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COMPOSITES THEORY AND PRACTICE

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PRELIMINARY ANALYSIS OF THERMAL RESPONSE OF DIELECTRIC AND CONDUCTING COMPOSITE STRUCTURES DURING LIGHTNING STRIKE

The phenomenon of a lightning strike occurring during aircraft operation may seriously affect the integrity of its components due to the electrically insulating properties of polymers and polymeric composites used for manufacturing the fuselage elements of an aircraft. Due to the very high magnitude of temperature fields appearing during lightning strikes, decomposition and vaporization of the matrix and reinforcement materials occur. This results in a pyrolysis reaction and leads to rapid degradation of polymeric composites. One of the ways to limit such degradation is to make the matrix electrically conducting. Such a material is currently being developed by the authors' team. In order to perform preliminary evaluation of the ability of the new material to minimize temperature magnitude and degradation during a lightning strike, a comparative study with a carbon fiber-reinforced polymeric composite, typical for aircraft applications, was performed. The comparative analysis was performed based on the coupled thermal-electrical analytical model of the considered composites subjected to a lightning strike. The obtained results show that the developed material, due to its electrical conductivity, receives much less thermal energy during a lightning strike and thus, minimizes degradation processes.

Keywords: **aircraft structures, lightning strike, conducting polymers, electrical conductivity, heat-induced structural degradation**

WSTĘPNA ANALIZA ODPOWIEDZI CIEPLNEJ DIELEKTRYCZNYCH I PRZEWODZĄCYCH STRUKTUR KOMPOZYTOWYCH PODCZAS UDERZENIA PIORUNA

Zjawisko uderzenia pioruna występujące podczas eksploatacji statków powietrznych może istotnie wpływać na integralność ich elementów ze względu na właściwości elektrycznej izolacji polimerów i kompozytów polimerowych stosowanych przy wytwarzaniu elementów kadłubów samolotów. Ze względu na bardzo wysokie wartości pól temperatury powstających podczas uderzeń piorunów zachodzi dekompozycja i odparowywanie materiałów osnowy i wzmocnienia. Powoduje to reakcję pirolizy i prowadzi do szybkiej degradacji kompozytów polimerowych. Jednym ze sposobów ograniczenia takiej degradacji jest wykorzystanie osnowy polimerowej zdolnej do przewodzenia prądu. Taki materiał jest obecnie opracowywany przez zespół autorów. W celu dokonania wstępnej oceny zdolności nowego materiału do minimalizacji wartości temperatury i degradacji podczas uderzenia pioruna przeprowadzono badania porównawcze z kompozytem polimerowym umacnianym włóknem węglowym, typowym w zastosowaniach lotniczych. Analiza porównawcza została przeprowadzona w oparciu o sprzężony termoelektryczny model analityczny rozpatrywanych kompozytów poddanych uderzeniu pioruna. Uzyskane wyniki wskazują, że opracowywany materiał, ze względu na swoją przewodność elektryczną, otrzymuje znacznie mniej energii cieplnej podczas uderzenia pioruna, a tym samym minimalizuje procesy degradacji.

Słowa kluczowe: **struktury lotnicze, uderzenie pioruna, polimery przewodzące, przewodność elektryczna, degradacja strukturalna indukowana ciepłem**

INTRODUCTION

Since polymeric composites, mainly carbon fiber-reinforced polymers (CFRP), have been widely applied in aircraft engineering, including manufacturing most of the elements of the fuselage, the problem of a lightning strike occurring during aircraft operation has become a serious problem. During a lightning strike, an electrical discharge between a cloud and the earth or between two clouds forms a lightning channel. In this lightning channel the almost insulating air becomes a plasma with a very good conducting ability and the temperature of the plasma in the lightning channel grows rapidly, even up to 25000÷30000°C. Free electrons reach a speed of more than 5000 m/s, to conduct 39550 J/Ω of energy during a 40 kA strike or even more (the discharges during a lightning strike may reach an electric current up to 200 kA), within microseconds [1]. As opposed to metallic elements which are resistant to lightning strikes in general (see e.g. results of the computational study in [2]), such conditions initiate various phenomena on the surface and inside a composite structure. The two most significant phenomena are overpressure and resistive heating. The first can cause breakdown of the external layers of a composite structure and initiate a dense net of cracks and delaminated regions. Resistive heating, which is important especially when considering a polymeric composite structure with a typically very low electrical conductivity, causes pyrolytic processes such as local decomposition and vaporization of the matrix and ablation of the reinforcement, and even decomposition of several types of reinforcement material. Mainly, these two phenomena cause serious structural damage in aircraft composite structures, which need to be repaired and tested again in order to verify their resistance to lightning strikes [3].

