Thermal optimization of pultruded composites

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Abstract: The objective of this research is to find the optimal heat flux and, additionally, the optimal speed in order to increase the production rate and obtain a pultruded part with a minimum established degree of cure. The optimization strategy is based on combining the numerical capability of ANSYS CFX®, a Computational Fluid Dynamics software distribution, with optimization algorithms developed in MATLAB®, based on the Particle Swarm Optimization (PSO) Method. Such algorithm has the task of estimating values of the project variables, which are the heat powers and the pulling speed. After each estimation, the process is simulated into CFX and the objective function value is consequently calculated and forwarded to the PSO algorithm. The optimal value of the objective function is found after a number of iterations, according to a stop criterion. A quadratic penalty function was also used to impose the desired restriction, which is the minimum curing degree of the resin to be attained. We have applied this approach to optimize a L-shaped pultruded composite, a shape that has never been optimized as far as we know. Additionally, several heating setups were optimized and compared in order to discover which one was the most financially viable with the studied system.

1. INTRODUCTION

Polymeric composites are manufactured by different processes, such as pultrusion, hand lay up, filament winding, etc. The pultrusion consists in pulling a fiber set through a resin bath and then into a heated die where the part is cured. Outside the die, the composite part is pulled by a continuous pulling system and then a cut-off saw cuts the part into a desired length. Typically the die is heated by electrical heaters coupled on its surface (SANTOS, 2014).

Optimization of pultrusion has been studied recently by some researches. Santos *et al.* (2014) proposed a CFD (Computational Fluid Dynamic) -based optimization model to minimize the energy consumption of pultrusion. The algorithm was developed in a FORTRAN90 code together with the ANSYS CFX® software. It was possible to verify that the energy requirements can be reduced by changing the heating configuration of the pultrusion die. For this, an alternative configuration with internal heaters inside the die body was simulated.

In Santos *et al.* (2015), a particle swarm optimization (PSO) algorithm and the computer code DASSL were used to solve/optimize the differential algebraic equation that represents the pultrusion mathematical model. The results of the optimization procedure were compared with results reported in the literature and revealed that this strategy may be a good alternative to find the best operational regarding energy cost.

In Stroher *et al.* (2013), the effect of some variable properties (thermal conductivity and volumetric heat capacity) during the pultrusion process of thermosetting composite materials is numerically studied. Moreover, the influence of the pulling speed and the die temperature in the thermal property variation is also analyzed. It is verified that the temperature profile at the pultruded bar centerline for the variable property case is smoother than the constant one, similarly when the pulling speed is increased.

In Silva *et al.* (2014), new relative positions for the heaters were investigated in order to optimize the energy consumption. Finite Elements Analysis was applied to identify the best relative position of the heaters into the die, taking into account the usual parameters involved in the process. However, an optimization study was not realized.

The goal of the present paper is to optimize a pultrusion process by using a CFD model and a MATLAB® optimization code. The particle swarm optimization (Santos *et al.*, 2014) was considered as optimization algorithm to perform this task. The objective function was formulated as the pultrusion energy cost and the heaters power were used as degree of freedom of the optimization procedure. It is the first time that a MATLAB® and ANSYS CFX® were used for this purpose.

2. PULTRUSION MODEL

In this section we present the methodology used for simulation the pultrusion process in the ANSYS CFX®. Pointwise, a mesh generation software for CFD, was also used. Our strategy is based on the work of Baran et al. (2014), who proposed the pultrusion model of a L-shaped part according to the system seen in Figure 1.

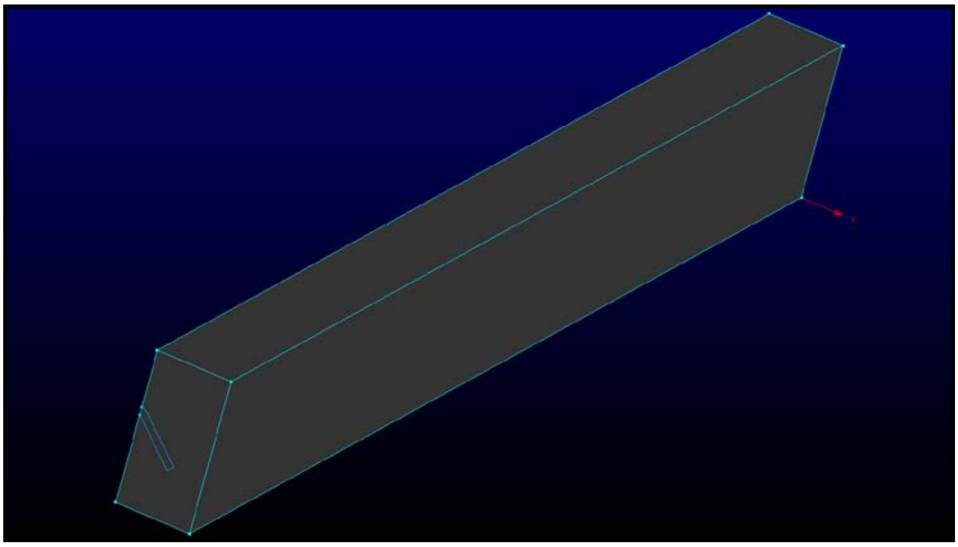

Figure 1 - Mold-composite system design made in Pointwise.

