Modélisation de lampes IR avec réflecteur intégré utilisées dans le procédé de fabrication de pré-imprégné thermoplastique

Modelling strategy of IR lamps with integrated reflector used in the manufacturing process of thermoplastic composite tapes

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Résumé

Cette étude propose une stratégie de modélisation pour simuler l'étape de chauffage dans le procédé de fabrication de pré-imprégnés thermoplastiques par imprégnation continue en voie aqueuse. Après imprégnation des fibres de carbone par du PEKK (Poly-Ether-Kétone-Kétone) sous forme de poudre, le produit est soumis à une étape de chauffage pour évaporer la phase aqueuse et faire fondre le polymère. Ces phénomènes dépendent fortement de la température, ce qui nécessite une modélisation avancée des transferts de chaleur au sein du four IR.
Dans la littérature, la majorité des modèles des fours sont proposés pour des lampes claires à émission Lambertienne. Dans notre cas d'étude, des lampes tubulaires avec un revêtement sur la face arrière (réflecteur intégré) sont utilisées. Ce réflecteur intégré modifie fortement la distribution spatiale de l'émission, la modélisation de la lampe ne peut donc pas être simplement représentée par une émission Lambertienne. Cette étude propose une méthode des radiosités prenant en compte l'émission spatiale de la lampe sans prendre en compte explicitement le réflecteur en termes d'échanges radiatifs. L'émission de la lampe a été caractérisée par analyse inverse en couplant des essais expérimentaux à des simulations numériques utilisant le logiciel commercial–COMSOL Multiphysics®.

Abstract

This study proposes a modelling strategy to simulate the heating stage during the production of thermoplastic composite tapes. Impregnation using a slurry powder technique with carbon fibres and PEKK (PolyEther-Ketone-Ketone) requires a heating step, to evaporate the aqueous phase and melt the polymer powder. These phenomenon are highly temperature dependant justifying the need to characterise heat transfer within the IR oven.
In the literature, most models refer to clear lamps with Lambertian emission. In this study, tubular lamps with a coating on the back side (i.e. integrated reflector) are used. This integrated reflector greatly modifies the lamps spatial emission, therefor the lamp can no longer be modelled using a cylinder with Lambertian emission. This study proposes an adaptation of the radiosity method to predict spatial emission of the lamp without explicitly accounting for the reflector in terms of radiative exchange. The emission of the lamp was characterised by inverse analysis combining experimental results with numerical simulation using the commercial software –COMSOL Multiphysics®.

Mots Clés : Rayonnement, analyse inverse, optimisation
Keywords : Radiation, inverse analysis, optimisation

1.   Introduction

In recent years, there has been a growing interest for the use of composite materials in the aeronautical industry. Thermoplastic composites are of particular interest as they can be welded or reshaped and recycling is possible. Processes like automated tape laying use thermoplastic composite tape to create larger structures [2][3]. Different processes can be used to create these

tapes such as fusion impregnation, fibre commingling, film stacking or powder impregnation [4]. In the case of wet powder impregnation (slurry powder), the wet impregnated tape undergoes a series of heating steps to evaporate the water [5] and melt the polymer powder [6]. These phenomenon are highly temperature dependent and to better understand the evolution of the product during these steps, it is first necessary to understand the heating conditions applied.

In the slurry powder impregnation process under study, the thermoplastic tape is heated using radiative technology. An oven composed of multiple infrared halogen lamps, reflective panels, glass plates, cooling air injection and air extraction system is used. Here the lamps have an integrated reflector in the form of a fine coating on the underside of the glass tube contrary to clear lamps with Lambertian emission that are more commonly used [7]. This reflector modifies the spatial distribution of the lamps emission. Methods such as ray tracing [8] can be used to model this type of emission but are highly time consuming, especially for a high number of emitters and considering optimisation procedure. This motivated the need to find a simplest model capable of predicting the lamps emission with reasonable computation time.

This study then proposes a modelling approach based on the radiosity method for the case of lamps with integrated reflector. The strategy used consisted in applying a weight factor to the emitted power around the circumference of the lamp, so as to represent the spatial distribution of the emitted radiation. The values of the different weight factors were identified from the comparison of numerical data with experimental data recorded with a specific experimental set up by using an inverse analysis method.

First, the infrared lamps and experimental procedure are presented. Then, a focus on experimental results is carried out before developing on the numerical model and identification of the model parameters.