Modern lightning strike protection (LSP) solutions are based mainly on immersing metallic nets and foils into aircraft composite structures [4-7], and there is a significant decrease in the area of damage when LSP is present [6, 7]. However, such LSP solutions still do not protect against damage of the external structural elements of aircraft fuselage. A group of novel LSP solutions assumes that the matrix needs to be electrically conducting which allows dispersing the electrical discharge throughout the entire structure and minimizes the resistive heating consequences. Most of these solutions are based on using carbon nanotubes (CNTs) and their derivatives like buckypaper [8, 9]. The authors of [10] also considered coating CNTs with conducting metals. Nevertheless, such solutions are still too expensive to apply in the aircraft industry on a large scale.

An alternative LSP approach is being currently developed by the authors' team and is based on mixing an electrically conducting polymer with a typical dielectric polymer used in manufacturing aircraft elements (e.g. epoxy resin) in such proportions that the resulting polymer is electrically conductive on the macroscale, and can be used as the matrix of a composite. Such an approach may significantly decrease the complexity of the manufacturing process of aircraft elements due to the lack of necessity of immersing a metallic mesh into the composite structure. The development of this |approach started from numerical simulations based on the percolation theory which gave theoretical values of volumetric content of both polymers [11]. Afterwards, coupled structural-electrical models were developed [12] in order to simulate the electrical and mechanical properties of the resulting polymer with various contents of conducting polymer and validate the theoretical results. Finally, the conducting polymer planned to be used in the resulting polymer was successfully synthesized and the electrical conductivity was determined experimentally [13].

The lightning strike phenomenon, due to its complex physical nature and importance for aircraft design and operation, is the focus of many research teams. In order to predict the structural behavior of aircraft composite elements, several computational studies have been performed to date. One of the fundamental studies is the paper by Ogasawara et al. [14], who formulated the basic theoretical assumptions on coupled thermal-electrical analysis and performed numerical simulations of temperature distributions and pyrolytic damage of CFRP structures during a lightning strike with experimental verification. Furthermore, the analytical and numerical coupled thermal-electrical-structural models of composites subjected to a lightning strike current have been developed by numerous researchers. The results of numerical studies of electrical field distribution and its dynamics were reported in [15]. Another report on the theoretical and experimental studies on the damage of composite structures subjected to a lightning strike, with special attention to a phenomenological description of the mechanochemical phenomena occurring during a lightning strike and interaction with metallic bolts was presented in [16]. Ranjith et al. [17] presented the results on a numerical finite element (FE) simulation of a composite structure struck by lightning within the operational aspects of aircraft like lightning zoning or lightning certification. Similar studies were performed by the authors of [18], who additionally verified their numerical results experimentally. The authors of [1, 19] considered the temperature dependence of the thermomechanical constants in the non-steady state heat transfer equation and further FE simulation. Special attention needs to be paid to the coupled thermal-electrical-structural analytical models developed by Zhupanska and her team. The authors of [20] formulated governing equations for electromagnetic, thermal and mechanical fields interaction considering the mechanical, thermal and electrical anisotropy of CFRP. Another extended study on analytical and numerical modelling was presented in [21-23], where the authors intensely studied the coupled thermo-electro-mechanical problem of electric arc interaction with the struck structure including supporting physical and chemical processes, the influence of external forces and simulations of the degradation of an aircraft composite structure.

The aim of this paper is the preliminary evaluation of the thermal response of the developed conducting composite and its comparison with the thermal response of CFRP based on an analytical model and numerical calculations based on this model. Since the thermal response of a structure is the most significant factor affecting the damage of a composite structure [14, 16], this study was limited to the thermal response evaluation only. The resulting heat flux and temperature distribution will be the first evaluation of the effectiveness of applying the developed material before experimental studies with a simulated lightning strike planned in the near future.