Figure 2 depicts the heaters configuration originally used by Baran et al.(2014):

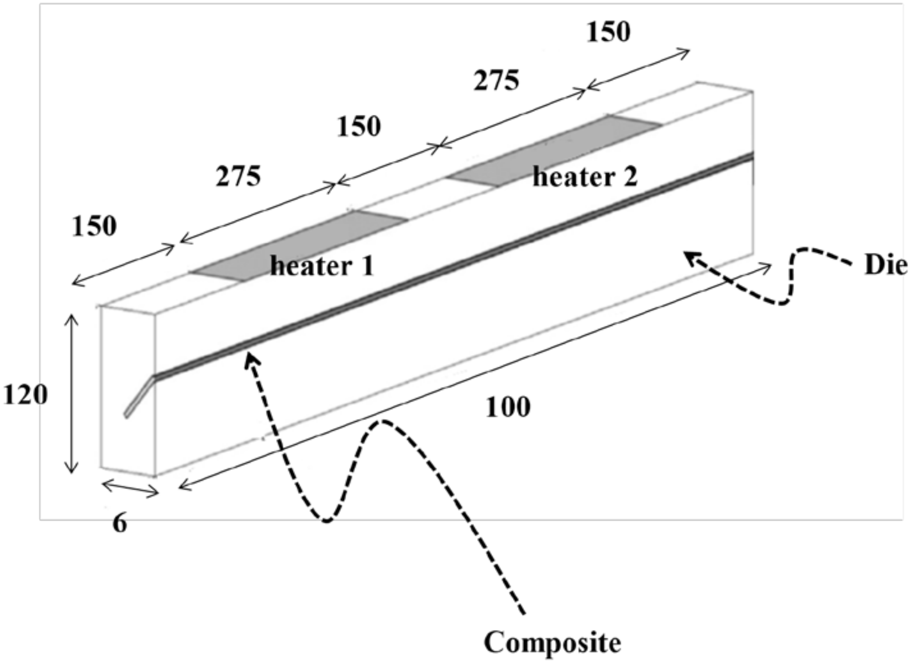

Figure 2 – Pultrusion die (in cm).

In the present model, mass and energy balances are needed in order to study the thermal behavior and degree of cure of pultrusion process. Hence, the control volume used for such procedure was the die region. As the goal of this work is to study the thermal and kinetic phenomena, the assumption of cure initiation after the resin impregnation was regarded here. In this way, the time dependent energy balance is given as follows:

$$\frac{d}{dt}\left(\rho C_p T\right) + \underline{\nabla}\left(\rho C_p \underline{v} T\right) = \nabla.\left(k \underline{\nabla} T\right) + C a_0 (1-\varphi) \Delta H_r R_a \quad (1)$$

where T is the composite temperature, t is the time independent variable, cp_c, k_c and ρ_c are composite specific heat, thermal conductivity and density respectively, ΔH_t is the total heat generated by the cure reaction, r_a is the resin reaction rate, φ is the fiber volume fraction (that is equal to the porosity of the system fiber-resin) and Ca_0 is the resin initial concentration. In our study a polyester resin and glass fiber were considered. The parameters can be checked in Baran *et al.* (2014).

It is reasonable to assume that the cure time is higher than the resin flow time. Thus, there is no need here to consider the momentum equation. The mass balance, in terms of concentration, may be expressed as:

$$(-r_A) = \frac{d\alpha}{dt} \tag{2}$$

where α is the degree of cure.

The resin cure kinetic has been investigated separately, both experimentally and theoretically. The cure kinetic model depends on the type of resin. For this paper, an autocatalytic model, that represents a polyester resin kinetic, was regarded:

$$r_a = A_0 e^{\left(-\frac{E_a}{RT}\right)} (1 - \alpha)^n \tag{3}$$

where A is the frequency factor, n is the reaction order, R is the universal ideal gas constant and E_a is the activation energy.

