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Analysis of Modelling Capabilities of Ablative Fire-Proof Properties in Polymer Fibre Composites in Conjunction with the Metal

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Abstract -The inverse heat conduction and radiation problems are advanced when it's apply to many different layers of the composite with the addition of the metal plate extreme temperatures on the outer surface. The approximate formulation and solution to the ablative problem were conducted by applying FEM Comsol software. A rectangular sample was replaced with a cylindrical sample of an equivalent volume. The tested model does not take into account the changes caused by the impact of the geometrical dimensions of the flame heat. The working conditions for the test sample were non-standard to such an extent that we were forced to estimate the thermophysical properties of the applied temperature range. In addition, the model does not take into account the combustion heat; the given forced heat transfer was modelled by adding, to the tested model, a plate with a given diameter of the burner with the condition of constant temperature, taking into account the radiation and convection. We assume that the considered simplifications are non-significant for the model. Typical results of numerical tests compared with our own experimental results have been listed in the paper. It can be concluded that the presented approximate model correctly represents the actual process of ablation.

Keywords**:** ablative, inverse problem, fire proof properties, polymer fibre composite

1. Introduction

The use of modified plastics as ablative materials protecting against an excessive temperature increase is connected with the middle of 20th century, directly with arms industry as well as aeronautical, rocket and space techniques. These materials can also be used in the design of passive fire-proof protections for large cubature supporting elements in building structures, as discussed by Dimitrienki Yu (1997a, b), communication tunnels and for the protection of data stored in electronic, optical and magnetic carriers. This paper reports results of studies on modelling ablative and thermal properties of epoxy composites with hybrid fabrics reinforcement (kevlar and carbon fibers) filled with a mixture of epoxy resin and mineral nanoclays (layered silicates) and with the addition of a metal plate. The composites were treated with hot combustion gases to detect the temperature profiles across the studied samples, the back side temperature of specimen t_s, the average linear rate of ablation v_a, and their mass waste U_a during ablation processes. The paper briefs assumptions and requirements on research how to create ablative and thermal properties of epoxy composites with hybrid fabrics reinforcement.

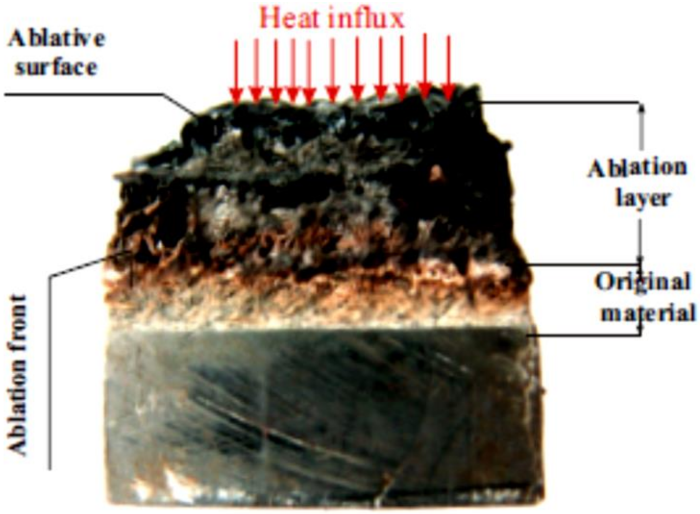

Fig. 1. Physical model of ablation [1]

2. Description of The Subject of Research

For the purpose of the research, aimed at defining the impact of the placement of a metallic reinforcement on the rear surface of the original composite, a polymer ablative composite was used. The composite was made of 14-layer aramid fiber fabric of 230 g/m^2 weight, 6-layer carbon fiber fabric of 160 g/m^2 and 2 mm thick metal plate (steel) ST 3 S. The epoxy resin matrix Epidian 52 used for this purpose, was cross-linked at room temperature with a TFF hardener, produced by the chemical plant Z.Ch. Organika-Sarzyna S.A. in Nowa Sarzyna. The ablative properties of the resin composition were modified by the layered silicate Bentonit Special Extra which contained 75% calcium montmorillonite - MMT - (mining-metal plant Zakłady Górniczo-Metalowe Zębiec in Zębiec). The composition of the composite was adopted on the basis of an analysis and comparison of thermal protection ablative properties of the composite, used for the heat protection element of the universal thermal protective casing of the flight data recorder, as discussed previously (Watts et al., 2008; Zhou et al., 2013; Suresha et al., 2010; Kucharczyk et al. 2014). In order to conduct this study, laminated control panels measuring 150 x 200 mm were prepared. The studied sample had the layers and the metallic reinforcement, as listed in Fig. 2.