COUPLED THERMAL-ELECTRICAL MODEL

The thermal response of a composite panel subjected to a lightning strike can be described by the non-steady state heat transfer equation:

$$\rho C_p \frac{\partial T(\mathbf{X},t)}{\partial t} = \nabla \cdot (k \nabla T(\mathbf{X},t)) + Q(t) \tag{1}$$

where ρ is the density of the composite, C_p is the specific heat, $T(\mathbf{X},t)$ is the spatially- and time-dependent temperature ($\mathbf{X}$ stands for the coordinates vector and t for time), k is the thermal conductivity, and $Q(t)$ is the thermal energy absorbed by the composite during a lightning strike, which is equivalent to the Joule heating flux $Q_J(t)$ appearing due to the electric resistivity of the structure. The Joule heating flux, under the assumption of the constant current value, can be expressed by Joule's law in the form of:

$$Q_J(t) = \frac{(J(t))^2}{\sigma} \tag{2}$$

where $J(t)$ is the electric current density, and σ is the electrical conductivity of the structure. The other parts of $Q(t)$ which appear during a lightning strike (e.g. mechanical energy dissipation resulting from the action of magnetic and overpressure forces) are negligible with respect to Q_J, and are not considered in further investigations.

Due to the fact that the struck surface of a composite is subjected to various thermo-chemical interactions during a lightning strike, one needs to formulate the boundary conditions on the surface in the form of (cf. [24, 25]):

$$-k \left. \frac{\partial T}{\partial z} \right|_{z=0} = Q_R + Q_V + Q_C \tag{3}$$

where Q_R is the radiative flux density, Q_V is the thermal flux due to the vaporization of the material, and Q_C is the conducting thermal flux. As reported by the authors of [21, 23], Q_R and Q_V are negligible. The character of Q_C depends on the polarity of the material, and in several studies [1, 16] it is assumed as an anodic flux Q_A. Following the authors of [26], the anodic flux that flows from the arc plasma to a composite surface can be described as:

$$Q_A(t) = J(t) \cdot \left(U_a + \Phi_{mat} + \frac{5k_B}{2e}(T_p - T_{mat}) \right) \tag{4}$$

where $J(t)$ is the electric current density, U_a is the voltage drop near the surface of the composite, Φ_{mat} is the material work function by J, k_B is the Boltzmann constant, e is the electron electrical charge, and T_p and T_{mat} are the temperature values of the plasma and material, respectively. However, according to [16, 25], U_a and Φ_{mat} do not exceed 5 V, therefore one can simplify (4) to the form of:

$$Q_A(t) \approx 10J(t) = 10\frac{I(t)}{\pi(R(t))^2} \tag{5}$$

where $I(t)$ is the current, and R(t) is the radius of the electrical plasma channel. Following MIL and SAE standards [27, 28], the current of a lightning strike of component A (see Fig. 1) can be modelled as a double exponential function in the form of:

$$I(t) = I_{peak}(\exp(-\alpha t) - \exp(-\beta t)) \tag{6}$$

where I_{peak} is the peak current of the lightning strike, and α and β are exponential model factors. Component A of a lightning strike is considered due to its highest current value. Assuming one of the standard pulsed lightning current waveforms specified by IEC standard [29], equation (4) takes the form of:

$$I(t) = I_{peak}\left(\exp\left(-7.3 \cdot 10^4 t\right) - \exp\left(-6.3 \cdot 10^5 t\right)\right) \tag{7}$$

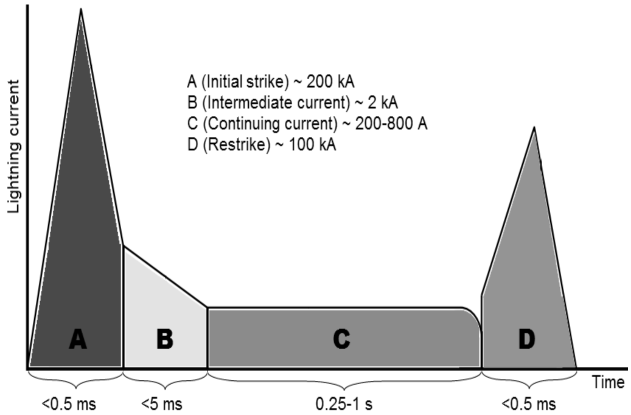

Fig. 1. Lightning current evolution according to MIL-STD-464 and ARP 5412 standards

Rys. 1. Zmienność prądu piorunowego według norm MIL-STD-464 i ARP 5412

The radius of an electrical plasma channel can be described by the dependence proposed by Baginskii [30]:

$$R(t) = \gamma \rho_0^{-1/6} (I(t))^{1/3} t^{1/2} \tag{8}$$

where γ is a constant, γ = 0.294 (this value was validated experimentally by Ploster [31]); ρ_0 is the air density at atmospheric pressure, ρ_0 = 1.2922 kg/m^3.