3. METHODOLOGY

For the simulation step, Figures 3 and 4 presents the mesh made at Pointwise:

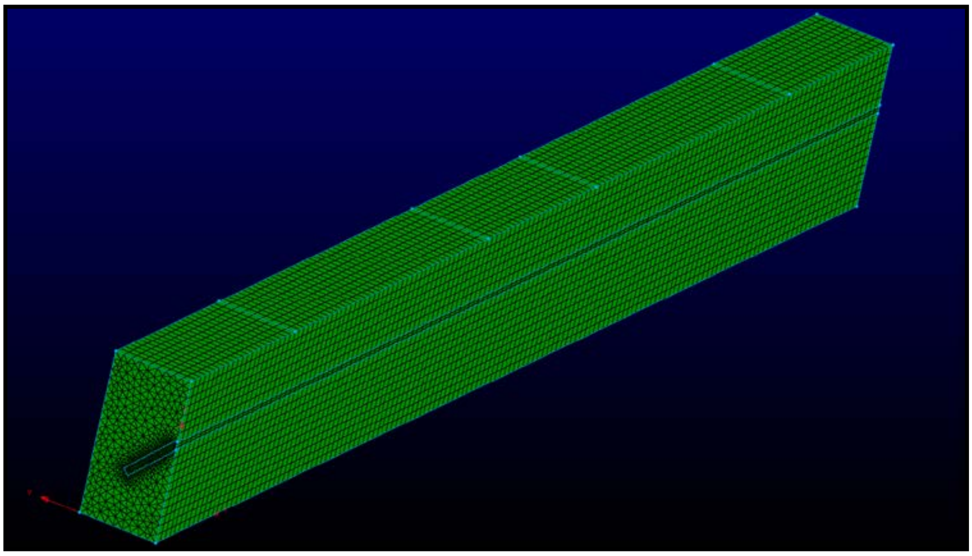

Figure 3 - Complete mesh.

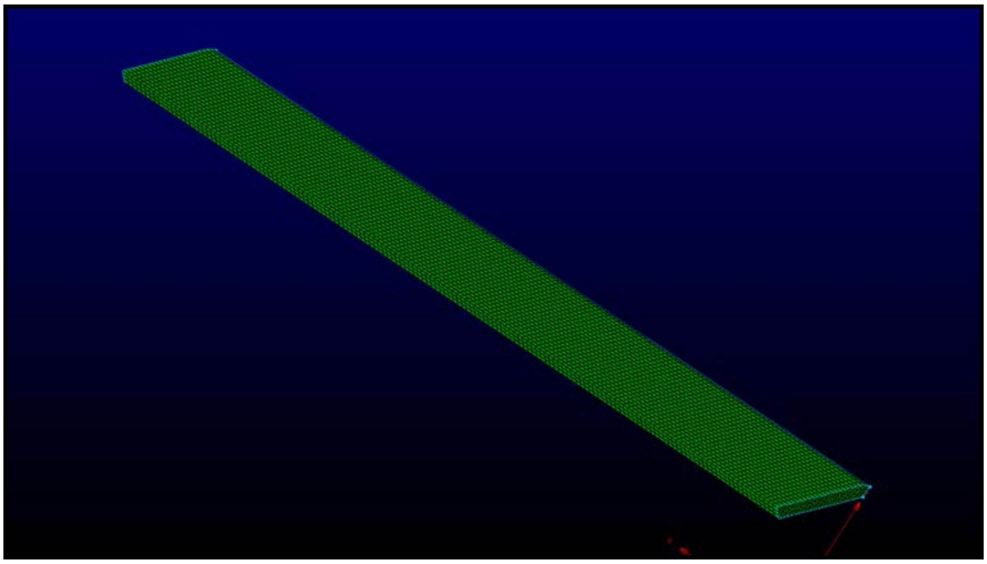

Figure 4 - Composite mesh.

Now for the optimization step, the procedure takes into account the energy consumption as objective function:

$$q_h = P_e \sum_i^n A_i q_i \quad (4)$$

where q_i is the power (in Watts) of each heater and n is the number of heaters. P_e is the energy cost in \$/Joules.

The production rate was also considered:

$$P = \upsilon A_t \rho_c P_c \quad (5)$$

where υ is the pull speed, A_t is the transversal section area of the composite part, ρ_c is the composite density and P_c denotes the composite price in \$/kg.

Given this, the objective function is written as:

$$F_{obj} = v_{op} A_c \rho_c P_c - P_e \sum A_i q_i \quad (6)$$

The goal is to maximize the function represented by Equation 6 according to:

$$\mathbf{max}\left[F_{obj}\right] \quad (7)$$

subjected to:

$$\alpha_{\mathbf{min}} \leq \alpha^* \quad (8)$$

where α^* corresponds to the minimum degree of cure to be attained in the die end. We have considered $\alpha^* = 95\%$ for this purpose. The heaters and pull speed are used as decision variables of the optimization. Introducing a quadratic penalty function:

$$P(\alpha, p) = p\,\mathbf{max}[(\alpha_{min} - \alpha),0]^2 \quad (9)$$

Equation (9) shows that for curing degree less than **95%,** the penalty function becomes greater than 0, decreasing the value of the objective function, moving away the optimal solution algorithm that is maximizing the function.

The particle swarm optimization (SANTOS, 2015) was used as optimization algorithm. For more details on PSO check SANTOS et al. (2015). The code was written in a MATLAB® package while the pultrusion model was implemented into ANSYS CFX®.

