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Extending Flash Thermography Method for Thermal Diffusivity Measurements using Finite Pulse Widths

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Abstract

It is shown that the scope of the flash method, to determine thermal diffusivity of materials, can be significantly extended by taking into account the finite pulse widths of realistic flash lamp excitations. The pulse profiles of a commercial flash system are determined and parameterized. A series of 1D FEM simulations are carried out to establish (a) the notion of equivalent rectangular pulse widths and (b) a universal curve that enables correction factors to be determined for thermal diffusivity evaluation. Simulations are validated with experiments carried out with seven flash excitation pulse widths and three materials.

Introduction

Infrared thermography provides an attractive practical method for thermal diffusivity measurements of a material as well as for the non destructive evaluation of defects [1]. Parker et al [2], Philippi et al [3] and Couto et al [4] have proposed methods to measure the thermal diffusivity by applying short heat pulses, using lasers or high speed flash lamps, on the surface and monitoring the radiation. Parker et al [2] proposed the $T_{0.5}$ and the T_x methods for determining thermal diffusivity of the material in transmission mode based on a modified form of the analytical solution for 1D slab of thickness (*L*), thermally insulated at both ends of the thickness, subjected to an instantaneous heat pulse of intensity Q (wm^{-2}) that is absorbed uniformly on front surface at ($x = 0$). The temperature distribution at rear surface ($x = L$; transmission mode of observation) as a function of time *t* is given as

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

where ρ is the density of the material (kgm^{-3}), *C* is the specific heat ($kJkg^{-1}\ K^{-1}$) and α is the thermal diffusivity of the material (m^2s^{-1}). The rear surface temperature distribution is plotted with dimensionless parameters as shown in figure 1.

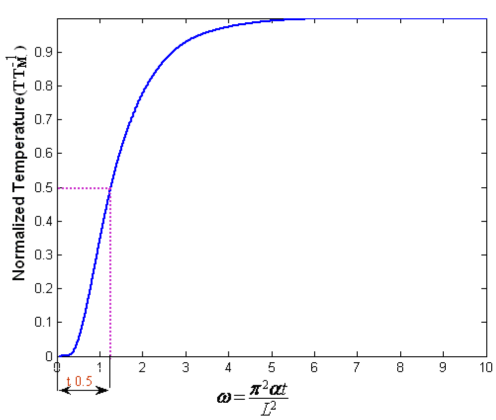

Fig.1. *The dimensionless plot of rear surface temperature time history for thermal diffusivity measurement by Parker's method. [2]*

It was found that the normalized temperature value of 0.5 is reached for a non dimensional variable $\omega = (\pi^2\alpha t/L^2) = 1.38$. Hence, by measuring the time at $T_{0.5}$ and knowing the thickness (*L*) of the sample, the thermal diffusivity (α) of any material can be estimated.

Heckman [5] and Cape [6] for the first time analyzed the finite pulse width effect and heat transfer losses on the sample surfaces. They provided correction factors for diffusivity estimate by assuming a triangular heat pulse, instead of actual pulse shape. Larson and Koyama [7] employed a mathematical model, which incorporates an empirical function closely describing the actual waveform of the heat pulse produced by a flash lamp, and described the effects of finite pulse duration. The present work presents a detailed study undertaken to understand the effect of finite pulse width on thermal diffusivity measurements and to determine the necessary correction factors required for its evaluation.

Present Work

It is shown that the flash method can be used even when the pulse widths are finite or when sample thicknesses are small. The universality of the extended flash method has been demonstrated through detailed FEM simulations and experiments on three different materials and a range of pulse widths encountered in practical flash systems. A simple photodiode circuit, shown in figure 2, was used to determine the actual pulse shape of the flashing system (BALCAR flash lamp model FX 60 powered by the A6400 Asynchronous Nexus power supply). The voltage history, measured using a Digital Storage Oscilloscope with 100 MHz sampling rate and 8 bit vertical resolution, across a fast response photodiode provided the actual profile of the flash pulse.

