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Stimulated infrared thermography applied to the local thermal characterization of fresco

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Abstract

In this work, we present a new method for estimating the local thermal diffusivity of fresco. This method uses a temporal analysis of the thermal response of a work of art submitted to a local laser excitation. First, we present the principle of the estimation method. Then, we show theoretically with the help of numerical simulations, the feasibility of the method. Finally, we show experimentally, that the method allows a good estimation of the thermal diffusivity of an academic plaster sample and of an academic fresco.

1. Introduction

The field of restoration and conservation of heritage artworks requests various non-destructive and characterization techniques. Among these NDT methods we can cite stimulated infrared thermography. The scientific literature already shows that this method is very efficient for the detection and localization of structural changes affecting the heritage artwork such as delamination [1-50]. The request of geometric characterization of these defects pushes the research teams to develop thermophysical properties estimation tools usable in situ. For example, wanting estimate by stimulated infrared thermography, the depth of a delamination, requires local knowledge of the thermal diffusivity of the artwork. In previous studies [51 – 53], we proposed three methods for local measurement of thermal diffusivity. They used a local laser excitation associated with a mathematical post treatment. The principles of these techniques were the followings: In the first case [51], the post treatment implemented, was an analysis of the spatial Fourier transform of the infrared thermogram obtained. In the second case [52], the post treatment was a temporal analysis of the characteristic radius of the thermal signature of the laser spot. Finally, in the third case [53], the post treatment was carried out in the temporal analysis of the maximum temperature of the thermal signature. The work presented here, aims to purpose a fourth estimation method. First it uses as the previous ones, a local laser excitation, providing an in situ analysis. Then it analyzes the temporal evolution of the area located under the spatial profile of the thermal signature of the laser spot. In this paper we present the results then obtained. We present first the principle of the estimation method. Then, we show theoretically, using numerical simulations, the feasibility of the method. Finally, we show experimentally that the method allows a good estimation of the thermal diffusivity of an academic plaster sample and of an academic fresco.

2. Local thermal diffusivity measurement method

The principle of the local thermal diffusivity measurement method developed for the study is the following: A sample is subjected on its front face to a localized laser excitation. This excitation is temporally close to a Dirac function δ (t) and is spatially Gaussian shape. The measurement of the spatiotemporal evolution of the temperature field induced by this excitation, using an infrared camera and a mathematical post-processing leads an estimation of the thermal diffusivity of the studied material. Let us examine the mathematical post-processing which is based on this measurement technique. Given a plate having thickness L. It is radially semi-infinite. Given a very short thermal excitation (Dirac function δ (t)). Its spatial shape is Gaussian. At the initial time t = 0 s, this excitation is applied in the center of the plate in order to eliminate edge effects. Given R, the characteristic radius of this exciting spot (measured at Q_{max} / e^2). Given λ, ρ, C and a, respectively, the thermal conductivity, the density, the heat capacity and the thermal diffusivity of the studied material. The sample is initially in thermal balance with its environment. Finally, in this model we neglect the radiative - convective exchanges between the studied sample and the environment. The mathematical translation of these hypotheses leads to the following differential system (1):

$$\Delta T(r,z,t)=\frac{1}{a}.\frac{\partial T(r,z,t)}{\partial t} \tag{1}$$

For z = 0 : $-\lambda\frac{\partial T(r,0,t)}{\partial z}=\frac{2Q}{\pi R^2}Exp(-\frac{2r^2}{R^2})\,\delta(t)$

For z = L : $-\lambda\frac{\partial T(r,L,t)}{\partial z}=0$

For t = 0 : $T = T_{ext}$

Solving this differential system uses two integral transformations; firstly a zero order Hankel transformation along the r axis (2)

$$H_0[\frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial T(r,z,t)}{\partial r})]=-\sigma^2\int_0^{\infty}r.J_0(\sigma.r)T(r,z,t).dr \tag{2}$$

And secondly, a Fourier transform along the time axis (3).

$$F(\frac{\partial T(r,z,t)}{\partial t})=\frac{i.\omega}{\sqrt{2.\pi}}\int_{-\infty}^{+\infty}T(r,z,t).\exp(-i.\omega.t).dt \tag{3}$$

Both integral transformations allow to obtain the expression of the spatio-temporal evolution of the temperature in front of the studied sample given by the formula (4).

$$T(r,0,t)\approx\frac{2Q}{b\sqrt{\pi^3 t}}.\frac{1}{R^2+8at}.\exp(-\frac{2r^2}{R^2+8at}) \tag{4}$$

Note

$$T_{max}(0,0,t)\approx\frac{2Q}{b\sqrt{\pi^3 t}}.\frac{1}{R^2+8at} \tag{5}$$

And calculate the spatial integral of (4). We obtain the formula (6):

$$I(t)=\frac{1}{2}.T_{\max}(0,0,t).(R^2+8at).\sqrt{\frac{\pi}{2}}.erf\left(\sqrt{\frac{2}{R^2+8at}}.r\right) \tag{6}$$

Let us now study the specifications of the “error function". Figure 1 shows that this function tends to 1 when its argument is greater than 2.

