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HEAT CONDUCTION IN COMPOSITE WITH DEPENDENCE OF FIBER ORIENTATION IN A SOLID ROCKET MOTOR ENVELOPE

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Abstract. *In recent years, polymeric composite has been adopted as structural material for envelopes of solid rocket engines. They present diverse advantages, like high strength with low weight and relatively low cost and easy manufacturing. Such composites are made with a combination of a matrix, which is a polymeric resin, and a fiber that is responsible for main of mechanical properties. Previous studies had demonstrated that properties are strongly dependent of fiber orientation relative to the axis of the rocket envelope. Due the aerodynamic warming of such vehicles, the accurate evaluation of heat transfer properties of structural material plays a critical role in its design. In this work, a conduction heat transfer process is simulated in the wall of a solid rocket engine envelope made of polymeric composite through the Finite Element Method, where the effect of inclination of fiber relative to axis over thermal conductivity and resulting wall heat flux are evaluated. Results show the dependence of this property with this geometric parameter.*

Keywords: *Polymeric composites, Effective thermal conductivity, Finite element method*

1. INTRODUCTION

Composite materials consist of two or more materials which together produce desirable properties that cannot be achieved with any of the constituents alone. Fiber-reinforced composite materials, for example, consist of high strength and high modulus fibers in a matrix material (Reddy J. N., 1996).

Composite materials reinforced with carbon fibers in one, two or three directions are frequently used in the Aeronautical and Aerospace industry. In rocket design, these types of composite materials are mainly used in rocket engines and nozzle throats. In the development phase of the design of these components, rigorous analyzes of mechanical and thermal stresses, ablation and heat transfer are carried out, and so it is necessary to know precisely their thermal and mechanical properties. The determination of the mechanical and thermal properties of these composite materials, taking into account several parameters internal to the material, has been the object of research all over the world.

In the engineering, these composite materials are designed as matrix and particles with a variety of different physical properties, sizes, shapes and volume fractions in order to improve the performance of the single original material under specific conditions (Hu et al, 2014 ; Kursa et al, 2014 ; Miranda et al, 2015 ; Mosanenzadeh and Naguib, 2016; Sburlati, 2016).

The effective thermal conductivity (ETC) of composite materials has been of significance from a scientific point of view. Several theoretical models, finite element simulation and even molecular dynamics simulations have been employed to predict the ETC of composite materials and investigate the effect of micro structural parameters on it (Xing et al, 2016; TabkhPaz et al, 2016 and Andrianov et al, 210).

According to Lijia et al (2017), thermal management of theses particulate composite material is dependent on the thermal conduction and heat dissipation. Furthermore, thermal management is crucial to its cost and capabilities to remains its physical properties.

One of the most important parameters in determining the thermal and mechanical properties of these materials is the angle of inclination of the fibers in relation to the heat flow direction. Silva et al (2015) studied the effect of the fiber orientation in a carbon-phenolic ablator. Experimental results were obtained from a test with a plasma jet emulating the gas flow within a rocket nozzle engine, using samples made by two different wrapping procedures and extracted from two different ways. The experimental data were compared with numerical results of computational simulation, obtained for the maximum and minimum values of thermal conductivity for the composite, according to the fiber orientation (perpendicular or parallel to the heat flux).

2. PHYSICAL PROBLEM

Rocket engines made of composite material are manufactured using the filament-winding process. The filament-winding process itself is comparatively simple. It consists of wrapping bands of continuous fiber and/or roving or strands over a mandrel in a single machine-controlled operation. A number of layers of the same or different patterns are placed on the mandrel, and the repetitive patterns and reinforcement spacing are subject to close control. The fibers may be impregnated with resin before winding (wet winding), pre-impregnated (dry winding), or post-impregnated. The first two winding sequence are analogous to wet or dry lay-up in other reinforced-plastic fabrication methods. The process is completed by curing the resin binder and removing the mandrel. Curing is normally conducted at elevated temperatures without pressure. Finishing operations such as machining of grinding are usually not necessary (Schwartz, 1984).