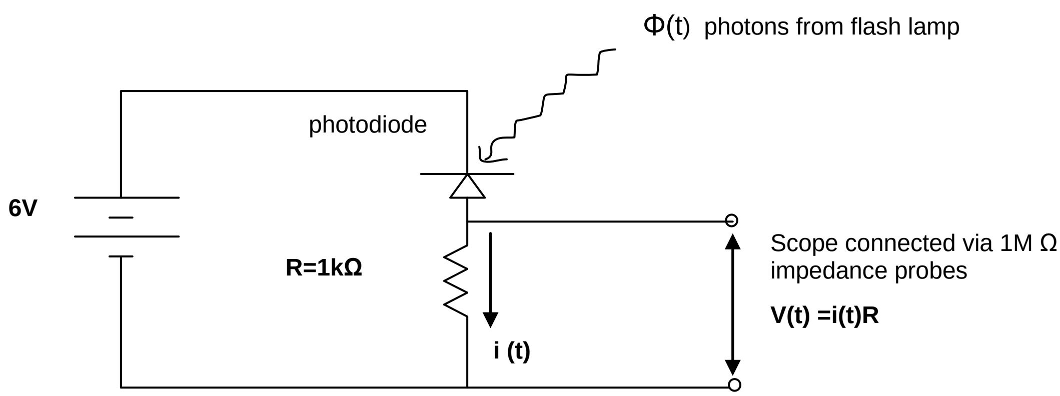

Fig. 2. *Circuit diagram to determine the actual pulse shape of the BALCAR system*

Figure 3 shows the photodiode response and was taken to be linear in the initial rising portion up to the peak amplitude time t_1 and exponential decay thereafter.

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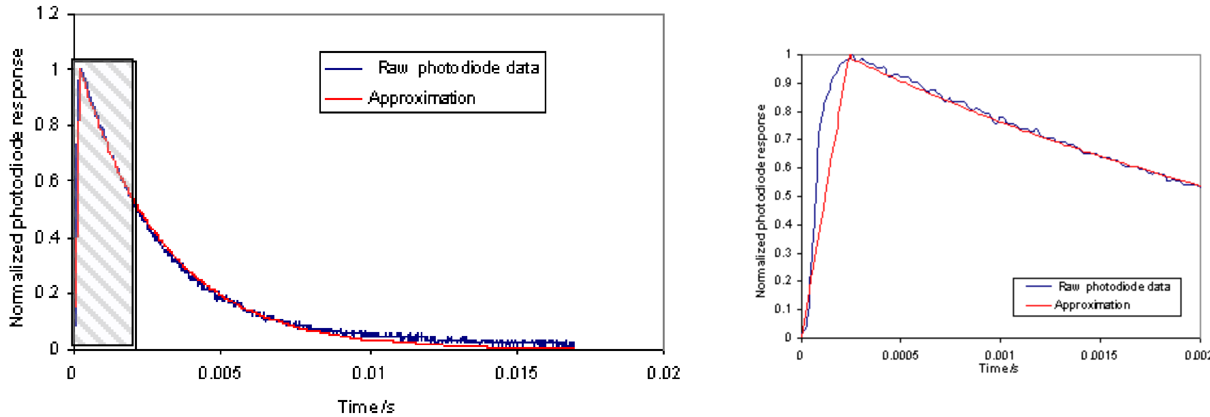

Fig. 3. (a) The measured photodiode response of the flash lamp and its approximation, and (b) Shaded region.

The rise and the fall regions of the pulse are expressed in terms of three pulse shape constants (*a*, *b*, and *c*) as follows:

$$
\begin{aligned}
f(t) &= ct & t \le t_1 \\
f(t) &= a\exp(-bt) & t > t_1
\end{aligned}
\tag{2}
$$

For different power settings of the BALCAR FX 60 flash lamp system powered by Nexus A6400 power pack used in the experiments, pulse shape constants and the peak time (t_1) were measured and are tabulated below in Table 1. These functions were used for subsequent simulations.

Table 1: Pulse shape constants for different lamp power (F) settings.