2. Experimental procedure

2.1 IR Lamps

'Clear' halogen infrared lamps are composed of a tungsten filament, a tubular quartz case and a small quantity of halogen gas. Because of the helical shape of the tungsten filament, the radiative emission of this type of lamp is Lambertian and mostly depends on filament temperature. This temperature in turn is determined by the supply voltage as the lamp is heated using Joule heating. In this study, halogen IR lamps (Dr. Fischer-2000 W, 400 V, Length L=411 mm, Diameter D=11 mm) with an integrated reflector are studied (Fig. 1). The integrated reflector is a fine coating on the underside of the quartz tube. This coating effects the overall emission of the lamp by redirecting part of the filaments radiation towards the front and away from the back. As the filament temperature varies with supply voltage so does the spectral emission of the lamp. For nominal filament temperature the wavelength of maximal emission is λmax=1.2 μm with 95% of emission in the range [0.6; 6] μm. By determining the relationship between supply voltage and filament temperature, the evolution of this range will also be determined.

(a)   (b)

Fig. 1. (a) Infrared halogen lamp with integrated reflector, (b) Schematization

2.2 Setup

The experimental setup designed to evaluate the infrared lamp's filament temperature and spatial distribution function is presented in (Fig. 2). The infrared heating was achieved by controlling the supply voltage U (V) applied to the tungsten filament. The lamp thus heated a flat panel on its front side, and the temperature on the back side of the sheet was measured using an IR camera (FLIR SC325, [7.5-13] µm). The lamp was directed with the 'clear' side facing upwards and the reflector facing downwards as can be seen in (Fig. 1), and was positioned centrally to the panel.
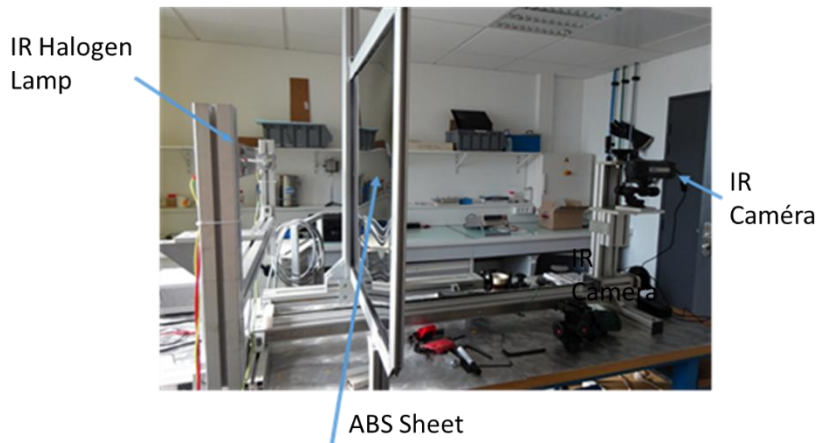

Fig.2. Experimental setup

2.3 Material

The material used in the experimental set up was a flat sheet of ABS (Acrylonitrile Butadiene Styrene), an amorphous thermoplastic polymer. The main thermal and optical properties of ABS can be found in (Tab. 1). The panel used in this study was 680 x 670 x 1.5 mm.

Properties	ABS
Specific heat capacity C_p	1300 W.kg^{-1}.K^{-1}
Thermal conductivity k	0.19 W.m^{-1}.K^{-1}
Density ρ	1050 kg.m^{-3}
Glass transition temperature	105 °C
Integrated emissivity ([0.95-20] µm) ε	0.94
Integrated emissivity ([8;12] µm) $ε_c$	0.96

Tab. 1. Thermal properties of ABS [9]

3

3.   Experimental results

The temperature field was measured on the back face of the ABS sheet for supply voltages between 40% and 100% of nominal voltage (400V). For each voltage, two lamp positions were used (Fig. 3), the first position with the clear half of the lamp directed towards the ABS sheet, for the second position the clear half was directed upwards.

For each experiment, the sheet was heated to a temperature of 60°C, the lamp was then turned off. The cooling stage was also recorded. The cut off temperature was chosen to ensure that the material temperature stayed much lower than the glass transition temperature (Tab.1). For some experiments, using lower supply voltages, the temperature was not reached, in this case, the lamp was turned off when the temperature variation became negligible, steady state however was not reached.