The schematic of filament winding process is shown in Fig. 1. Fibers are collected and put in the order through a comb, and then fiber strands are wetted with the resin in resin bath. Furthermore, fiber with the resin passes through another comb and a pay-out eye device. During the process, traverse mechanism can move forward and backward in the delivery system. In addition, fibers with impregnated resin are wound around a rotating mandrel at various winding angles to satisfy mechanical requirements, such as thermal conductivity, strength, elasticity, ductility, stiffness and fatigue strength. The tubular structure is then cured at ambient temperature or special temperature and the mandrel is removed. To remove the mandrel from the composite products, hydraulic rams may be used on different filament winding machine. Hollow pipe and other shape parts are fabricated via filament winding technique. Fiber tension force is critical specification in filament winding because compaction is achieved by the fiber tension, which is a necessary parameter should be under control. The fiber tension will affect the properties of the composite products. There are many tension device types such as magnetic or friction brakes, electronic rewind, rotating scissor bars and high performance solenoids. Filament winding has another main advantage is that a high fiber volume fraction can be achieved in the composite material with filament winding process technique (Quanjin et al, 2018).

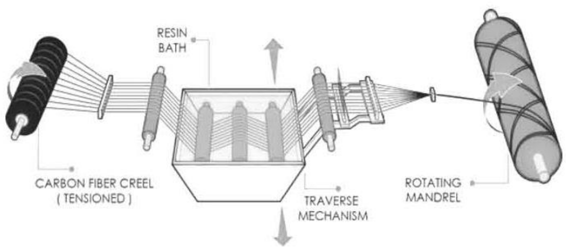


Figure 1. Filament winding process schematic.

Thermal conductivity is attributed to the exchange of energy between adjacent molecules and electrons in the conducting medium.

Heat transfer processes can be quantified in terms of appropriate rate equations. The rate equation in this heat transfer model is based on Fourier's law of thermal conduction. This law states that the time rate of heat transfer through a material is proportional to the negative gradient in the temperature and to the area, at right angles to that gradient, through which the heat flows. Its differential form is:

$$q = -K \nabla T \tag{1}$$

Where:
q = heat flux (W/m^2)
K= material thermal conductivity (W/m ^{o}C)
∇T = temperature gradient (^{o}C/m)

3. METHODOLOGY

The finite element method has been used in the modeling of composite materials, in order to determine their effective thermal conductivity. More recently, with the development of computing ability of computer, the finite element analyses (FEA) are widely used in numerical calculation of thermal conduction (Kai *et al*, 2016). Li et al (2011) predicted the in-plane and out-of-plane thermal conductivities of woven fabric composites through the representative volume element method implemented using two unit cells established at different length method scales with periodical conditions. Gou et al (2015) established three reducing-size unit cells formulated by using different symmetries based on FEA numerical approach to predict the effective thermal conductivities of plain woven composites. Although these methods can effectively calculate the thermal conductivities of plain woven composites, the interior thermal conductive structural effects, including the temperature distributions and heat flux transferring paths, are seldom reported. Fourier's law for heat conduction, in the case of steady-state, applied in the finite element method can be written as:

$$\{Q\} = [K].\{\nabla T\} \tag{2}$$

Where

$\{Q\}$ = is the heat flux vector
$[K]$ = is the material conductivity matrix
$\{T\}$ = is the temperature gradient vector

In this study, the effective thermal conductivity of a composite material, reinforced one-directionally with a carbon fiber fabric, is calculated through a finite element simulation. The carbon fiber fabric is impregnated with epoxy resin matrix. A sample of this composite material measuring 0.040 m x 0.040 m x 0.010 m is analyzed through a finite element model, whose elements have micrometric dimensions. The finite element model is considered a two-phase domain and is formed by layers of epoxy resin and layers of carbon fiber fabric with thicknesses equal to 0.45 mm, which means that resin represents 50% of composition in volume. The carbon fiber fabric layers form an angle ϴ with the direction of heat flow. Two metallic plates with a thickness of 0.50 mm, made of a material with high thermal conductivity were placed on the upper and lower surfaces of the sample. Figure 2 shows all the details of the finite element model.

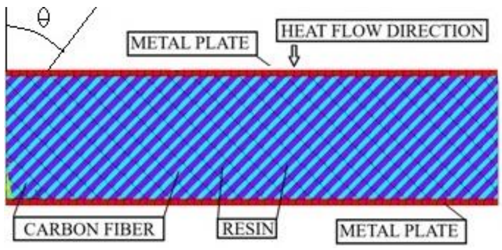


Figure 2. Domain and mesh used in the Finite element method.