Lamp Power Settings	*a*	*b*	*c*	t_1 ($\times 10^{-3}$ s)
F9 (3200 J)	1.071	212.64	2500	0.420
F8 (1600 J)	1.079	345.35	3846	0.260
F7 (800 J)	1.104	618.45	4767	0.210
F6 (400 J)	1.253	1210.35	5263	0.190
F5 (200 J)	1.432	2023.54	7692	0.130
F4 (100 J)	1.420	2761.46	8620	0.112

The transient thermal diffusion process was simulated using the implicit solver option under the transient analysis module of the Finite Element Model (FEM) package COMSOL® [8]. The 1D model of the sample was modeled and meshed using linear elements. The discretized time steps required for the calculation were found to be extremely short (1/6000 s) in order to represent the profile adequately. However, this increased the number of computation steps resulting in high computation time and resource requirements suggesting that piece-wise computation would be required for getting the complete time history plot for each specimen.

The possibility of representing the actual pulse by an equivalent rectangular pulse was explored for carrying out simulations. Two approaches to the Equivalent Rectangular Pulse (ERP) as shown in figure 4 were considered:

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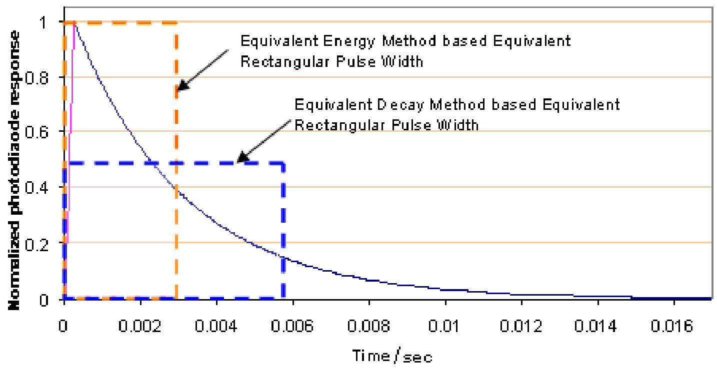

***Fig. 4.** Representation of the Equivalent Rectangular Pulse Width based on Energy Method and Decay Method*

Equivalent Energy Method: The area under the Actual Pulse gives the energy in the pulse, Here the areas corresponding to Actual pulse and Equivalent Rectangular Pulse were equated and the pulse width of the ERP was computed based on the representation that τ_p =Energy under actual pulse/Peak Amplitude (of the rectangular pulse). And, τ_p (Pulse width) was found equal to the width at 1/e of the total height of normalized signal of actual pulse

Equivalent Decay Method: Here, the pulse width of the Equivalent Rectangular Pulse was found equal to twice the width at 1/e of the total height of the normalized signal of the actual pulse and represented by τ_p = 2 width at 1/e of the total height of normalized signal of actual pulse.

It was found that the Equivalent Decay Method was found to better represent the actual pulse and henceforth used for subsequent simulations dealing with ERP pulses. It has been shown that the use of an equivalent rectangular pulse (ERP) for simulation purposes has the advantage that it is computationally faster without loss of accuracy. The results from FEM simulations for thermal diffusivity estimates using the ERP method were validated through experiments using Aluminum, Steel and Zirconium specimens with thicknesses ranging from 1 mm through 15 mm. The maximum error between the experimentally measured results and the FEM simulations was less than 2%. Appropriate material independent proportionality factors have been derived to enable thermal diffusivity estimates to be made for a wide range of material thicknesses, thermal diffusivities and pulse widths.

The flash method originated by Parker et al [2] calculates diffusivity using the proportionality factor of 1.38, which turns out to be a constant, when very short flashes are employed. But when pulses with finite widths are used, the proportionality factor is no longer a constant but instead depends on the material thickness and pulse width of the heating source. The use of an equivalent pulse width is found to establish a relationship between the excitation pulse, the specimen thermal diffusivity and an appropriate proportionality factor. Figure 5 presents the simulated data for three materials and several pulse widths (denoted by F# ranging from F4 to F9) in the form of the proportionality factor as a function of the dimensionless variable $L/\sqrt{(\alpha_o\tau_p)}$ where τ_p is the excitation pulse width. The universality of the proportionality factor is striking. The proportionality factor of 1.38 originally given by Parker et al [2] can be seen to be applicable for $L/\sqrt{(\alpha_o\tau_p)} > 18$. It is shown that a simple modification of the proportionality factor is all that is necessary to handle lower values of $L/\sqrt{(\alpha_o\tau_p)}$ dealing with longer pulse widths or higher diffusivities.