Figure 3 shows the temperature profiles measured for the two heating positions for nominal supply voltage. With the lamp turned towards the sheet, the temperature profile is centred and circular, this differs from the case of circular lamps where the profile is elliptical. When the lamp is turned upwards, the effect of the integrated reflector is evident, the point of maximum temperature is shifted vertically towards the top of the panel.
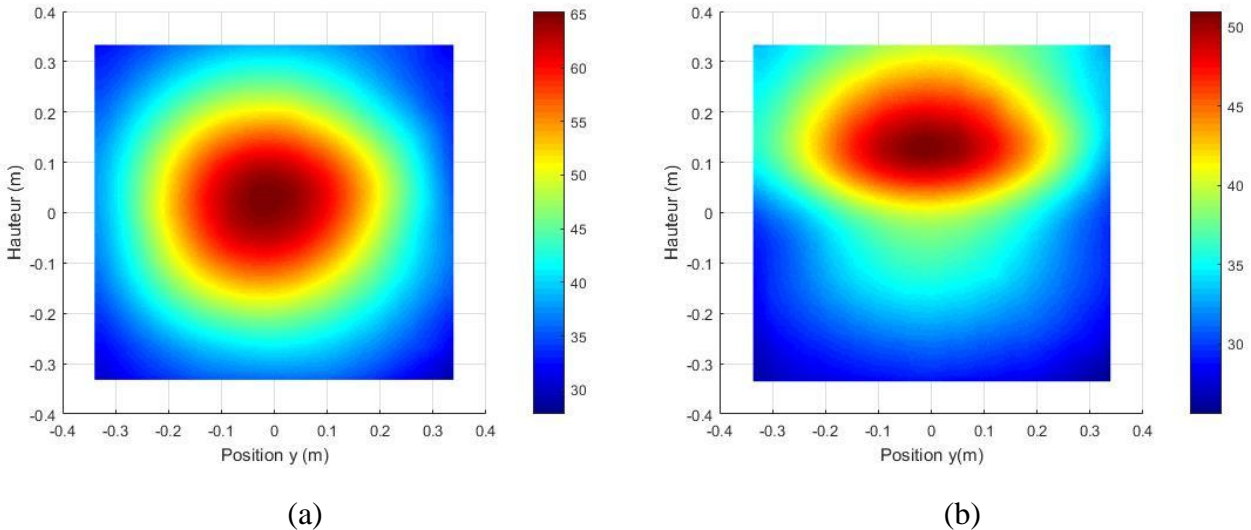

| (a) | (b) |

Fig. 3.(a) Temperature field at time t= s for U=400V with the clear section of the lamp directed towards the ABS sheet , (b) Temperature field at time t= s for U=400V with the clear section of lamp directed upwards. Parallel and perpendicular profiles intersect at point of maximum temperature.

4.   Numerical simulation

4.1 Model

To model the Lambertian emission of a 'clear' lamp, only the filament needs to be considered [10]. An equivalent cylinder is used to model the spiralled filament. A temperature T (K) and an integrated emissivity ε_f dependant on filament temperature are attributed to the cylinder in order to define the lamp's radiosity J (W.m^{-2}) according to (Eq. 1) where σ=5.670367e-8 W.m-2K-4 is the Stephan-Boltzmann constant

$$J = \varepsilon_f(T)\sigma T^4 \qquad\qquad (Eq. 1)$$

For a lamp with a coated reflector, this model has to be extended. A model capable of taking into account spatial effects in the form of a distributive function on the filament emissivity was thus proposed. As described by (Eq. 2), the filament circumference was divided into N zones ((Fig. 4) shows an example for 6 zones), surface emissivity was weighted by a coefficient k_i. The sum of these coefficients should be equal to the number of zones to conserve transmitted power by the filament (Eq. 3).

$$\varepsilon_i = k_i \varepsilon_f(T) \tag{Eq. 2}$$

$$\frac{1}{N} \sum_1^N k_i = 1 \tag{Eq. 3}$$

Numerical simulation was carried out using commercial software COMSOL Multiphysics®. Boundary conditions were assumed only radiative and convective on the front and back faces of the sheet (Eq. 4), thermal insulation was applied to the four edge faces.

$$\vec{n}(k\nabla T) = h(T_{air} - T) + \varepsilon\sigma(T_{air}^4 - T^4) \tag{Eq. 4}$$

As a first approach, convection in this study was taken to be constant and equal to an average value $h=4.5$ W.m^{-2}.K^{-1} calculated using the data from the cooling phase of the tests.

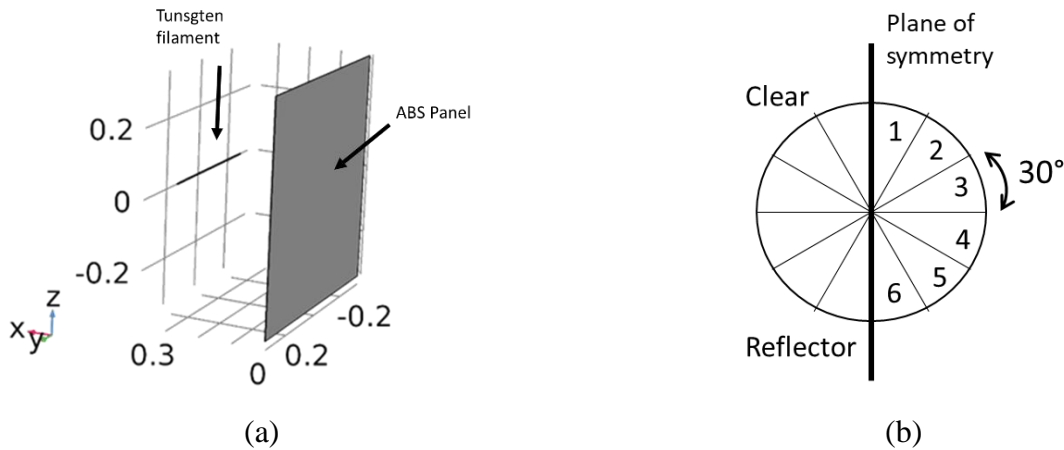(a)   (b)