4. RESULTS

Tables 1 and 2 present the physical-chemical and kinetic parameters used:

Table 1 – Physical parameters

Resin density	1100	kg/m^3
Fiber density	2560	kg/m^3
Air density	1.18	kg/m^3
Steel density	7833	kg/m^3
Resin thermal conductivity	0.17	W/m K
Fiber thermal conductivity	1.04	W/m K
Air thermal conductivity	0.027	W/m K
Steel thermal conductivity	40	W/m K
Resin viscosity	0.001	Pa s
Air viscosity	0.0000187	Pa s
Resin thermal capacity	1830	J/kg K
Fiber thermal capacity	670	J/kg K
Steel thermal capacity	460	J/kg K
Air thermal expasion coefficient	0.003354	K^{-1}
Porosity	0.2	

Table 2 – Kinetic parameters

Frequency factor	7.5581×10^{-9}	s^{-1}
Activation energy	82.727	kJ/mol
Heat of reaction	190	J/g
Ideal gas constant	8.314462	J/mol K
Order m	2	

4.1. Comparison with the results obtained by Baran et al. (2014)

The two large differences between the simulation done in this work and that done by Baran et al. (2014) are:

- BARAN et al. (2014) simulated the cavity of the mold, as well as the part up to 5 m after the exit of the mold;

- Here, because of convergence problems with the solver, a kinetic of order n = 2 was used for curing modeling, not the typical autocatalytic model for polyester resins, used by the author.

Figure 5 shows the temperature profile at the center of the composite obtained by BARAN et al. (2014) and obtained in the present simulation, made under the same conditions. Although the first curve is narrower, it is possible to notice that the two profiles presented the same tendency. The maximum temperature reached was about 170 °C. Additionally, in the post cure, the temperature dropped to 160 °C. The same could be concluded for the degree of cure (Figure 6): the maximum value was approximately 95% up to 1 m. After that, the system cured up to 100 %.

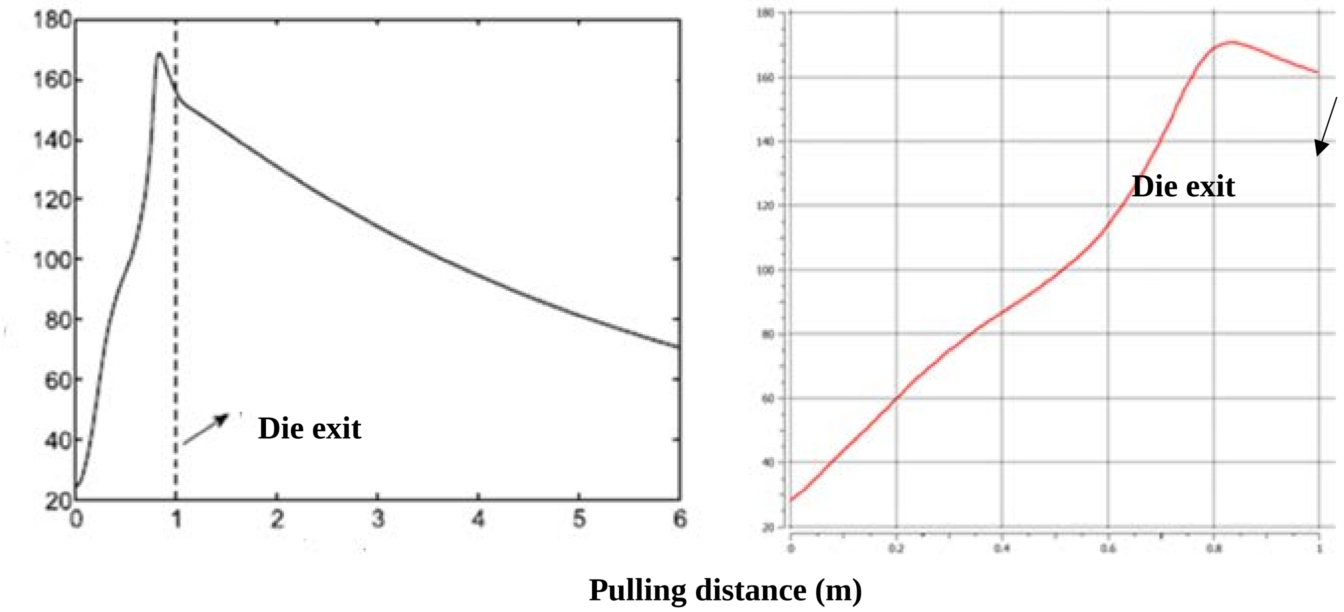

Figure 5 – (a) Temperature profile (BARAN et al., 2014) and (b) Temperature profile (simulated).