The laminate samples of 30 x 35 mm were prepared for the ablative study of thermal protection properties. The laminate was obtained using water jet cutting method with the machine WaterJet DARDI. The ablative study was performed on a test bench in the Polish Air Force Academy WSOSP with the adopted assumptions: testing time $\tau = 150$ s, thermophysical properties of materials ($\lambda(t)$, $\rho(t)$, $c_p(t)$) listed in Table 1; with constant heat flux during the ablative experiment; the ablative surface is an isothermal surface of the ablation front; the heat exchange with the environment on the external surface was ignored.

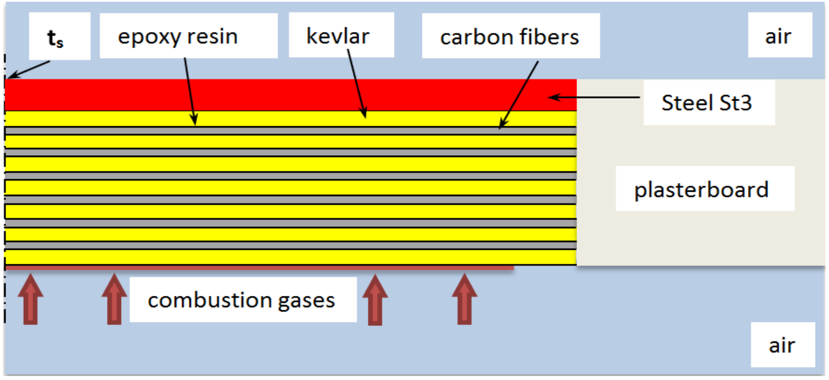

Fig. 2. Sample structure

3. Numerical Modelling

3. 1. Description of Numerical Model

We prepared a geometry model as well as performing numerical simulations in the COMSOL 3.5a environment, by COMSOL Multiphysics. The analysis was conducted by means of the heat transfer module (Lagrange – T_2J_1), where we simulated the physical processes of heat exchange, through radiation and convection.

During the numerical analysis we introduced simplifications of the following:

- the process of gas combustion was simulated through an introduction of a uniform distribution of the temperature field on the surface of the examined sample, with a geometry close to the radius of flame geometry, as well as introducing a replacement value for air, due to a turbulent flow of heated air;
- the 3D model was replaced with a two-dimension axially symmetrical model, with the volume of the tested sample similar to the volume of the actual sample (Fig. 2);
- the introduced thermophysical values of the materials are replacement and approximate values (some values were used as values dependent upon temperatures – Table 1).

COMSOL Multiphysics program set parameters determining the convergence of the simulation model solutions in the following way: the relative tolerance was set at 10^{-6} and applies to a convergence criterion based on a weighted Euclidean norm for the estimated relative error; the nonlinear-solver iterations stop when the relative error is less than the relative tolerance. The maximum number of iterations equals 25, and limits the number of nonlinear iterations. Computational was set at 160 seconds with a time step of 0.1. The absolute and relative tolerance parameters for the time-dependent solver were set at respectively 0.001 and 0.01.

3. 2. Modelling Construction Elements of the System

The thermophysical properties of the specimen and the nearest environment of the simulation examination of the numerical model (fig. 2) were adopted on the basis of available scientific journals, and are listed in the table below (see Table 1):

Table. 1. Materials properties

	Replacement parametres for numerical calculations		
Materials	Heat capacity [J/kg K]	Thermal conductivity [W/m K]	Density [kg/m^3]
Air	1	2+0.005(T-273)*	1.2-0.001(T-273)
Epoxy resin by Johnston (1997)	2030 przy T=473 K	1	1200
Carbon fibers by Schulz (2002); Ohlhorst (1997)	$1921/(1+2.189 \cdot e^{-0.0064\,(T-273)})$	10	1760
Kevlar by Shalin (1995); Web-2;	1380+7.5·(T-273)	$0.05+(T-273)\cdot 10^{-6}$	1440
Steel St3 (unpublished date)	475	44,5	7850
Plasterboard (Web-1)	0.8	0.17-0.00025 (T-273)	600
*replacement value resulting from an introduction of air flow through a heat stream from the burner			

