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 dimentionless plot of $T(L,t)/T_{Max}$ against $\alpha t/L^2$ is shown in Figure 1. T_{Max} is the maximum temperature reched 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 rarranged 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 occours on a sample the the region of 300 K. This means that for this experiment voltage can be cosidered 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 aquisition 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 a minimum of 30 seconds should pass between samplings, buth this could vary significantly depending on the thickness of the sample and energy output of the flash gun.

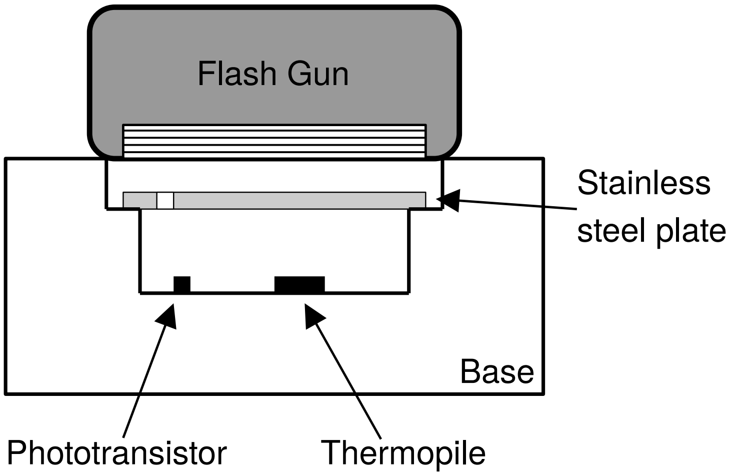

Figure 2: Experimental setup for measuring the thermal diffusivity

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.

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 shows the relationship between plate thickness and half time that was detailed in equation 3, and the gradient can simply be used to work out the thermal diffusivity. The thermal diffusivity for stainless steel thus comes out as $2.75351577122 \times 10^{-6} \pm$ $\mathrm{m}^2\mathrm{s}^{-1}$.

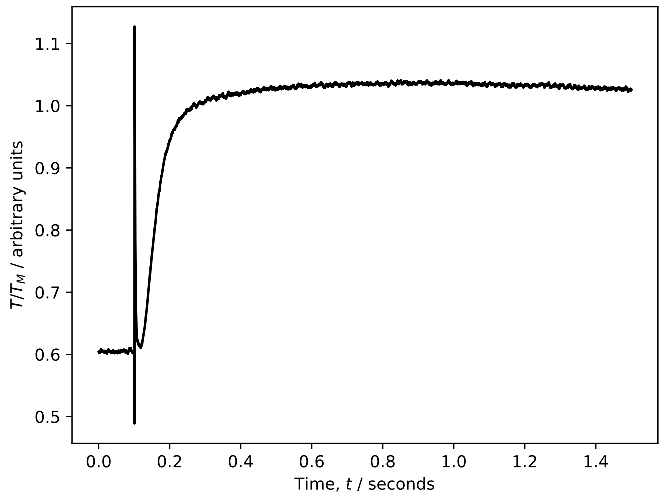

Figure 3: Graph of temperature against time. The spike early on is electrical noise from the flash gun.

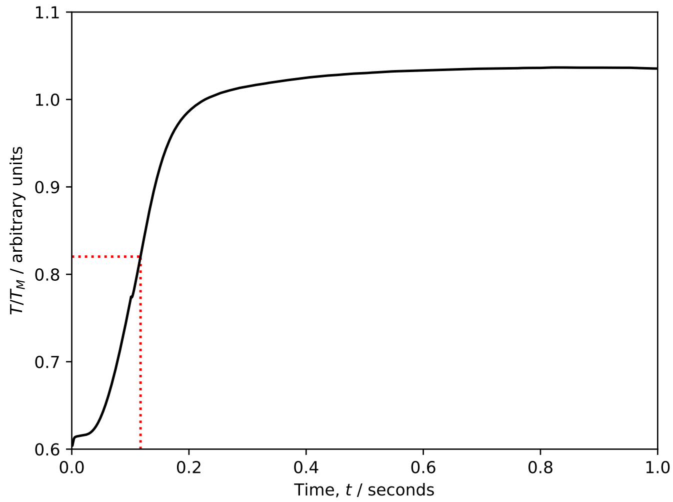

Figure 4: Graph of temperature against time. The graph has been smoothed with a rolling mean to remove the spike. The dotted lines mark the middle temperature, and thus $t_{\frac{1}{2}}$.

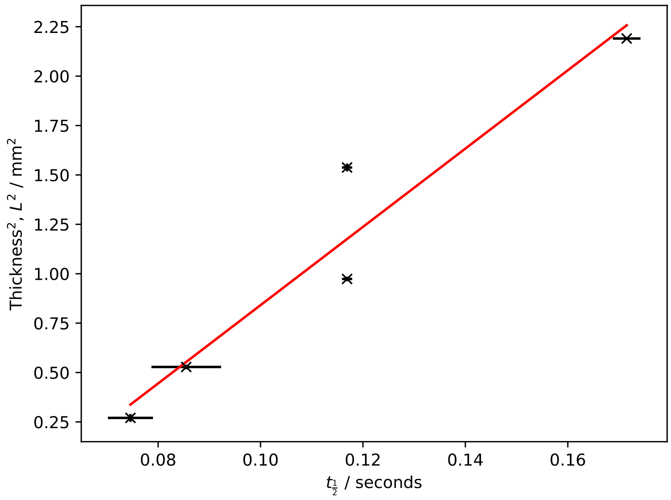

Figure 5: Graph of L^2 against $t_{\frac{1}{2}}$. The gradient is 19.81 mm^{2}s^{-1} and the Y-intercept is -1.14 mm^2

4 Discussion of Results

5 Conclusions