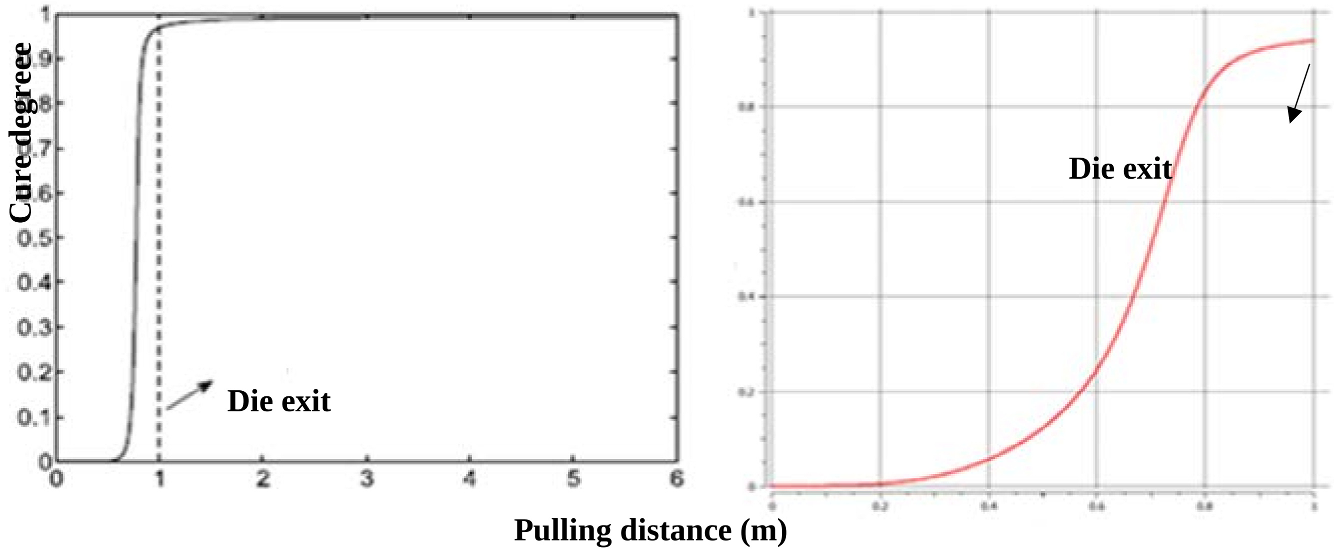

Figure 6 – (a) Cure profile (BARAN et al., 2014) and (b) Cure profile (simulated).

The curing profiles and temperatures in the control volume of the composite obtained in the simulation are shown in Figures 7 and 8. In the temperature profile, it is possible to note that the temperature increase is not substantial close to the die entrance. However the temperature peak is reached near the end of the second heater. n addition, it is also clear that the temperature falls slightly close to the die outlet, characterizing the beginning of the post-cure period of the part. In Figure 7, it is apparent that the cure degree (product mass fraction in this simulation) increases very slowly before 0.5 m. However, the curing rate rapidly increases near the second heater, stabilizing after the temperature peak, being in agreement with the results obtained in Figures 6.

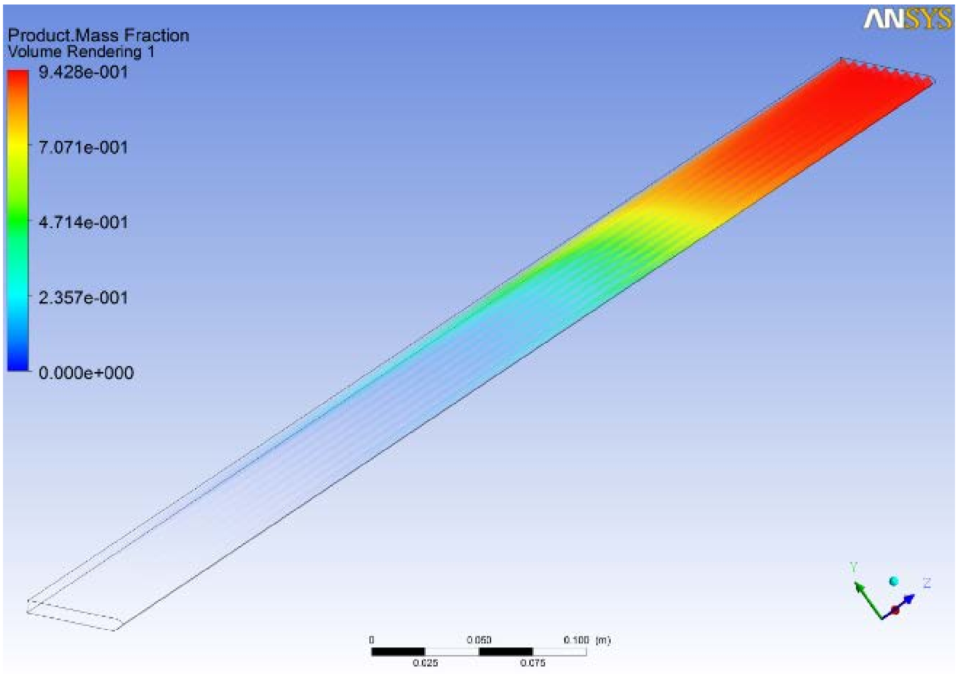

Figure 7 – Curing profiles (not optimized).