4. Analysis Results

4. 1. Temperature Field and Ablation Layer of the Examined Material

Fig. 3 shows a graphic distribution of the temperature field for the constant replacement value on the surface of the tested sample, at t=160 s. The measurements of the temperature field for the introduced numerical model prove that the temperature on the opposing surface to the surface of the thermal activation surface, after a time span of 160 sec, does not exceed 50° C. Moreover, the ablation surface of the composite material was marked, equalling approximately 1.8 mm, with a radius of r=0, where the temperature exceeded the critical value for the examined material.

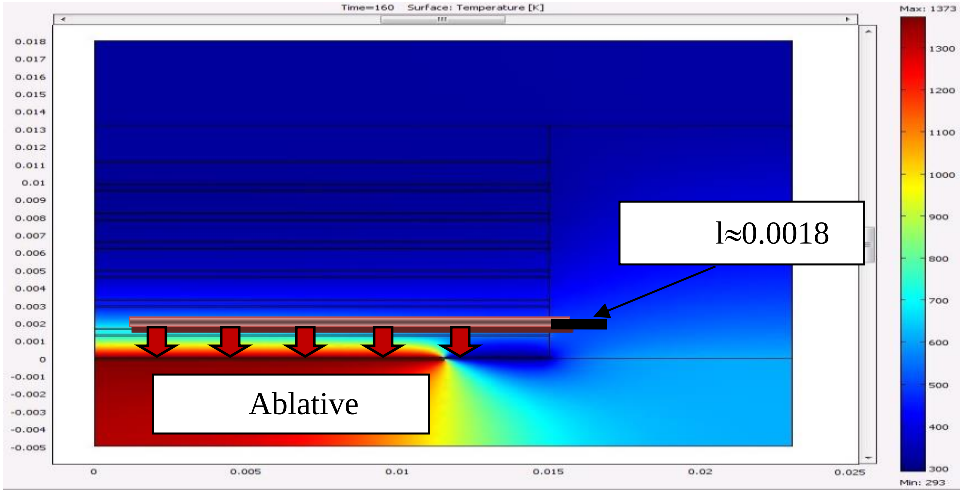

Fig. 3. Ilustration of the ablation layer, after a simulation of the examined sample

In addition, we also presented temperature distribution in the function of time for different values of the distance to thermal activation (Fig. 4). It depicts rough values of the change of the ablation front across particular material layers in the time function (for better illustration of simulation calculations, the temperature measurements were placed where the metal plate was added, on the rear surface, and the exact values on the metal surface were presented in the next subchapter)