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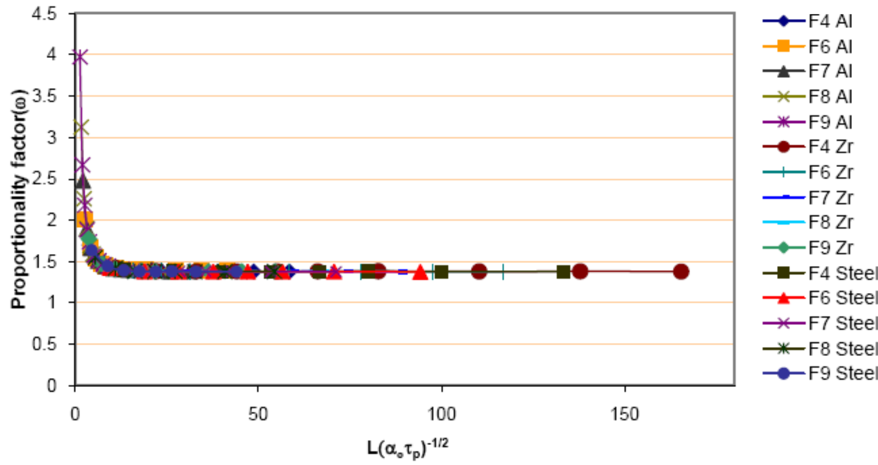

Fig 5. *Universal curve for proportionality factor from FEM simulations*

Summary and Conclusions

It is shown that the flash method can be used even when the pulse widths are finite or when sample thicknesses are small. It has been shown that the actual pulse can be represented by an equivalent rectangular pulse for simulation purposes having the advantage that it is computationally faster without loss of accuracy. Further, the equivalent pulse width helped establish universality of the extended flash method through detailed FEM simulations and experiments on three different materials and a range of equivalent pulse widths encountered in practical flash systems. Specifically, the equivalent rectangular pulse based on the equivalent decay method using the pulse width equal to twice the width at 1/e of the maximum was found to be effective for FEM simulations instead of actual profiles. The ERP method was found to be within 3% of the results obtained using parameterized pulse shapes (obtained from measured values). The results from FEM simulations for thermal diffusivity estimates using the ERP method were verified by experiments using Aluminum 6063 samples of different thicknesses. The maximum error between the experimentally measured results and the FEM simulations was less than 2%. Appropriate material independent proportionality factors have been derived to enable thermal diffusivity estimates to be made for a wide range of material thicknesses, thermal diffusivities and pulse widths.

REFERENCES

[1] Maldague X., "Theory and Practice of Infrared Technology for Nondestructive Testing", John Wiley & Sons, Inc (New York, NY), 2001.

[2] Parker W.J., Jenkins R.J., Butler C.P., and Abbott G.L., "Flash Method of Determining Thermal Diffusivity, Heat Capacity, and Thermal Conductivity", Journal of Applied Physics, 32(9) (1961), 1679–1684.

[3] Philippi, J. C. Batsale, Maillet D., and Degiovanni A., "Measurement of Thermal Diffusivities through Processing of Infrared Images", Rev. Sci. Instrum., 66(1) (1995), 182-192.

[4] Couto P., Orlande H.R.B., Cotta R.M., Oliveira S.P., Cruz J. A., Santos P. R. F., Costa C. S. P. and Massard H., "Flash Method Standardization in Brazil for the Measurement of Solid Thermo-physical Properties", METROLOGIA-2003 – Metrologia para a Vida, Sociedade Brasileira de Metrologia (SBM), Setembro 01-05, 2003, Recife, Pernambuco – BRASIL.

[5] Heckman R. C., "Finite Pulse Time and Heat Loss Effects in Thermal Diffusivity Measurements", Journal of Applied Physics, 44(4) (1973), 1455-1460.

[6] Cape J. A, "Temperature and Finite Pulse Time effect in the Flash Method for Measuring Thermal Diffusivity", Journal of Applied Physics, 34 (1963), 1909-1913.

[7] Larson K. B., and Koyama K., "Correction for Finite -Pulse-Time Effects in Very Thin Samples using the Flash Method of Measuring Thermal Diffusivity", Journal of Applied Physics, 38(2) (1967), 465-474.

[8] FEMLAB 3.1 User's Guide, "The Time Dependent Solver", Chapter 6, pp.305-312.