4.2. Optimization

In the study by BARAN et al. (2014), no optimization was made with respect to the system's tensile velocity or the energy expended by the electrical resistors. The intention at this section is to evaluate if the speed - power configuration of the heaters used by the author is advantageous, compared to different configurations, seen in this and the next items of this chapter.

Thus, the objective here is to optimize the process profit, with an objective function based on the works of COELHO and CALADO (2002) and SANTOS (2009), presented by Equation (6). Table 3 shows the parameters used in the swarm algorithm and the constraints that delimit the feasible region of the problem.

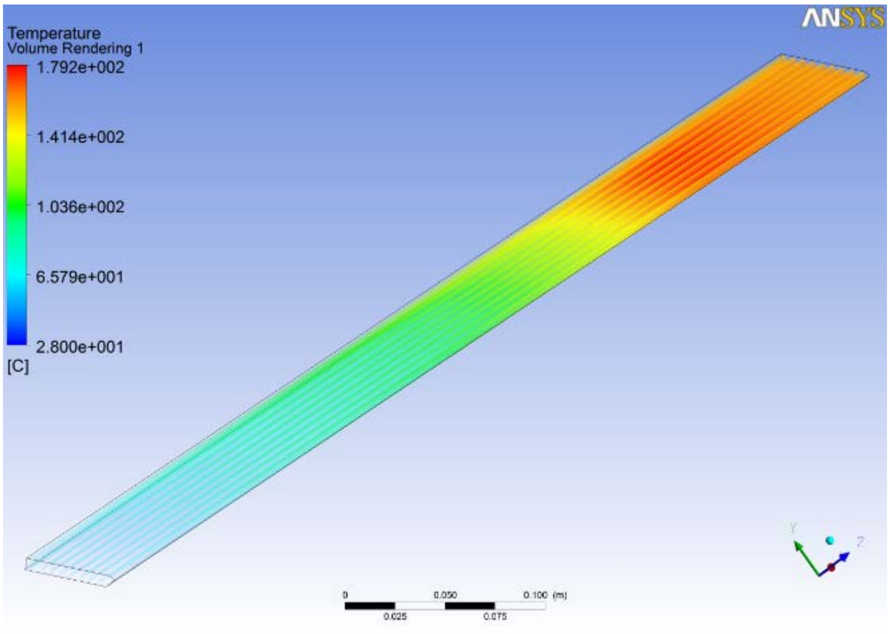

Figure 8 – Temperature profiles (not optimized).

Table 3 – PSO algorithm parameters

Number of iterations	20	
Number of particles	10	
Self confidence	1,5	
Swarm confidence	1	
Penalty parameter	200000	
Min. heat flux	0	W/m^2
Max. heat flux	5000	W/m^2
Min. velocity	0	mm/s
Max. velocity	10	mm/s
Min degree of cure	0.95	

Table 4 presents the results of the optimization. The algorithm finds the optimal solution in the fourteenth iteration. The results show that with this configuration of heaters and decision variables, the optimal process profit is 0.0041 $/s. The relatively low value for velocity is probably on account of the range chosen for the powers.

Table 4 – Results of the optimization

Iteration	**q_1 (W/m^2)**	**q_2 (W/m^2)**	**v (mm/s)**	**F_{obj} ($/s)**	**α**
14	4833,1	5000	3,9892	0,0041	0,95

The next figures illustrate the temperature and curing profiles for the optimization:

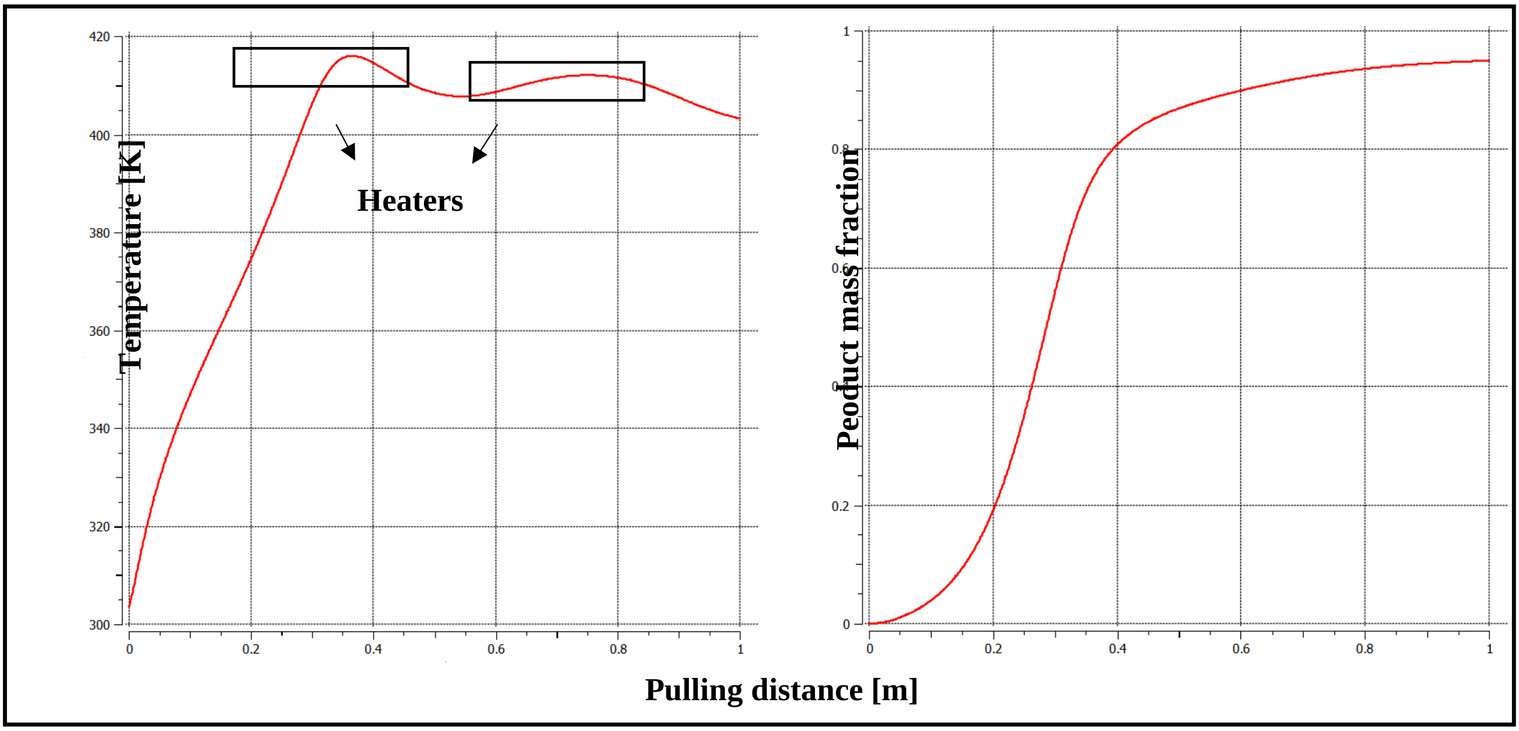

Figure 9 – (a) Temperature profiles and (b) curing profiles for the optimized case.

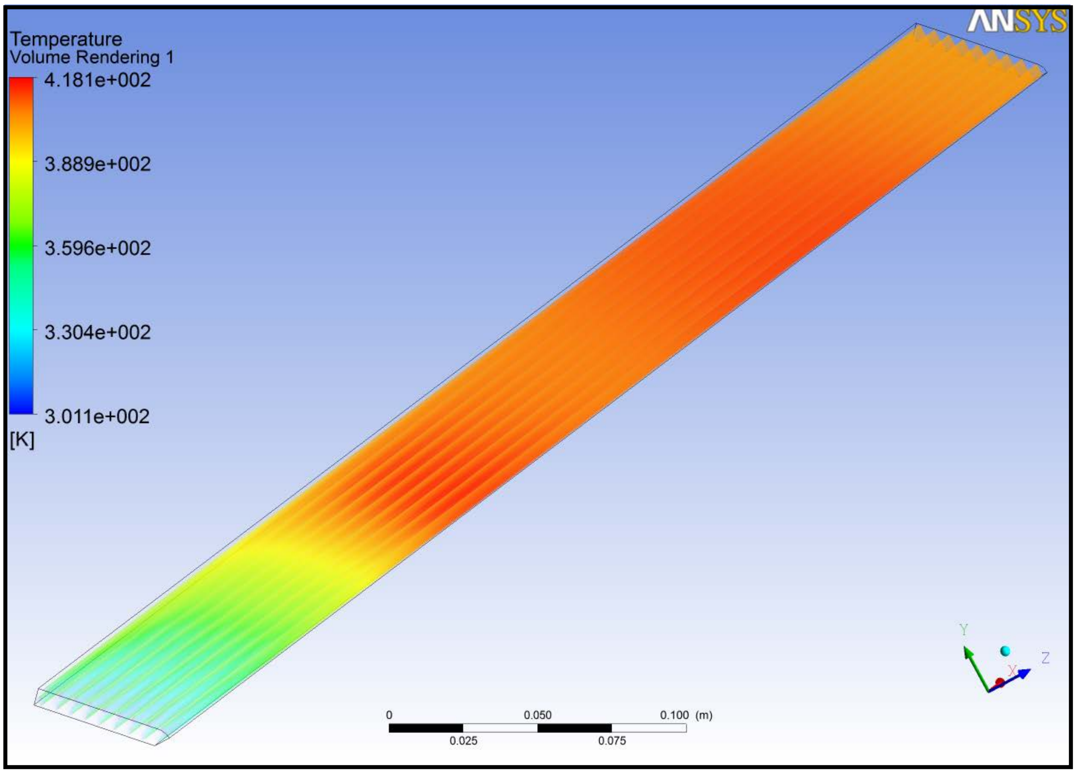

Figure 10 – Temperature profiles for the optimized case.