Seven different finite element models were made with the angle value equal to 0^0, 15^0, 30^0, 45^0, 60^0, 75^0 and 90^0. The boundary conditions applied in all models were as follows: on the free surface of the upper metal plate a constant heat flux was prescribed, on the free surface of the lower metal plate a constant temperature was prescribed and in all other free areas of the model they were considered if an adiabatic boundary condition. For each finite element model, three steady-state thermal analyzes of heat transfer were performed, considering the three prescribed heat flux values (100 kW/m^2, 200 kW/m^2, 300 kW/m^2). The carbon fiber fabric and resin were considered isotropic materials. The table 1 shows the material properties used in the analyses. The effective thermal conductivity (ETC) of composite materials sample can be calculated by:

$$K_{eff} = \frac{Q.e}{(T_S - T_i)} \tag{3}$$

Where

K_{eff} − Effective thermal conductivity of the sample on the heat flux direction, W/mK.
Q – Imposed heat flux, W/m^2.
e – Sample thickness, m.
T_S , T_i – Temperatures of upper and lower metal plates, respectively, ^{o}C or K.

Table 1. Material properties.

PROPERTY	RESIN	CARBON FIBER	METAL PLATE
K (W/m *K*)	0.80	10.5	10^3
ρ (*k*g/m^3)	1700	1760	10.500

4. RESULTS

The temperature values for all thermal analyzes performed with the seven finite element models are shown in Tab.2. The effective thermal conductivity of the composite material sample was calculated using the equation (3) and appears in the last column of Table 2. The values of effective thermal conductivity for $\theta = 0^o$ and 90^o where validated through a direct comparison with analytic results, resulting in a difference below 0.1%. Figure 3 presents temperature distribution for $\Theta = 45^0$ and heat flux = 100 kW/m^2. The effect of the angle in fibber distribution is easily observed, resulting in an asymmetric distribution within the domain. Figure 4 shows the effective thermal conductivity of the composite material sample versus angle Θ. This curve was fitted by a fifth degree polynomial and used to generate the values of ETC for any fiber slope.

Table 2. Temperature values for upper and lower metal plate.

Θ (°)	Heat flux (kW/m^2)	Temperature T_i (° C)	Temperature T_s (° C)	Effective Thermal Conductivity ETC (W/m . *K*) (*)
0	100	100	275.48	5.6984
	200	100	450.97	
	300	100	626.46	
15	100	100	287.58	5.3309
	200	100	475.16	
	300	100	662.75	
30	100	100	322.91	4.4861
	200	100	545.82	
	300	100	768.73	
45	100	100	390.90	3.4375
	200	100	681.81	
	300	100	972.71	
60	100	100	513.76	2.4168
	200	100	927.53	
	300	100	1341.31	
75	100	100	677.32	1.7321
	200	100	1254.64	
	300	100	1831.96	
90	100	100	772.62	1.4867
	200	100	1445.02	
	300	100	2117.86	

(*) For heat flux = 100 kJ/m^2.

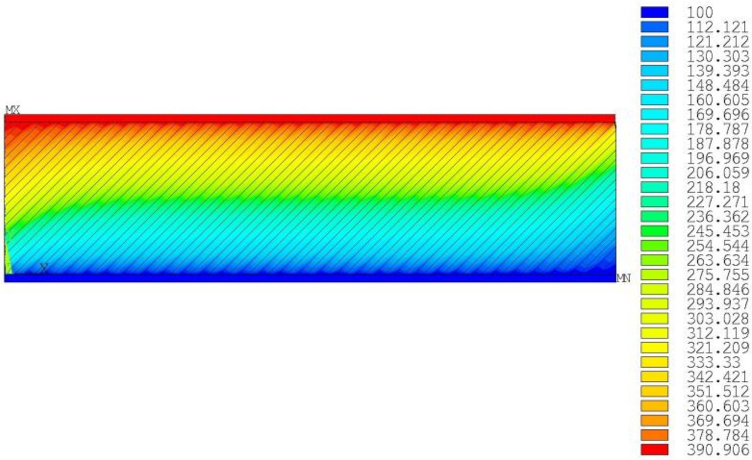


Figure 3. Temperatures for angle $\Theta = 45^0$ and heat flux = 100 kW/m^2.