Fig. 4. (a) Simulation geometry for tungsten filament heating and ABS sheet, (b) Filament model

4.2 Optimization

Parameter optimisation was carried out using the SNOPT solver [11] implemented in COMSOL Multiphysics®, with a least square objective function (Eq. 4). Initial and optimized values can be found in (Tab. 2).

$$min \sum (T_{exp} - T_{num})^2 \tag{Eq. 4}$$

Properties	k_1	k_2	k_3	k_4	k_5	k_6	Tlampe (K)
Initial Value	1/6	1/6	1/6	1/6	1/6	1/6	1900
Optimized value	0.63023	0.19598	0.10211	0	0	0.36477	1899.9

Tab. 2. Initial and optimized lamp parameters.

In this first approach, no constraints were applied, only lower and upper bounds for the lamp parameters were used. This led to an error of 2.8% on the temperature on the back face for the optimised position (U=160V, lamp directed upwards). The surface temperature and comparison between the experimental and optimized perpendicular temperature profiles can be seen (Fig. 5).
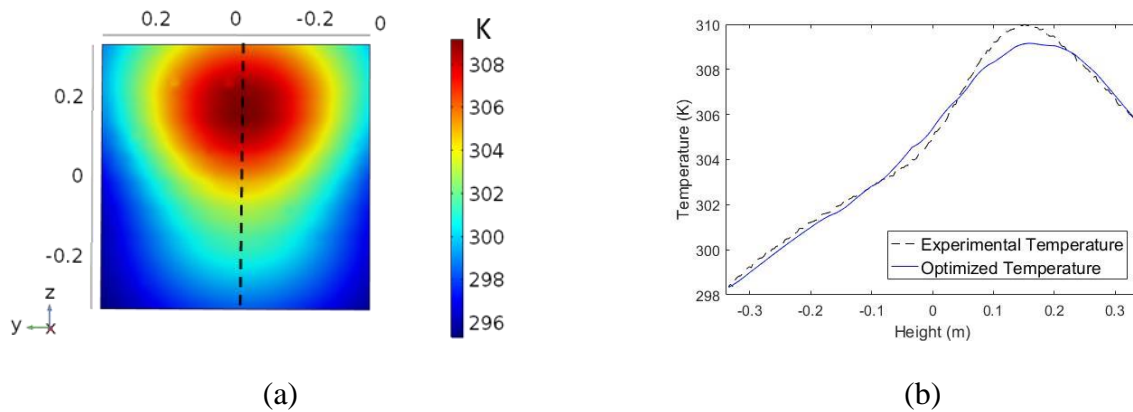

(a)   (b)

Fig. 5. (a) Optimized surface temperature on the back face of the ABS sheet(b) Comparison between Experimental temperature and optimized temperature on the perpendicular profile.

However when the optimized coefficients and filament temperature were applied to simulate the second case, directed towards the sheet, the error became 26.4%. A closer look at the optimized parameters shows that two of the six coefficients are equal to zero. This does not represent the physical reality of the process as the reflector is not totally opaque. The 6th coefficient is also higher than all but the first coefficient and the condition exposed in equation (Eq. 3) is not taken into account so the conservation of power is not respected.

5.   Conclusion and perspectives

This work proved promising for modelling the spatial emission of tubular IR halogen lamps with a coated reflector. A second approach is currently being studied. Optimization is carried out using Matlab® coupled to COMSOL via the Livelink module. This new approach allows for more flexibility via the possibility to use constraints, to adapt the objective function and also to use unsteady experimental data. In addition to these elements, optimization can be carried out on multiple positions allowing a better fit of the filament temperature and thus the ponderation coefficients.

In this work, an average convection coefficient was used, in further work an effort will be made to better integrate convection into the problem, which will be more complex inside the industrial IR ovens.

Once the distribution function has been found, it will be integrated into a model of the IR oven, simulations will be carried out to compare experimental heating of an instrumented ABS sheet with the heating simulation.

Acknowledgments

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