The distribution of $Q_A(t)$ is of Gaussian nature which was conducted in experimental studies [32, 33]. Following this, the heat flux distribution function can be presented according to [25] as:

$$Q(r,t) = \left(\frac{10I(t)}{\pi(R(t))^2} \right) \exp\left(\frac{\ln(0.1) r^2}{(R(t))^2} \right) \quad r \le R(t) \tag{9}$$

The variation of the radius of a plasma channel in time according to (8), and several examples of heat flux distribution at various times according to (9) are presented in Figures 2 and 3, respectively.

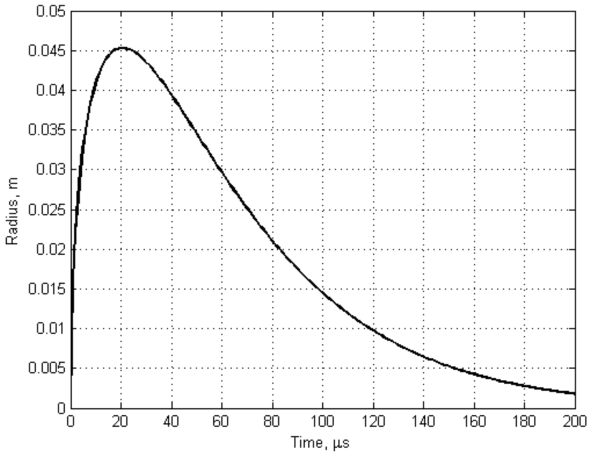

Fig. 2. Variation of radius of plasma channel with respect to time

Rys. 2. Zmienność promienia kanału plazmowego w zależności od czasu

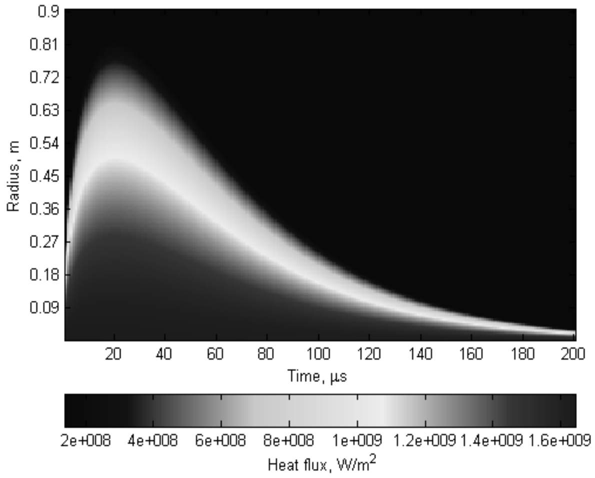

Fig. 3. Heat flux distribution over radius of plasma channel with respect to time

Rys. 3. Rozkład strumienia ciepła względem promienia kanału plazmowego w zależności od czasu

DESCRIPTION OF CONSIDERED MATERIALS

Based on the results of numerical and experimental studies on a simulated lightning struck composite structure [1, 14], the considered problem can be limited to the planar problem of heat flux and temperature distribution ($\mathbf{X}$ = {x,y} in (1)). A comparative study was performed for CFRP (epoxy was considered as the matrix in typical aircraft composite structures) and the developed mixture of conducting/dielectric polymers with carbon reinforcement. As the conducting polymer, polyaniline (PANI) was selected, and as the dielectric - epoxy, with their contents assumed based on the computational study presented in [11]. The matrix of the resulting material consists of two polymeric solutions, however, at the macroscopic level one can assume without loss of accuracy that the resulting polymer (PANI-epoxy) is mechanically, thermally and electrically homogeneous. The properties of CFRP and CF-PANI-epoxy were calculated using the rule of mixtures, similarly as in [20]:

$$P = F_1 P_f + (1 - F_1) F_2 P_{md} + (1 - F_1)(1 - F_2) P_{mc} \qquad (10)$$

where P is the homogenized parameter, the lower indexes for P denote f - fiber, md - matrix (dielectric polymer), and mc - matrix (conducting polymer); F_1 and F_2 denote the volume fractions of the fiber and dielectric polymer, respectively. Note that for CFRP F_2 = 1. Assuming a 60% fiber volume content in the composites and a 35.74% content of PANI (in order to achieve fully electrically conducting CF-PANI-epoxy) [11], the thermophysical properties for this study were calculated and presented in Table 1. The electrical conductivity for CFRP equals 7.78 S/m [17], since there are no fibers on the surface where the lightning strikes, and for CF-PANI-epoxy as for PANI (4340 S/m) [13] due to the electrical percolation properties of the resulting mixture of conducting/dielectric polymers (see [11] for details).