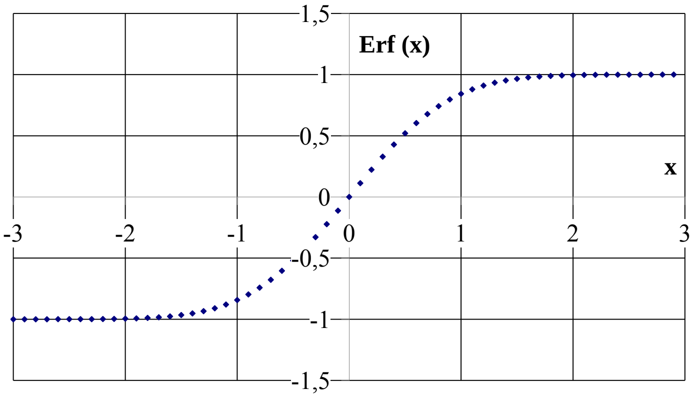

***Fig 1.** The error function properties*

In our case study, it gives:

$$r^2 > 2\ (R^2 + 8at) \tag{7}$$

Considering now a radius of excitation R equal to 1.8 mm, a thermal diffusivity of the studied sample equal to 3.5 10^{-7} m^2/s and an analyze duration equal to 1s ((these are the experimental conditions usually considered in our study), this formula becomes :

$$r > 1{,}6\ R \tag{8}$$

It is therefore possible to ignore the error function in expression (6) as soon as the integration boundary will be greater than 1.6 R. With these conditions, formula (6) becomes formula (9)

$$I(t) = \frac{1}{2}.T_{\max}(0{,}0{,}t).(R^2 + 8at).\sqrt{\frac{\pi}{2}} \tag{9}$$

Which can be written (10)

$$M(t) = R^2 + 8at = \frac{2}{\pi}.\left(\frac{I(t)}{T_{\max}(0{,}0{,}t)}\right)^2 \tag{10}$$

This expression shows the possibility to estimate the thermal diffusivity of the studied sample from the estimation of the slope of the temporal evolution of the ratio of the spatial integral of the thermal signature of the laser spot and the maximum temperature of this signature.

3. Theoretical study

To test this new technique of local thermal diffusivity measurement, we have developed mathematical simulations. The latter use the finite element method to solve the above differential system (1). Simulations conditions selected for the study are the followings: First, we have considered a 3D geometry. Then we considered a block of plaster, with thermo-physical properties similar to those of a real mural painting. We considered a thermal conductivity equal to 0.4 W / m K, a density equal to 1100 kg / m3, a specific heat equal to 830 J / kg K and a thermal diffusivity equal to 4,38.10^{-7} m^2 / s. For simplify the study, the shape of the plaster block was chosen rectangular. Its dimensions are a length equal to 12 cm, a width equal to 12 cm and a thickness equal to 3 mm. An excitation was applied in the center of the plaster block. The temporal shape of this excitation is a crenel. The duration of this excitation is equal to 20 ms. The spatial shape of this excitation is a Gaussian. The characteristic radius of excitation is equal 1.8 mm. The exciting power used is equal to 3 W. These values correspond to those conventionally available by experience. Finally, to reduce the computation time, we considered a progressive mesh of the studied sample. It was taken thinner at the location of the laser excitation and wider elsewhere. From thermograms calculated at each moment, we have drawn spatial profiles of temperature measured at the location of the laser excitation. We then calculated the M (t) function. The figure 2 presents an example of result obtained. It shows like theoretically expected, an increasing straight line. We finally estimate the thermal diffusivity from the slope of the M (t) function. We obtain a slope equal to 3.5 10^{-6} m^2/s, which leads to a thermal diffusivity equal to 4,37 10^{-7} m²/s. The theoretical value is equal to 4,38.10^{-7} m²/s. These values are very close, which shows the feasibility of the method.

