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# Simulations of an Infrared Composite Curing Process

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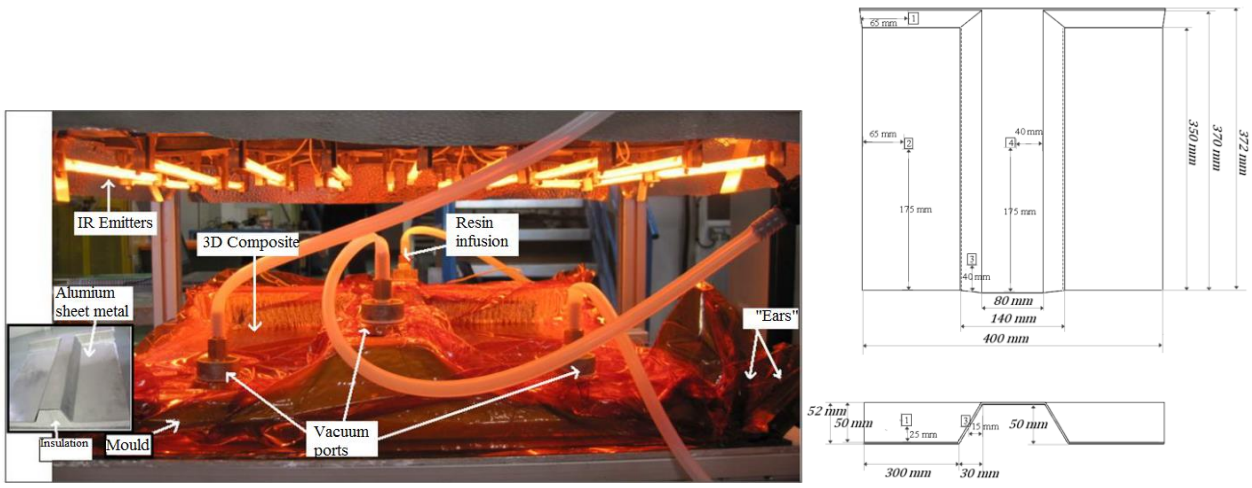
**Keywords:** Curing composite, infrared oven, Radiation, Optimization, Epoxy resin, Carbon fibers

**Abstract:** A 3D composite geometry (carbon fiber reinforced epoxy matrix) has been optimally cured using a well-designed infrared oven. The main purpose of this study is to validate a FE thermal model based upon commercial software COMSOL Multiphysics™ developed for the prediction of the infrared incident heat flux on the top surface of the composite during the curing process. Through the FE thermal model, an optimization study on the percentage power of each infrared heater was performed in order to optimize the incident IR heat flux uniformity on the composite. In order to achieve validations, an experimental set-up using an IR camera and some thin thermocouples has been developed in order to achieve temperatures measurement. The recorded temperatures at different positions on the 3D composite part will be compared to computed temperatures.

## Introduction

Epoxy resins have several applications in the aerospace and automobile industry. Because of their good adhesive properties, superior mechanical, chemical and thermal properties, and resistance to fatigue and micro cracking, they produce high performance composites. In a second hand rising energy costs have also promoted an interest in using infrared energy to manufacture these composites [1, 2]. In the technology presented here, the composite is cured using an IR oven which includes halogen lamps (fig. 1.a). The liquid resin infusion (LRI) process is used to manufacture the composite, whereby liquid resin is infused through a fiber reinforcement previously laid up in a one-sided mold (fig. 1.a). The 3D geometry used to validate numerical simulations is a simplified underbody car and its dimensions are sketched in Figure 1.b.




(a) (b)

Fig.1- Infrared Composite Curing Process

The objective of this paper is to compare the temperature measurements of the 3D composite geometry realized using an infrared camera and thin thermocouples (fig.1) versus numerical simulations.

