Pulsed thermography in the assessment of in-plane thermal diffusivity: aperiodic, periodic and random patterns

Bison P[(1)]*, Ferrarini G[(1)], Glorieux C[(2)]

(1) ITC-CNR, Padova, Italy

(2) Laboratory for Soft Matter and Biophysics, Department of Physics and Astronomy, KU Leuven, Belgium

*Corresponding author's email: paolo.bison@itc.cnr.it

Background – Parker's method [1] is widely used in commercial and laboratory setups to measure the thermal diffusivity of solids. It adopts a photothermal *transmission* scheme in which one side of a slab, of the material of which the thermal diffusivity is to be assessed, is heated by a light pulse and the temperature of the other side, typically detected by IR radiometry or IR thermography, is recorded and analysed in time. When the thickness of the specimen is so large to prevent a reliable measurement (poor S/N ratio), or, when the transmission mode is not feasible, a *reflection* scheme must be adopted. In case of a thermally thin plate, both the *in-plane* and *in-depth* thermal diffusivity can be measured. For thick samples (ideally semi-infinite), only the in-plane diffusivity can be measured. In case the in-plane thermal diffusivity is the quantity of interest, then use can be made of contactless photothermal excitation, by illuminating the sample surface by a time dependent (e.g. pulsed or step-like) inhomogeneous light pattern. The measured surface temperature field is then initially isomorphic with the (sharp) illumination pattern $I(x,y)$ [W m^{-2}], and gradually evolves to a smooth pattern, where the smoothing distance is of the order of the thermal diffusion length $\mu = \sqrt{\alpha \cdot t}$ with a [m^2 s^{-1}] the thermal diffusivity and t [s] the time. Several patterns have been proposed in literature, ranging from a gaussian spot [2], to a gaussian line, a periodic grating source [3,4] and a random pattern [5].

This article reports on the use of different impulsive light patterns, projected on different specimens, and of a 2D spatial Fourier transform approach that was used to extract the thermal diffusivity from the spatiotemporal evolution of the temperature, as measured by an IR camera. Limitations of the technique, related to the finite spatial resolution and spatial windowing are discussed.

Methods – When the surface of an opaque semi-infinite body is impulsively (delta function) heated by a generic spatial function, then, assuming absence of heat exchange with the environment, the spatial Fourier transform of the surface temperature field is described by:

$$\Theta\left(k_x, k_y, z = 0, t\right) = \frac{g\left(k_x, k_y\right)}{e\sqrt{\pi\, t}}\; e^{-\left(k_x^2 + k_y^2\right)\alpha t}$$

with k_x and k_y the wavenumbers [m^{-1}] of the x and y directions, respectively; z [m] the in-depth coordinate, t the time, g the spatial Fourier Transform of the function describing the heat released on the surface as a result of the excitation pattern $I(x,y)$, and e [J m^{-2} K^{-1}s$^{-1/2}$] the thermal effusivity. The experimental lay-out that was used to approximately realize the above geometry is depicted in Fig. 1. A slab of clay brick of 2.8 cm x 2.5 cm x 1 cm with nominal thermal diffusivity $\alpha \cong 5.0\times10^{-7}$ [m^2 s^{-1}] (top-left) was mounted on the sample holder (top-center). A pulsed Nd:YAG laser beam (Fig. 1 bottom-left) (1064 nm, max energy 30 J, pulse duration 50-2000 µs) with a top-hat beam profile with 0.5 inch diameter, was patterned by passing through a metallic flame diffuser (Fig. 1 top-right), and was photothermally exciting the sample. A FLIR SC3000 IR camera (LW), was collecting a sequence of images @150 Hz from shortly before the impulsive excitation till about 2s after. One pixel of the image covered an area of 108x108 μm^2. An example of the IR image, acquired immediately after the laser pulse is shown (bottom-right).