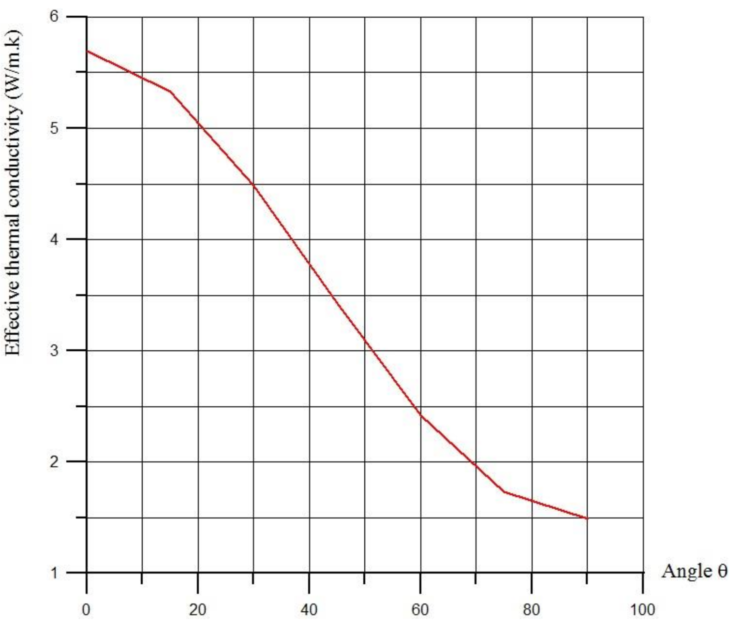


Figure 4. Curve angle Θ versus effective thermal conductivity.

Results generated by the fitted curve for ETC (θ) were applied to the case of ablation in cylindrical samples submitted to a plasma jet, were the value of the thermal conductivity of the virgin material plays an important role in temperature results. The experimental results were extracted from the work of Silva et al (2015) and compared to the values obtained with the average value of thermal conductivity used for simulation in that work. The samples were extracted form nozzles manufactured through biased wrapping, presented in Figure 5, which permits to vary the relative angle of inclination of fibers. The sample extraction is presented in Fig. 6 and the performed experiment is presented in Fig. 7.

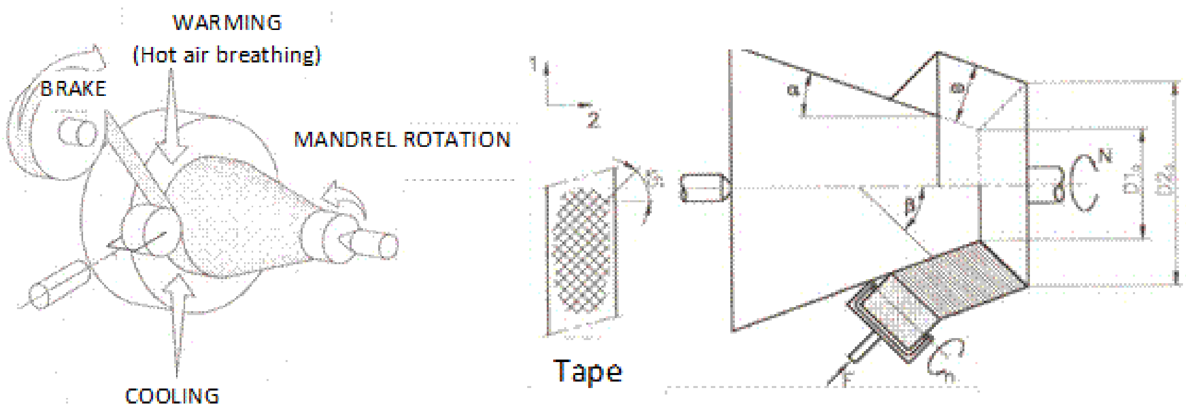


Figure 5. Biased wrapping on conical mandrel. β: angle between tape and mandrel axis; ω: tape width; D10: inner diameter at initial position; D20: outer diameter at initial position.