**Experimental set-up**

In order to measure surface temperatures, we have used a microbolometer camera equipped with a lens's focal length $F = 18\,\text{mm}$. Its resolution is 320 X 240 pixels. Its spectral range corresponds to the average infrared $(7.3 - 13\,\mu\text{m})$. The image frequency is 60 Hz. In Fig.2, the position of the camera is sketched as well as the corresponding measured surfaces $(S_2, S_3)$.

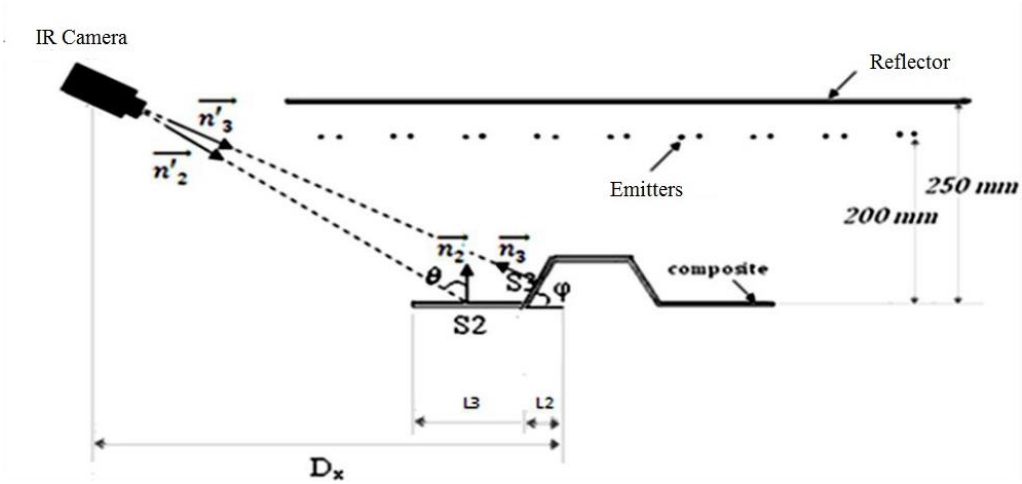



Fig.2 – Positions of IR camera and measured surfaces

The infrared camera is located outside the oven. The axis of the camera $\vec{n}_3^{'}$ has been adjusted such as to be parallel to the normal $\vec{n}_3$ of the surface $S_3$. For the temperature measured on surface $S_2$, the angle $\theta$ between the axis of camera and normal of surface has been adjusted to $60°$. This value guarantees the accuracy of the measures and especially that the emissivity of such dielectric materials is not varying too much up to an angle of 60°. In order to ensure this assumption, spectrometric measurements of emissivity at different angles were performed but not addressed in the present paper. The apparent emissivity of the composite in the spectral range of the camera $\varepsilon_{7-13} = 0.95$ has been calculated thanks to the apparent reflectivity $R_{7-13}$ [3].

$$\varepsilon_{7-13} = 1 - R_{7-13} \tag{1}$$

The apparent reflectivity has been deduced from spectral reflectivity measurements (fig.3), performed thanks to an infrared spectrometer Bruker Vertex 70. It is to be noted that this spectrometer is equipped of two detectors allowing to cover all the IR spectral range $(0.8 \text{ to } 25\,\mu\text{m})$. An important detail is that the resulting measurement includes all the different films used for resin infusion (recovery surface, demoulding fabric) as well as carbon fibers.

In addition, four K-type thin thermocouples of 80 µm diameter have been placed at different positions inside the composite geometry (numbers 1 to 4, fig.1.b), and especially where the IR camera has not the capability to achive measurements.