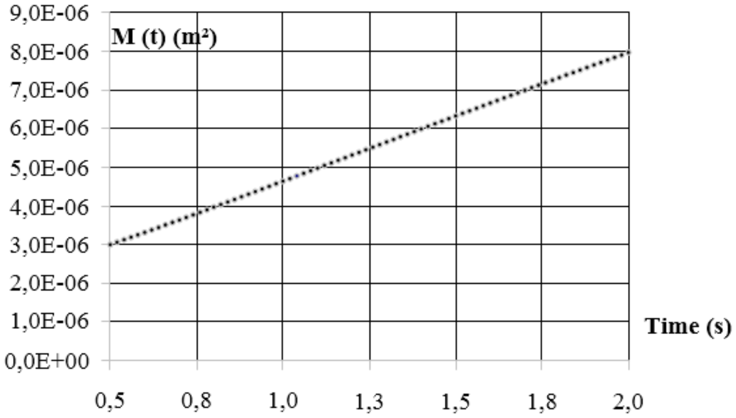

Fig 2 . *Time evolution of the spatial integral of the thermal signature of the laser excitation*

4. Experimental study

4.1. The experimental device implemented

The results obtained in the theoretical study being encouraging, we switched in a second step to an experimental study. The experimental setup used is the SAMMTHIR device of the GRESPI/CATHERM laboratory. The excitation source is a laser diode. The wavelength of emission is equal to 810 nm. It is associated with collimation and focusing optics. The infrared optical acquisition is a FLIR “long-wave” bolometers camera. It is used in a macro mode (to obtain a sufficient spatial resolution). The latter is placed perpendicularly to the sample. The distance between the camera and the sample is equal to about 5 cm. The laser beam, due to the size of the camera, lights the studied sample in a tilted way. The laser spot is then slightly elliptical. The duration of excitation is equal 20 ms. Its power is equal to 2W. The acquisition frequency of the infrared thermography camera is equal to 50 Hz.

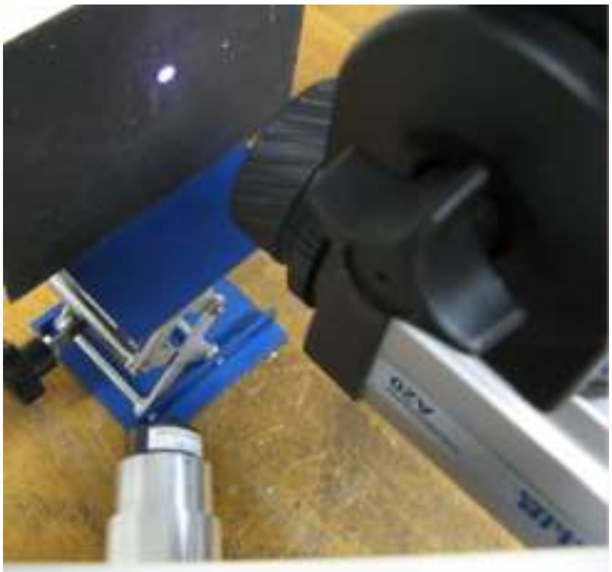

Fig 3 . *The experimental device used for the study*

4.2. Study of a sample academic

The first sample analyzed, is an academic sample. It is a plaster sample. It is a parallelepiped block. Its length is equal to 15 cm. Its wide is equal to 12 cm. Its thickness is equal to 2.3 cm. To determine its real thermal diffusivity, we have used a metrological laboratory rear face flash diffusivimeter. An example of obtained result is presented with this metrological device is presented in Figure 4. It shows that the best fit theory / experience is obtained for a thermal diffusivity equal to $3.49.10^{-7}$ m^2 / s.

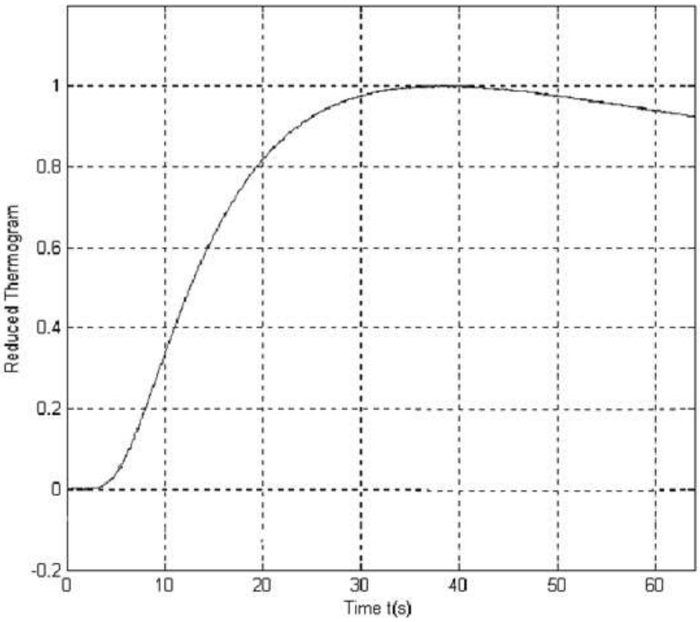

Fig 4 . *Characterization of the academic sample using a metrological laboratory flash diffusivimeter*

This plaster sample was then analyzed using the experimental device SAMMTHIR. From the photothermal response obtained, we drawn first spatial profiles of the spot laser thermal signature at different moments. We estimate then thermal diffusivity value using our analyze method. An example of obtained result is presented in Figure 5. It shows like theoretically expected, an increasing straight line. Its slope value is estimated equal to 2.74 10^{-6} m^2/s. Its thermal diffusivity is then estimated equal to 3.43 10^{-7} m^2 / s. This value is close to the reference value. This confirms experimentally the feasibility of the method.