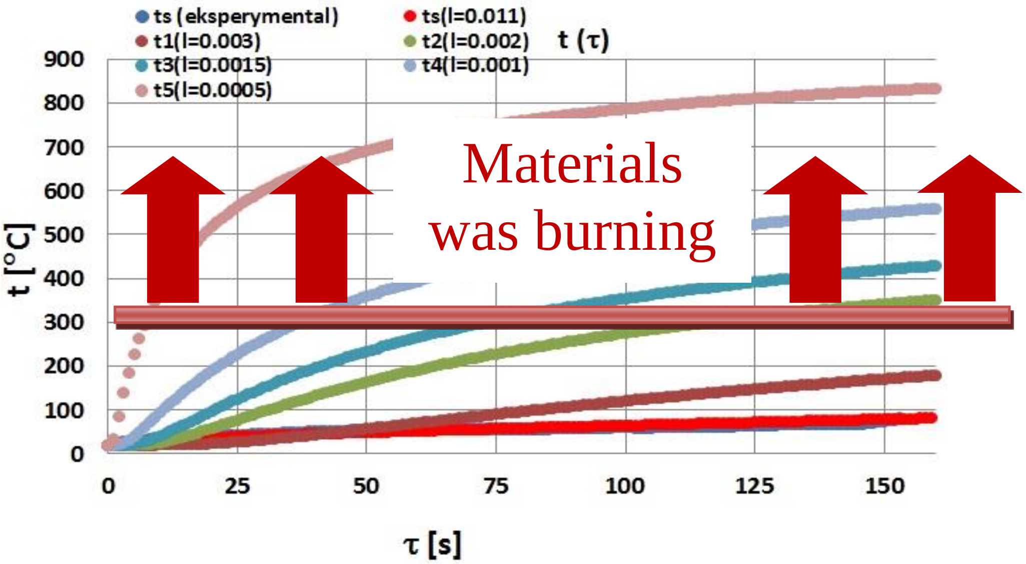

Fig. 4. Simulation result of the examined sample

4. 2. Heat Resistance Properties of a Material

The fundamental parameter which specifies the heat resistance properties of a material is the temperature on the rear surface of the examined sample (t_s) illustrate in figure 5. During this study four samples were tested. The temperature distribution on the rear surface of all four tested samples (3.1-3.4) is presented below in the comparison chart (fig. 5). In the next stage, a numerical simulation of the modelled material, similar to the material experimentally tested, was performed. There were two functions approximating the results involved: the first one – using the average experimental values; the second – the values obtained in simulation. Both functions are marked in fig. 5 with formulas. There is slight discrepancy between the approximations obtained from the experimental and simulation results, which may indicate that the simplifications of the numerical model with reference to the real model were made correctly. Furthermore, it was observed that the initial and final temperature values on the rear surface were similar in experimental and simulation study. The variation can be explained by the dynamic physicochemical alteration of the tested material.

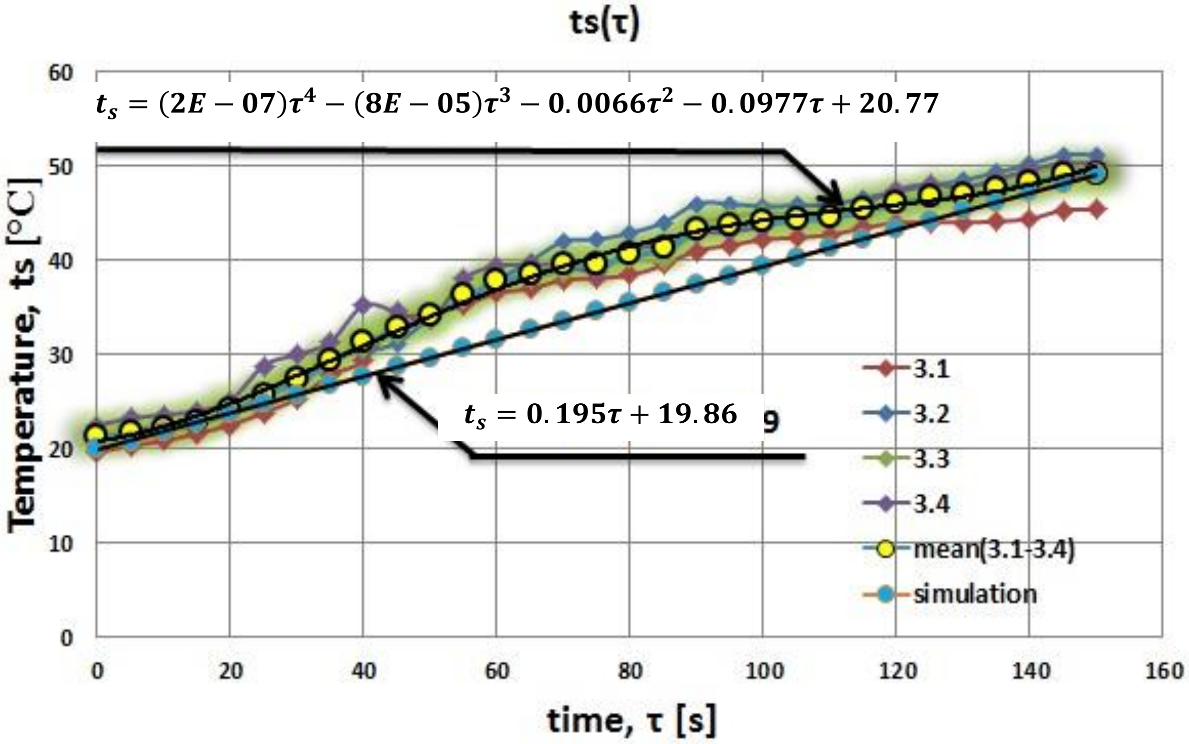

Fig. 5. Numerical and experimental results t_s

In the chart of temperature distribution on the rear surface for all performed experiments, the curve shape is similar. It must be noted that the addition of the metallic reinforcement (in comparison with the composite material without the steel plate) caused a temperature decrease on the rear wall of the isolating sample t_s by approx. 30°C (from ≈79°C – without metal plate; to ≈49°C – with metal plate). The obtained characteristics of each individual experimental laminate study could be different in the case of testing bigger structures. For this reason, it was decided to perform a series of additional tests with ready structural elements.