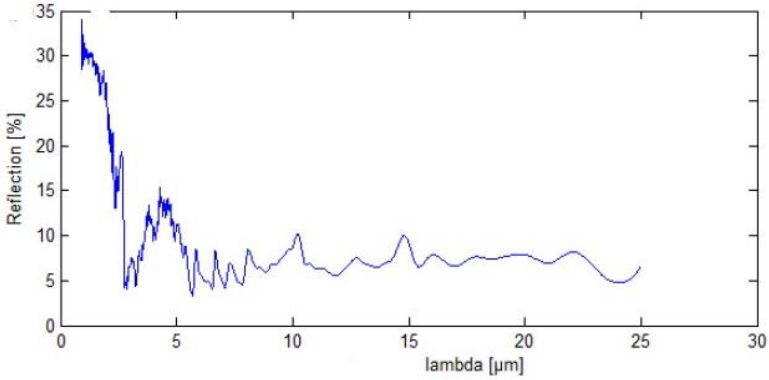



Fig.3 – Spectral reflection $R_\lambda$ on the top surface of composite
(Recovery surface + demoulding fabric+ carbon fibers)

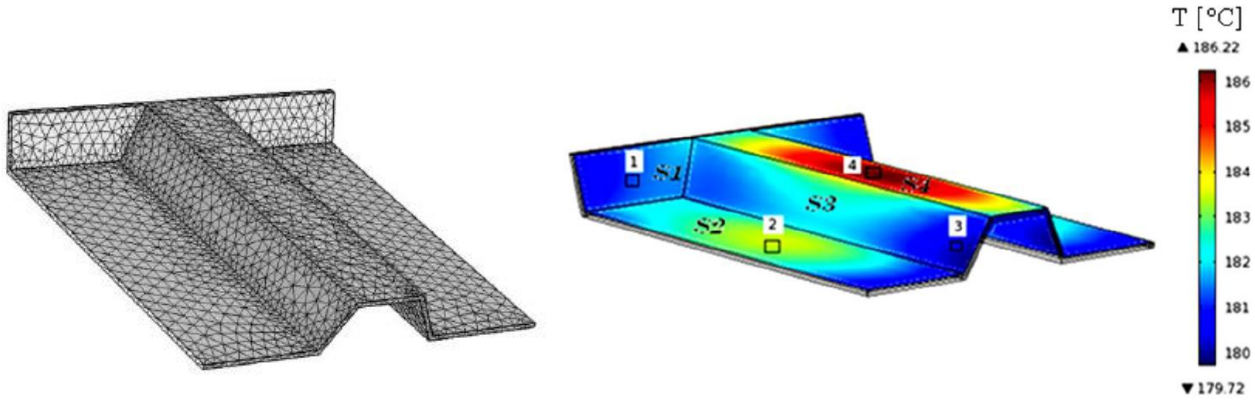
**Numerical modeling**

In previous papers [4, 5], a FE thermal model based upon software COMSOL Multiphysics™ was fully detailed, for the prediction of the infrared incident heat flux on the top surface of the composite during heating. Although we have applied ray tracing method previously [6], it is not convenient to use it for an industrial application because of the computational expense when solving the radiation problems and time-consuming resulting from coupling ray tracing method with the optimization algorithms. The method employed by the FE heat transfer solver to compute the radiation heat transfer between opaque diffuse surfaces is based upon radiosity which is defined as the total radiative flux leaving a surface. The radiosity method subdivides a scene into surface patches that possess Lambertian optical characteristics and subsequently determine a condition in which the light transfer between the patches constitutes an energetic equilibrium [3]. The fraction of radiative energy absorbed by the composite has been calculated via view factor computations thanks to the hemicube method [7]. In order to achieve numerical simulations, the radiative power of each halogen lamps is computed using the following relationship:

$$P_L = \sigma_{SB}\varepsilon_f(T_f)T_f^4 S_t \qquad (2)$$

Where $\sigma_{SB}$ is the Stefan-Boltzmann coefficient, $\varepsilon_f(T_f)$ the integrated emissivity of tungsten filament, $T_f$ the temperature of tungsten filament and $S_t$ the equivalent surface of filament. It is noticeable that the emissivity is strongly dependent of the temperature of filament. This last parameter has been previously measured by comparing different technics such as color temperature, the resistivity method and a semi-analytical model based upon flux balance [8].