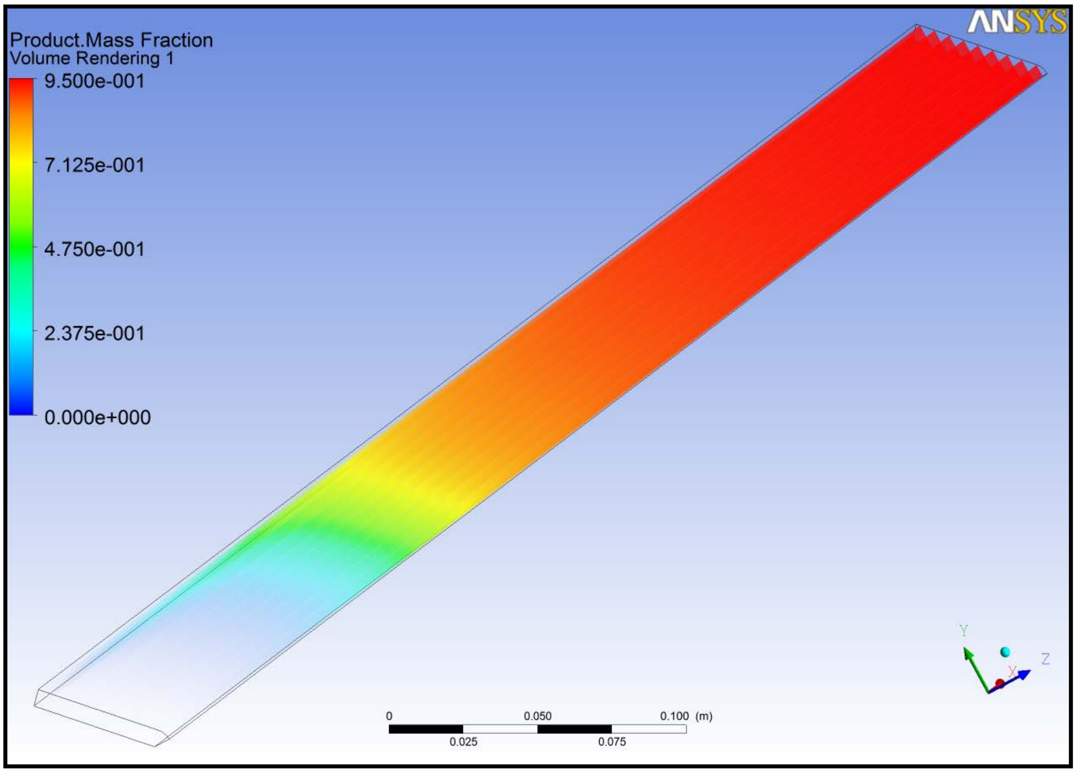

Figure 11 – Curing profiles for the optimized case.

There is a considerable difference in relation to the previous simulation, especially in the temperature curve. This is due to the fact that, unlike the simulation with the two heaters at fixed temperatures, where we had the first heater at a substantially lower temperature than the second, the algorithm calculated very close heat fluxes, causing these two peaks in the curve. Another disparity, also because of the flows of the heaters, is the almost immediate beginning of the curing reaction with a high curing rate in the first half of the mold. It is observed that the composite is almost fully cured prior to entering the second heater.

5. CONCLUSIONS

In this paper we have developed an optimization strategy wich joins MATLAB® and ANSYS CFX® solver. In such strategy, the minimization of energy used during the pultrusion process was computed. Given this, the following conclusions can be obtained:

(i) The degree of cure can be maximized even spending a smaller quantity of energy provided by the die heaters;
(ii) At the same time, the pull speed can be increased if less energy is used to warm the part.
(ii) The CFX simulation coincided well with the results of BARAN et al. In spite of this, the present study showed certain limitations and complications in the implementation of some models that may make the use of more accurate software of the area, such as LIMS, more viable.
(iii) The PSO algorithm is a robust method because of its stochastic and easy to implement nature. He was perfectly capable of maximizing the proposed Profit function. However, there is a need for deeper studies regarding the parameters of the technique, such as which ratio to use for inertia weight and how many iterations and particles. It is also evident that

the algorithm tends to maximize speed, probably because the limit set as the restriction for the flow was only 5000 W / m2. In future studies, it is believed that it is better to fix flows or velocity as a decision variable, working on it. In spite of this, the algorithm is useful in evidencing the ideal speed range within a pre-established heat flow range and vice versa;
(iv) The interface proposed by SANTOS (2009) proved once again a useful methodology, efficiently manipulating the output files of the simulations made throughout the iterations. The use of MATLAB in programming was also presented as a very powerful way, allowing the implementation of the algorithm in a code of few lines.

6. REFERENCES

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