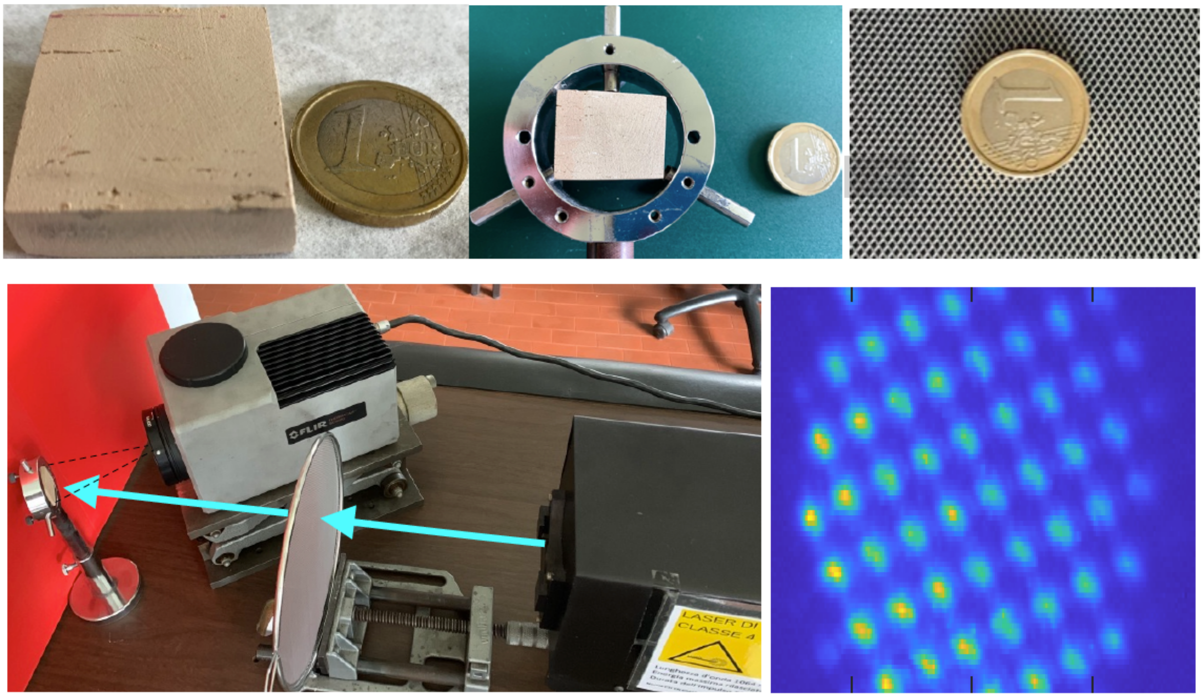

Fig. 1. Top: the clay brick sample (left), sample holder (center), pattern generator-flame diffuser (right). Bottom: experimental lay-out (left) including sample holder, IR camera, laser, flame diffuser; IR image just after the laser pulse (right).

Results – A spatial fast Fourier transform (FFT) was applied to each IR image, thus acquiring the temporal evolution of $\Theta(k_x,k_y)$. The thermal diffusivity was then determined by performing linear regression on $\ln(\Theta(k_x,k_y)t^{1/2})$ for different wavenumber combinations, yielding slope values s [s^{-1}] and diffusivity values $\alpha = -s/k^2$, with $k=(k_x^2+k_y^2)^{1/2}$ the wavenumber magnitude. Slope values that correspond with pronounced and therefore most reliable spatial Fourier components were selected and are shown in Fig. 2. Linear regression of $s(k^2)$, with intercept forced to zero (cfr model expectations), yielded α = (5.1±0.3) 10^{-7} $m^2 s^{-1}$, consistent with the nominal value. Not forcing the intercept yielded α = (4.4±0.4) 10^{-7} $m^2 s^{-1}$.

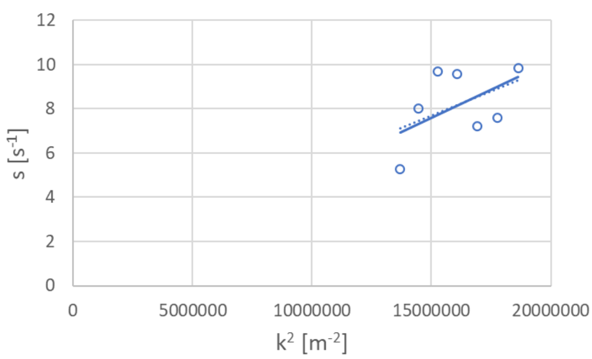

Fig. 2. Dependence of the slopes that were obtained by linear regression of $\ln(\Theta(k_x,k_y)t^{1/2})$ vs time on the square of the wavenumber magnitude. The trendlines are linear regression fits with (dotted line) and without (full line) intercept forced to zero.

Acknowledgements – This work has been supported by the Consiglio Nazionale delle Ricerche, Short Term Mobility Program – 2021 (STM 2021) n. 57862.

References

[1] W.J. Parker, R.J. Jenkins, C.P. Butler, G.L. Abbott, Flash Method of Determining Thermal Diffusivity, Heat Capacity, and Thermal Conductivity, J. App. Phys. 32, 1679-1684. https://doi.org/10.1063/1.1728417.

[2] F. Cernuschi, A. Russo, L. Lorenzoni, A. Figari, In-plane thermal diffusivity evaluation by infrared thermography, Review of Scientific Instruments 72 (2001) 3988-3995 https://doi.org/10.1063/1.1400151.

[3] G. Kalogiannakis, D. Van Hemelrijck, S. Longuemart, J. Ravi, A. Okasha, C. Glorieux, Thermal characterization of anisotropic media in photothermal point, line, and grating configuration, Journal of Applied Physics 100, 063521 (2006). https://doi.org/10.1063/1.2335381.

[4] J.C. Krapez. Diffusivity measurement by using a grid-like mask. Journée SFT Thermographie infrarouge 03 1999.

[5] J.-C. Batsale, J.-L. Battaglia, O. Fudym, Autoregressive algorithms and spatially random flash excitation for 2D non-destructive evaluation with infrared cameras, Quantitative InfraRed Thermography Journal, 1:1 (2004) 5-20. DOI: 10.3166/qirt.1.5-20.