The composite was meshed into 8248 tetrahedral elements. A very dense mesh is used for the volume material discretization along and near the edges highlighted in fig.4.a, as higher temperature gradients will occur here, while a coarser mesh is used in the remaining volume. The resulting temperature distribution is represented in fig4.b. Due to optimization procedure [4], the maximum temperature difference throughout the composite geometry is less than 5°C. Again, the positions and associated numbers of thermocouples and surfaces are sketched in fig. 4.b.




(a) (b)

Fig.4 – 3D mesh of the composite geometry and computed temperature distribution

**Discussion**

In fig. 5, measured temperatures issued from both thermocouples and IR camera, and computed ones are plotted versus time. The three-dimensional numerical model is developed in the finite element software COMSOL Multiphysics™, where the heat balance equation is coupled with the cure kinetic model of the resin [9]. The computed radiative heat flux is exported to COMSOL Multiphysics™, and imposed as a boundary condition on the top surface of the composite. This numerical model allows the calculation of the temperature distribution in the composite during curing as well as the degree of curing. From a global point of view, the agreement is unexpectedly good considering all the input data involved in the numerical model. At position 1, the measured temperature using thermocouple (TC1) and computed one are in good agreement, especially during temperature rise. However, a temperature difference of 5°C is calculated during the steady state. At position 2, the surface temperature measured by IR camera is slightly higher than those measured by thermocouple (TC2). Nevertheless, the measured and computed temperatures exhibit again a good agreement.

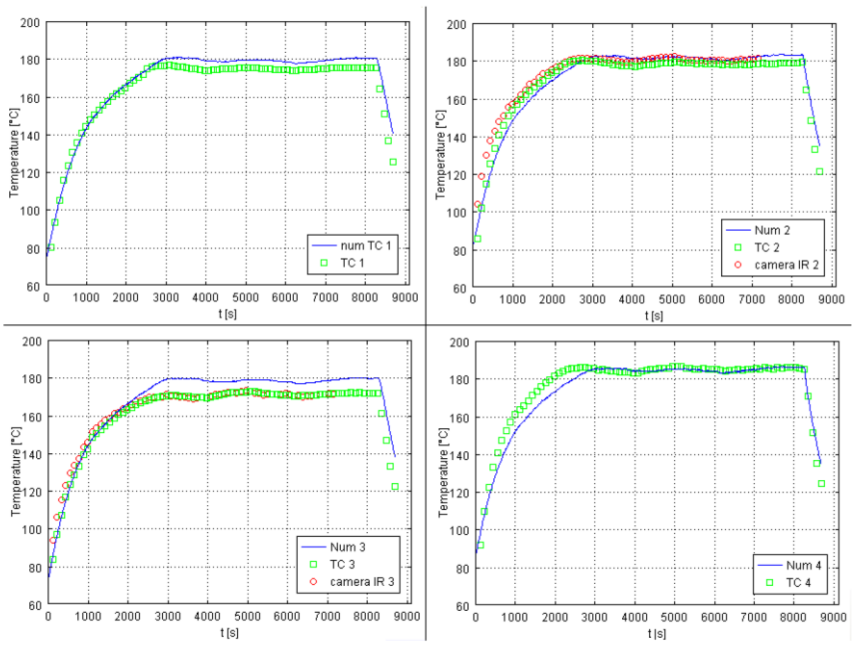



Fig.5 – Comparison between measured and computed temperatures

At position 3, again the best agreement between experimental and numerical temperatures occurs during temperature rise (transient state). A temperature difference of 8°C is observed during the

steady state, both with IR camera and thermocouple measurement. Indeed, the proximity of this thermocouple of a vacuum port leads to underestimate the measured temperature.
From these results, we can conclude that the measured temperatures on horizontal surfaces ($S_2$ and $S_4$) have the best agreement with computed temperatures during the steady state. In addition, the measured temperatures on inclined surfaces ($S_1$ and $S_3$) have the best agreement with computed temperatures during the transient state. These differences may be attributed to the fluctuation of air temperature inside the oven. Only one air temperature measurement has been recorded using a thermocouple located at the center of the oven (above the $S_2$ surface).The recorded air temperature is plotted versus time in fig. 6.