TABLE 1. **Thermophysical properties of considered materials**

TABELA 1. **Właściwości termofizyczne rozpatrywanych materiałów**

	Carbon fiber	Epoxy	PANI	CFRP	CF-PANI-epoxy
Specific heat [J/kg °C]	920 [20]	1110 [34]	470* [36]	996	904.5
Thermal conductivity [W/m °C]	18 [20]	0.363 [35]	0.09* [36]	10.945	10.906
Density [kg/m^3]	1790 [20]	1100 [35]	1150* [36]	1514	1521.1

* For PANI doped with camphor sulphonic acid (CSA) as the polymer synthesized in experimental studies [13]

RESULTS AND COMPARATIVE STUDIES

The heat transfer problem presented in the previous section was solved numerically using the Finite Element Method (FEM). The problem was defined as 2D non-steady heat transfer in a square plate of a side length of 0.5 m, and implemented in the Matlab® environment. The model was meshed using ca. 10000 triangular elements. Dirichlet boundary conditions were applied on the edges of the plate at the temperature of 0°C. According to (8), the radius of the plasma channel was determined for discrete time values. In the geometrical center of the plate, the area inscribed by this radius determined the boundary of the plasma channel. The Neumann boundary condition (3) was applied on this boundary. Additionally, in order to simulate Joule heating, the source function (2) was simulated on the area of the plasma channel. Component A of a lightning strike was modelled (see Fig. 1 and (7)), due to its highest current value and recommendations of MIL and SAE standards [27, 28]. Two materials were considered: typical CFRP and CF-PANI-epoxy with calculated thermophysical properties (see Table 1). From the calculations, the maximal value of $Q_J(t)$ for CFRP was $2.4569 \cdot 10^7$ W/m^2, while for CF-PANI-epoxy it was $4.4044 \cdot 10^4$ W/m^2, which resulted from the much higher electrical conductivity of the latter. The initial temperature was assumed as 0°C. The resulting temperature distributions for both considered cases at the time of 20 μs after the lightning strike (peak current - see Figs. 2 and 3) are presented in Figure 4. In this figure the colors denote the temperature values, and the arrows - the temperature gradients.

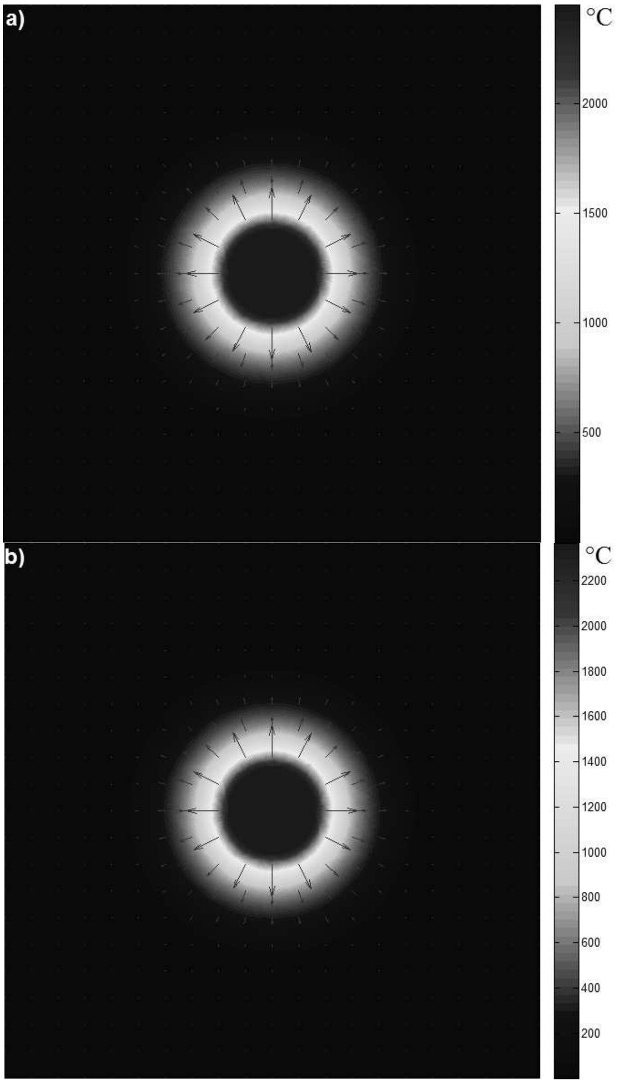

Fig. 4. Temperature distributions at time of 20 μs after lightning strike for: a) CFRP, b) CF-PANI-epoxy plate