5. Conclusion

This paper presents the findings of a numerical analysis of a complex heat transfer for composite materials (polymer fibre composite of geometry illustrated in Fig 2). During the assessment of the analysis, it is essential to emphasise the introduction of several simplification assumptions:

- partial implementation of variables of thermophysical parametres, which has got an error due to an incomplete temperature range of the examination of parameters of particular composite materials,
- the pattern has got an error in the measurement of temperature, resulting from very high temperatures (1100° C) on the front surface, and the rear surface, after measuring the temperature by touching the surface with a thermoelement,
- lack of proper insulation of the pattern zone, where there are extremely high temperatures and the air flow is distant from the examined sample,
- assumption about a uniform temperature field, through gas combustion, on the surface of the heated sample,
- the composite material underwent an analysis as layered composition of several components, disregarding the permeation of its components.

The distance from the heated surface, where the material is burnt and the ablation surface is formed equals 1.8 mm, on the basis of a simulation, in comparison with the experimental value of 2.02 mm in the middle layer of the sample, and is a very good approximation. The discrepancy may also be linked to the actual change in the sample geometry while burning part of the material. In addition, the ablation volume is connected with the heating radius of the front surface (the radius of flame is lower than the radius of the sample), which can be observed in Fig. 5.

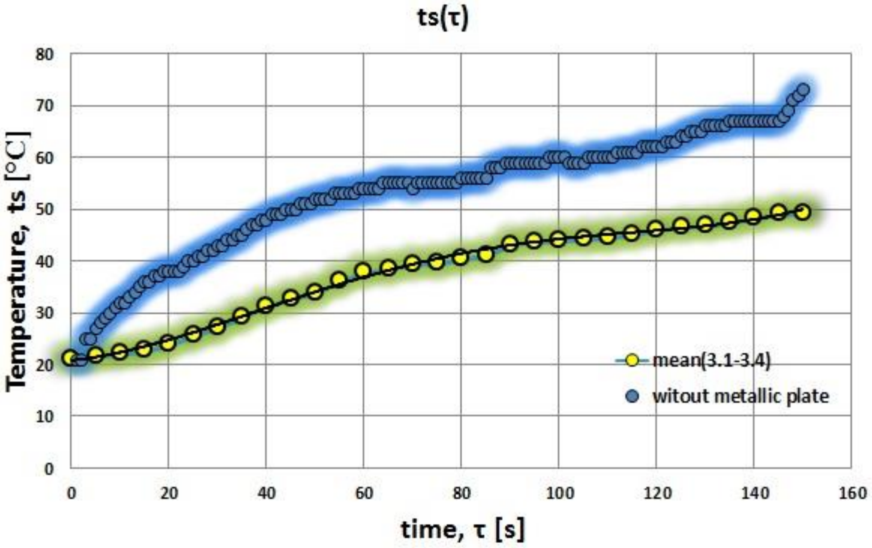

Fig. 6. Numerical and experimental results t_s

The series of tests on the samples with a metallic reinforcement showed a significant temperature reduction on the rear wall t_s as illustrated in fig. 6. The next stage of research is the measurement of temperature increase on the rear surface, in the case of a considerably prolonged flame exposure, as well as the time measurement until the composite material burns out to the metal plate, with a simultaneous measurement of mass reduction of this material by the end of the experiment.

Moreover the presented findings of the simulation examination prove that it is essential to expand the range of the research by temperature measurements of different widths of the examined material, which will considerably allow to observe the thermal field distribution in a material. Thus, it will be easier to introduce more accurate values of thermophysical properties in a wider range of temperatures. In this way, it will be possible to analyse a numerical model, closer to reality, and more precisely determine the ablation surface of the examined materials.

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