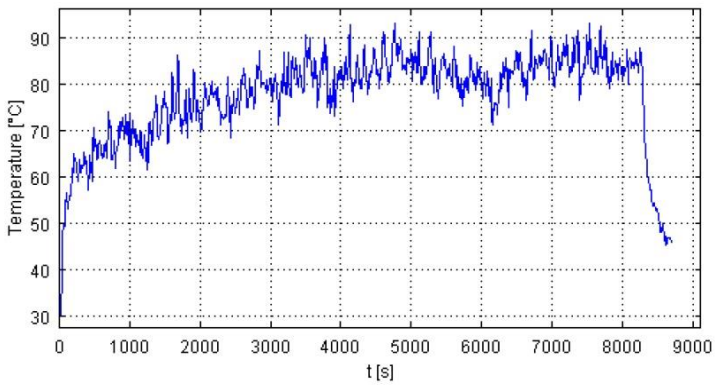



Fig.6 –Recorded air temperature versus time

If we are going back and examining carefully the measured temperatures (fig. 5), it is noticeable that slight fluctuations are observed around t=5000s. This fluctuation can be correlated with those observed on air temperature. This fluctuation is due to the variation of room temperature where curing process has been achieved (air flow, opening and closing of doors …). In addition, the root mean square error Err including the four thermocouples measurements is calculated thanks to the following equation and plotted in fig. 7:

$$\mathrm{Err} = \sqrt{\frac{\sum_{i=1}^{4}\left(T_{exp}^{i} - T_{num}^{i}\right)^2}{\sum_{i=1}^{4}\left(T_{exp}^{i}\right)^2}} \times 100 \qquad (3)$$

Except at the beginning and the end of the heating where the error is greater, it is noticeable that the average value is less than 4%. Again, this is a good result considering the great number of parameters involves in this kind of numerical simulations.

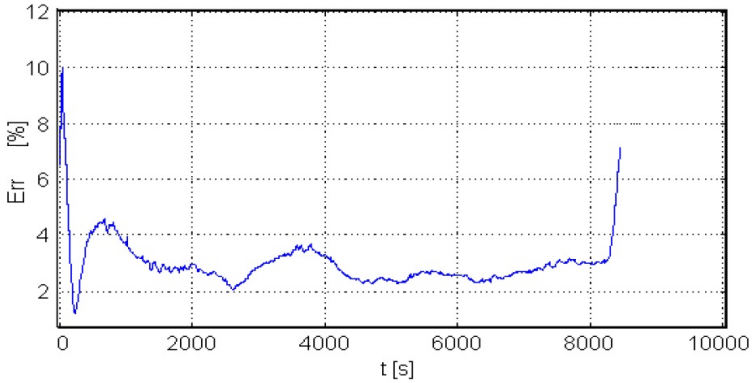



Fig.7 – Root mean square error versus time

**Future works**

Different temperature measurements thanks to IR camera and thermocouples allow validating computed temperatures. In order to simulate the curing process, 3D radiation numerical simulations include also a kinetic model based upon modified Kamal-Sourour equation [5,9]. For estimating the influence of IR radiation upon mechanical properties of the final composite piece, it would be important to achieve mechanical tests (DMA, 3-points bending, shear test …). For example, comparisons may be performed between samples cured by conduction mode (or autoclave), and in other hand by infrared oven. In addition, careful examinations of MEB images would lead to better understand the microstructure of composite piece obtained using IR curing process.

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