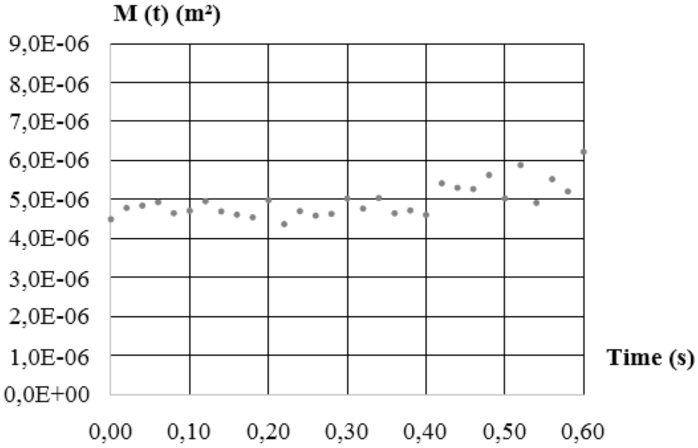

Fig 5. *Characterization of a plaster sample using the SAMMTHIR system*

4.3. Study of an academic fresco

Following this encouraging first experimental study, we studied in a second step, an academic fresco. This is a copy of the “Saint Christophe” from the “Campana” collection of the Louvre (Figure 6).

Fig 6 . *The academic fresco studied*

This academic fresco has been already analyzed and characterized three times. In the first case, we have used a spatial Fourier analysis [51]. In the second case, we have used a temporal analysis of the radius of the thermal signature of the laser spot [52]. In the third case, we used a temporal analysis of the maximum temperature of this same signature [53]. In all cases the analysis was developed at the place of the right eye of the infant Jesus. The thermal diffusivity values then estimated was equal respectively to: 5,13 10^{-7} m^2s^{-1} [51], 5,09 10^{-7} m^2s^{-1} [52] and finally 4.96 10^{-7} m^2s^{-1} [53]. It is always for this position we have developed our new analysis. We used the same experimental protocol as for the study of the academic plaster sample. We present in Figure 7 the temporal evolution of the ratio calculated between the spatial integral of the thermal signature of the laser spot and its maximum value. It shows like theoretically expected, an increasing straight line. Its slope value is estimated equal to 4.08 10^{-6} m^2/s. Its thermal diffusivity is then estimated equal to 5.10 10^{-7} m^2 / s. This value is close to the reference value. This confirms experimentally once more time, the feasibility of the method.

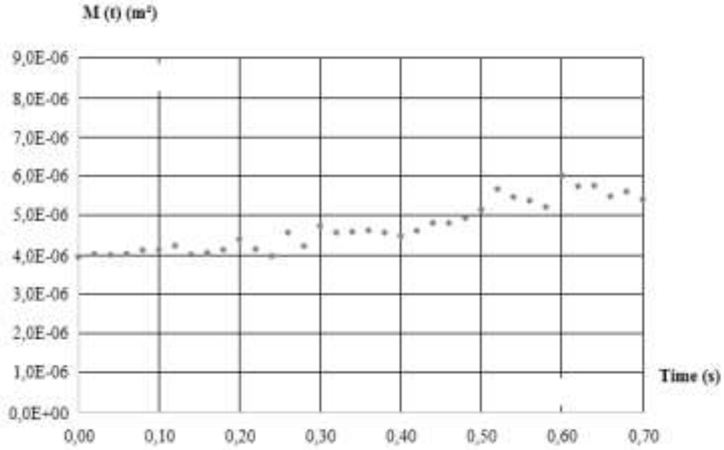

Fig 7. *Characterization of an academic fresco using the SAMMTHIR system*

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5. Conclusion

In this work, we studied the possibilities of the stimulated infrared thermography for in situ estimation of mural painting thermal diffusivity. We presented first the principle of the measuring method. It is based on a temporal analysis of the thermal signature of a laser spot. We then presented simulations developed for the study and shown theoretically that the photothermal method allowed a good estimation of the local thermal diffusivity of a plaster block. The theoretical results obtained being positive, we developed an experimental study. We then presented the experimental device developed for the study. Finally we have shown experimentally that the method gave access to a good estimation of the local thermal diffusivity of an academic plaster sample and of a partial copy of the "Saint Christophe" of the "Campana" collection of the Louvre. These theoretical and experimental results seem to open the way for the photothermal *in situ* characterization of mural painting. They now need to be sharpen and generalize, to be implemented during of real works of art. Studies in this direction are in progress.

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