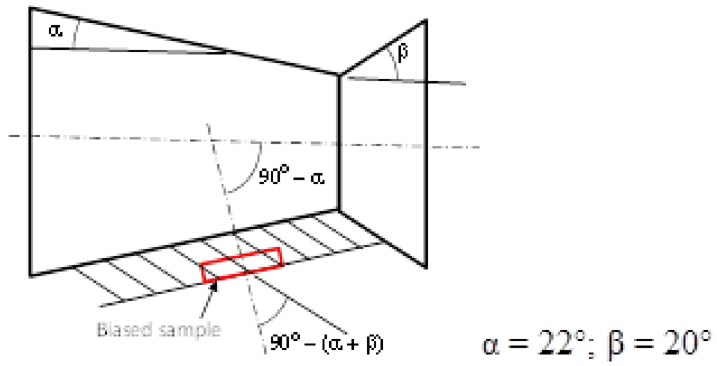


Figure 6: Position for sample extraction.

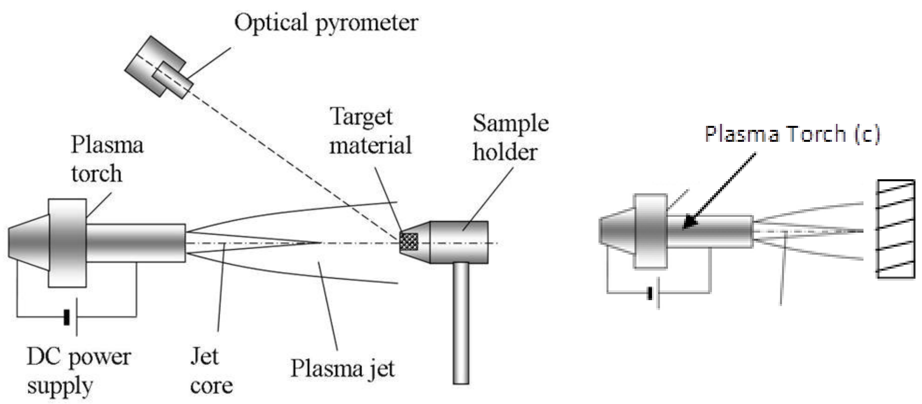
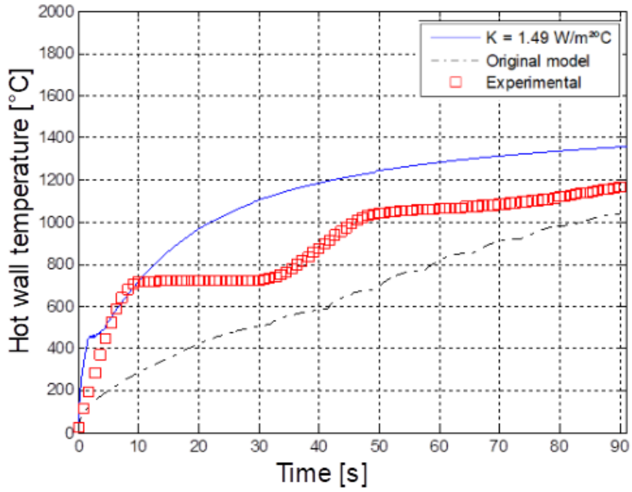
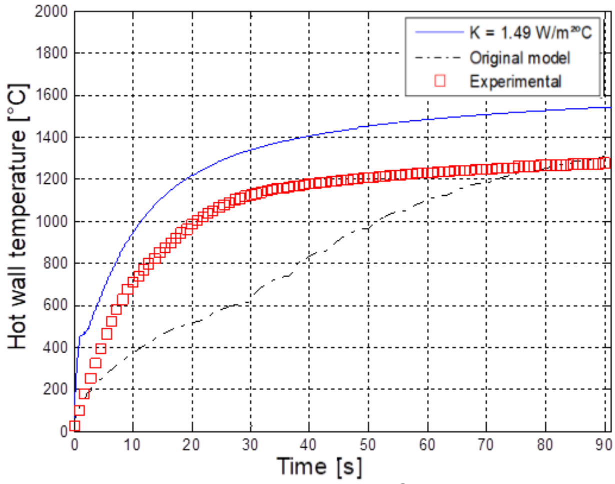


Figure 7. Scheme of an apparatus for ablation test using arc plasma torch.