Rys. 4. Rozkłady temperatury w czasie 20 μs po uderzeniu pioruna dla płyty z: a) CFRP, b) CF-PANI-epoxy

One can observe differences both in the temperature and its distributions. The maximal temperature in the considered cases equals 2518.1 and 2431.9°C for CFRP and CF-PANI-epoxy, respectively. The temperature distribution corresponds to irreversible changes in the polymeric structure and its evaporation during a lightning strike. One can define two thresholds that describe the material damage during a lightning strike. The first threshold can be assumed as the temperature at which an ultimate drop of mass occurs. According to the result of the thermogravimetric analysis [14] the decomposition temperature of the epoxy in CFRP equals 500°C, while for PANI this temperature equals 600°C [37]. The second threshold for both materials can be assumed based on the temperature of sublimation reaction of 1100°C [25]. The radii related to these thresholds were determined for the first 50 μs (see Fig. 5).

It can be observed that the resulting radii of polymer decomposition and further sublimation are slightly lower for the conducting material. The small difference results from the conducting properties of the carbon reinforcement considered in the model, thus the conducting polymer only slightly increases the electrical conductivity and decreases the temperature around the plasma channel. Based on the results presented in Figure 5, one can determine the areas of sublimated material and those of decomposed material. These areas for CF-PANI-epoxy are lower by 5.2 and 15.8%, respectively, than for CFRP.

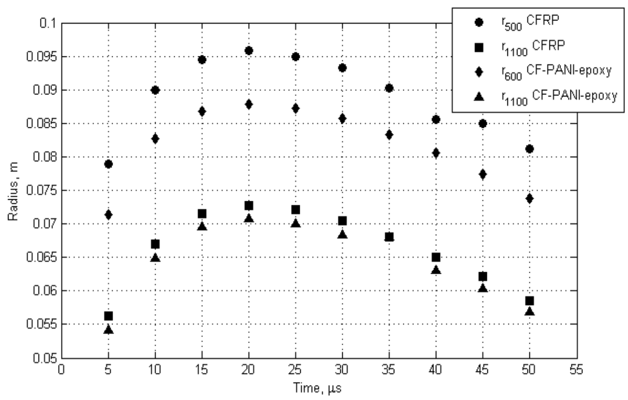

Fig. 5. Radii of temperature contours on distributions corresponding to decomposition and sublimation reaction temperatures

Rys. 5. Promienie konturów temperaturowych na rozkładach odpowiadające temperaturom dekompozycji i reakcji sublimacji

DISCUSSION AND CONCLUSIONS

The numerical study on thermal response during a lightning strike of a typical CFRP structure and a structure with an electrically conducting filler was performed, and the resulting temperature distributions with their evolution was analyzed. The heat transfer problem was modelled by a 2D non-steady parabolic partial differential equation with a source function that represented Joule heating during a lightning strike and Neumann boundary conditions applied on the radius of the plasma channel variable in time in the form of a heat flux resulting from electrical conductance. For simulation purposes, the thermophysical properties of both considered materials were determined according to the rule of mixtures of three components - reinforcement, dielectric polymer and conducting polymer (this expression was reduced for CFRP to two components). The lightning strike was modelled according to the appropriate standards, and component A with the highest current value was considered since during a lightning strike within this period the resulting heating of a structure is also the highest.

The comparative study of the thermal response of both structures shows that the difference in the conducting thermal flux is significant, however, it has no dominating influence on the resulting temperature distributions, the difference in temperature for the peak current equaled 3.2%. Nonetheless, taking into account the calculated area of decomposed material after the lightning strike, the material with the electrically conducting filler reveals a smaller damaged area by 15.8%. From the performed studies one can conclude that the major influence on reducing the damaged area after a lightning strike is not only the electrical conductivity, but also thermal conductivity of the material and its highest possible temperature of decomposition. The simplified model was used in this study to evaluate the level of differences between the developed and typical aircraft materials in their ability of thermal absorbance, nevertheless, a more accurate model is planned to be developed by taking into consideration the properties of the mentioned materials obtained experimentally. Moreover, experimental verification of the electrical and thermal conductivity of the developed material (simulation of a lightning strike in laboratory conditions) is planned in the near future.

The developed conducting composite could be an advantageous alternative to the currently applied composite structures for aircraft fuselage, without an increase in manufacturing costs.

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