SIMULATIONS ON THE ACCURACY OF LASER-FLASH DATA ANALYSIS

METHODS

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INTRODUCTION

The Laser-Flash thermal diffusivity measurement method can be considered one of the most successful applications of photothermal techniques. This due to the phenomenological and experimental simplicity and ease of reaching better than 1% accuracy over a wide temperature range. The method is based on observing the temperature rise of the sample back face resulting from the absorption of a laser pulse at the other face. There are various approaches for the data reduction and, especially for high temperature measurements where heat loss effects need to be accounted for, they are based on approximations. This is because the inverse function relating thermal properties and heat exchange conditions with the temperature rise temporal shape is not available in closed form. Therefore, detailed error propagation calculations analyses that would take into account all the steps of the data analysis procedures have not in general been performed for data. In this work, simulations of the noise sensitivity and accuracy of selected data reduction schemes were studied using synthetic data. The work was done in connection with the design of a high temperature laser-flash instrument for the measurement of ceramic composites for fusion reactor applications.
The laser-flash thermal diffusivity measurement method is based on applying uniform laser (heat) pulse heating on the sample face and observing the temporal evolution of the temperature on the other side \[1,2\]. A typical measurement setup is shown in Fig. 1. Under optimal conditions the half rise-time of the temperature curve and the sample thickness are enough to reliably extract the material’s thermal diffusivity. At room temperature and with a sensible measurement system the heat losses due to radiation, conduction, or convection are usually negligible, therefore there is no need to use elaborate data reduction procedures; a simple theory will suffice in predicting the temperature rise \[3\]. However, at elevated temperatures the heat loss is no longer negligible while the data is collected: a better data analysis procedure is needed. This situation is illustrated in Fig. 2; the heat loss is visible in the 3000 K curve as a fall at later times. The parameters used in the calculations were: sample thickness 3 mm, laser pulse Energy 1 J, beam (and sample) radius 5 mm, density 1.77 g/cm$^3$, diffusivity 0.72 cm$^2$/s, specific heat 0.65 J/gK, thermal conductivity 90 W/mK, emissivity 1, and temperature 300 and 3000 K, respectively. For the optimal, lossless situation (see Fig. 2, 300 K case) the thermal diffusivity is obtained by

$$\alpha = 0.138 \frac{l^2}{t_{1/2}}$$  \hspace{1cm} (1)

where \(l\) is sample thickness and \(t_{1/2}\) is the half rise-time of the the temperature curve \[1\].

Figure 1. Laser-flash system.

Figure 2. Theoretical temperature vs. time.
The use of fractions other than \( t_{1/2} \) is possible [1]; Fig. 3 shows the result for 10 to 90 percent for the 3000 K data. For higher fractions of the 3000 K curve the diffusivity value is severely overestimated because the curve shape no longer matches that of the theoretical expectation. The data reduction method of choice for high temperature Laser Flash thermal diffusivity measurements can be considered to be that of De Giovanni, which uses temporal moments of order 0 and -1 of the temperature data [4]. The diffusivity is then obtained from a simple polynomial expression.

CALCULATIONAL METHODOLOGY

Simulated data was calculated using the closed form solution given by Watt with the parameters of a graphite sample at a temperature of 3000 K. The high temperature was chosen to emphasize the heat loss effects [5]. The data reduction method is described in Fig. 3b. Data reduction was tested using synthetic data that had a known amount of noise added. To obtain a distribution of values of the diffusivity the same theoretical curve was run through the analysis procedure while only varying the noise. Fig. 4a presents the result for the high temperature case, and Fig. 4b the room temperature case. The noise added was evenly distributed and had amplitude limits of +/- 2% around the normalized curve, as seen in Fig. 3a. The simulated experimental data had 500 points that corresponded to our experimental system; the simulation was run 1000 times in order to obtain the distributions. In the data analysis procedure the rise times to 10% and 80% of the maximum were obtained from 6-point line fits, and the maximum from an 8-point second-order polynomial fit.

\[
\alpha_{\text{calc}} = \alpha_{\text{theor}} \times \frac{t_{\text{rise,10\%}}}{t_{\text{rise,80\%}}} \times \frac{T_{\text{max}}}{T_{\text{norm}}} \times \frac{A}{A_{\text{theor}}}
\]

Figures 3a and 3b. Line/curve fits to data with noise added (a) and the data reduction procedure (b).
CONCLUSIONS

The simulations show that thermal diffusivity can be recovered at an accuracy of 2% and that the relationship between the noise in the waveform recorded and the data follows a near 1 to 1 relationship for the choice of parameters in this simulation. These values of datapoints, noise level, etc. are representative of our thermal diffusivity measurement system. Thus an estimate of the accuracy of measurements obtained using the system can be directly deduced by observing the noise level on the experimental waveform. An acceptance level can be thus set beyond which choice of data analysis method and noise are no longer limiting factors in the accuracy of the diffusivity determination. Eventually a neural network system will be implemented to give the operator warning of non-optimal experimental conditions. The system will be trained with data obtained from the simulations above. However the slight upward shift of the values needs to be further examined. The effect seems to be a worse for the 3000 K situation than for 300 K and gets worse with increasing noise amplitude and noise level.

REFERENCES