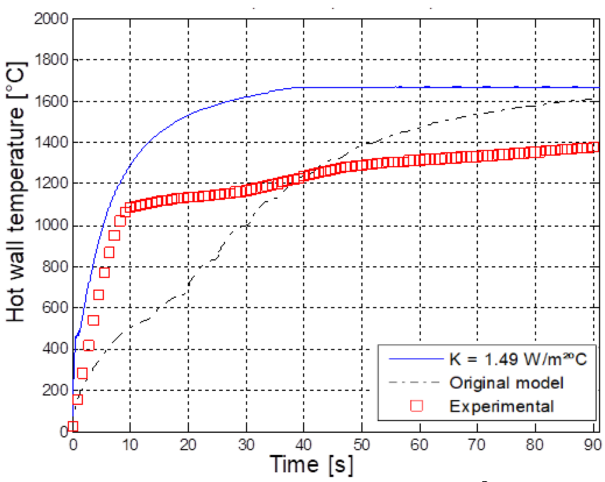
The computational procedure was the same for that reference and the current work and was described in detail in the work of Pesci (2021). The previous results from the simulation (Pesci, 2021) used a thermal conductivity K = 0.867 W/m. *K*, which resulted in the so called “original model” curves. Figures (8-9) present the data for temperature measured in the opposite face of sample exposed to the plasma arc jet in a face, compared to results from numerical simulation, performed with the value of K extracted from literature and the values of ETC obtained from the fitted curve.



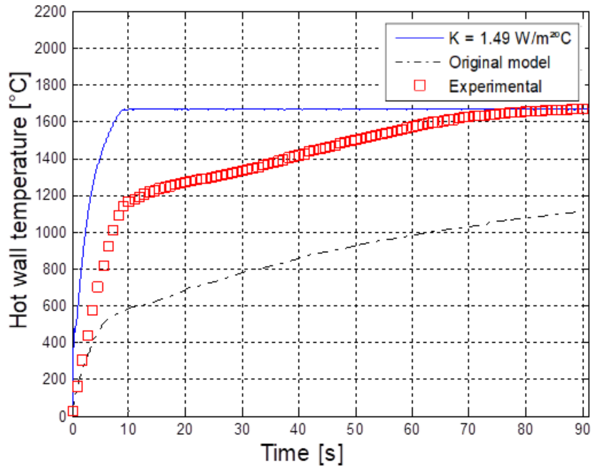
(a) Q = 0.464 W/m²



(b) Q = 0.626 W/m²



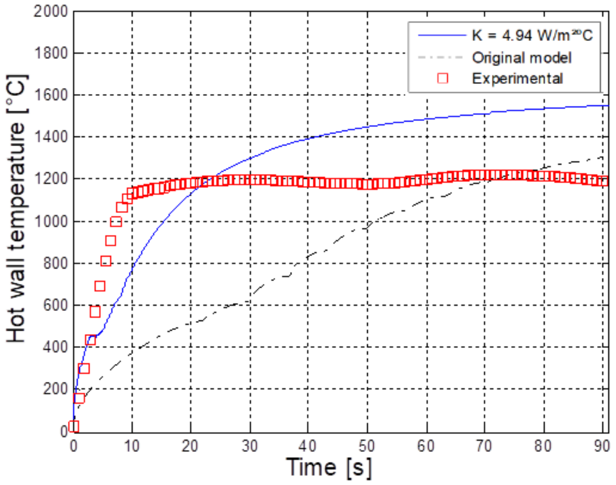
(c) Q = 0.903 W/m²



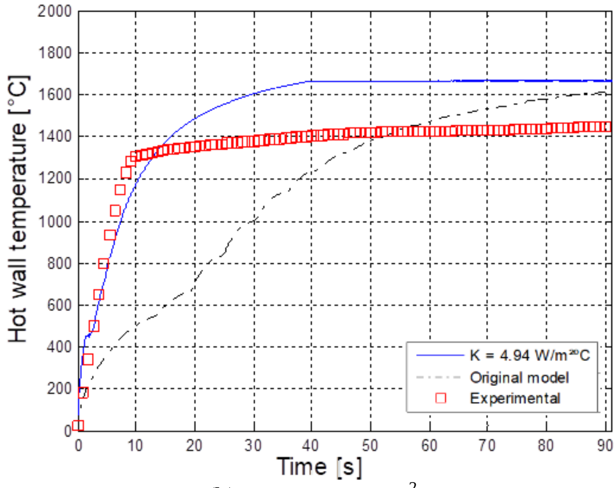
(d) Q = 1.372 W/m²

Figure 8. Temperature (^{o}C) in the opposite face to the plasma jet imposed to the sample with time (s), for $\Theta = 90^{o}$.

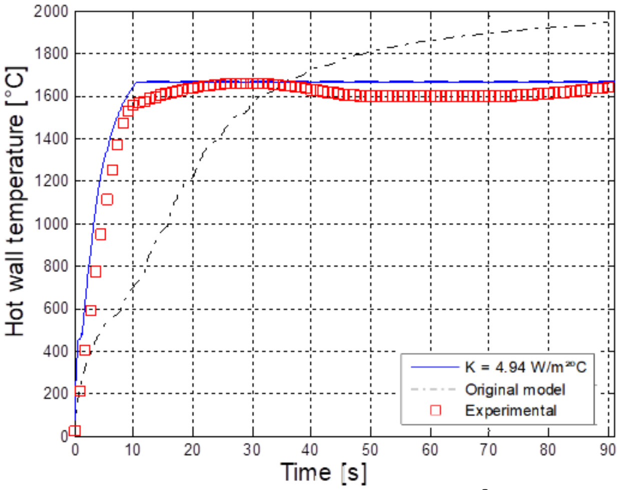
Results show that, in all cases, the curve for the effective thermal conductivity values, obtained in the current work, improves the agreement between the experimental results and numerical simulation, when compared to the value used in the original model, which was chosen considering average data extracted from literature. This is remarkable that the agreement becomes even better with the increasing of heat flux imposed to the sample, since the heat conduction intensity rises with this parameter. The agreement is clearest in Figs. 9.c.d, where the simulation with ETC almost matches both curves for the highest heat fluxes.



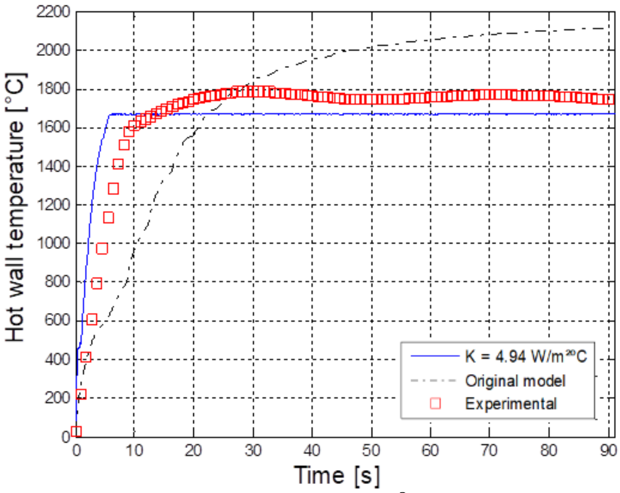
(a) Q = 0.626 W/m²



(b) Q = 0.903 W/m²



(c) Q = 1.373 W/m²



(d) Q = 1.725 W/m²

Figure 9. Temperature (^{o}C) in the opposite face to the plasma jet imposed to the sample with time (s), for $\Theta = 22^o$.

5. CONCLUSION

In this work, a simple model for estimation of the effective thermal conductivity of a polymeric composite was presented that takes into account the slope of the fiber and its proportion relative to the resin. The model was applied in a one dimensional heat conduction problem, in order to simulate the wall of a solid rocket envelope, manufactured with carbon fiber and phenolic resin by a biased wrapping process.

The effective thermal conductivity (ETC) was estimated after a numerical simulation via the FEM in a two dimensional domain, by the straight application of the Fourier law. The numerical data for diverse values of the slope allowed obtaining a fitted curve for K_{eff} x θ.

The numerical results of the present work were compared with the experimental data for an ablation process in an arc jet torch and also with numerical data obtained using the average value of thermal conductivity extracted from literature. Results proved that the use of ETC improved the agreement, especially at high heat fluxes.

Future work should improve and apply the model to other physical properties, including mechanical properties, in order to increase the accuracy in dimensioning solid rocket motor envelopes made with wrapped polymeric composites.

6. ACKNOWLEDGEMENTS

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