Evaluation the complex of thermal properties for epoxy-based GFRP used in wing of tourist class reusable space vehicle

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Abstract. In general, the prediction the effective properties of fiber reinforced composites is a complicated task due to its heterogeneous properties. Therefore, new approaches can make possible obtaining of the reliable thermal properties of composites with least time and financial costs. This work presents the approach for determination of thermal properties of epoxy-based glass fiber reinforced composites. Firstly, to evaluate the thermal behavior of considered material the numerical modeling was conducted via finite element analysis in commercial software MSC Digimat. To validate the model, two-stage experimental study was carried out. As the result of the experimental research thermal conductivity through-plane was obtained by laser flash method as well as thermal conductivity in-plane – by specialized heat equipment developed in Bauman University with subsequent solution of the inverse heat conduction problem. Summing up, the analytical and experimental data showed good agreement that demonstrates the feasibility of the approach.

1. Introduction

Over the past decades the interest to the business-driven space transportation systems has considerably increased. Human spaceflight and space exploration have become a domain of not only government, but also private companies, entrepreneurs and research groups [1]. The prominent branch of space industry that have advantageous potential is space tourism [2]. The space tourism is expected to progress and to become the catalyst for less expensive, more frequent access to space [3] and point-to-point suborbital space travel routes [4]. Nowadays more than 40 private companies and research groups all over the world have been engaged with the development of transportation systems into space – tourist class reusable space vehicle. Today, the most known space tourism vehicles are SpaceShipTwo (Virgin Galactic, USA), New Shepard (Blue Origin, USA), Dragon (SpaceX, USA), Spica (Copenhagen Suborbitals, Denmark), IAR 111 (ARCA Space Corporation, Romania) and others. In Russia, several projects are also under development – suborbital reusable complex (KosmoKurs), Oduvanchik (BMSTU), Fanstream (MAI), and others [4-6]. There are a few types of space routes: orbital, suborbital that proposes reach the Karman line and then falling back to Earth, and the spaceflight to celestial bodies (Moon, Mars, etc.). Suborbital spaceflight is more attractive for business caused by comparatively less tour cost, passenger health requirements, significantly lower level of thermal and force loads results from the atmospheric re-entry, etc. [7-9].

In Bauman University [7, 8, 10] during some years the winged spacecraft Oduvanchik is being developed. The general scheme of RSV design is presented in Figure 1 [10, 11].
Figure 1. Suborbital tourist class reusable space vehicle, Bauman University, 2008

Weight and cost efficiency are the key issues in spacecraft design. Hybrid polymer matrix composites (herein after hybrid composites) that contains in microstructure two or more types of reinforcing components have proved their effectiveness for structural application in industrial fields, aerospace as well, for decades. Combination of expensive carbon fibers that demonstrate high strength-to-weight performance with less expensive but lower in terms of mechanical and thermal properties glass fibers would provide appropriate design solution from technical and economical positions [12]. By changing the types of reinforcing fibers, their ratios, orientation angles, it is possible to vary properties over a wide range, as well as to create materials with the required anisotropy of properties and adjust the required characteristics of such compositions [13, 14].

In this study particular attention is focused on the essential structural element of the suborbital spacecraft that significantly determines its design appearance and weight efficiency – the wing. For wing design the reliable information on the materials properties used in its structure is required. However, in the reference literature such information is practically absent due to the specialness of the composites [15]. Therefore, to conduct an in-depth analysis of the structure, it is necessary to create an approach for obtaining the materials properties for the principal structural element of the wing, notably with the least time and financial costs [16-18].

According to flight profile [19] the spacecraft operates in a wide range of velocities (its maximum speed is 3.6 M at an altitude of about 40 km) and is exposed to intensive aerodynamic heating [20, 21]. Therefore, the spacecraft design requires data on the thermal properties of hybrid composites applied in structure (thermal conductivity coefficients in different directions, heat capacity and density) in dependence on temperature. If the last two properties can be determined with a sufficient accuracy level using the mixture rule [22], then it is proposed to use the numerical analysis to find the thermal conductivity coefficients followed by validation of its results based on the experimental data. The properties of the used materials are mostly defined by experimental testing, numerical simulation can help to eliminate the excessive number of trials and thus to reduce time, labor and financial costs [9, 10, 12, 23].

For technological and economic reasons, in the wing made of hybrid composites, glass fibre fabric with harness-satin weave and FibArm Tape 230 unidirectional carbon fibre tape with AKSA / Carbon fiber A-49 24K4 fiber, as well as an epoxy resin Noapox 7510 are used.

Consequently, current work aims to develop an approach for obtaining of thermal properties of epoxy-based glass fibre fabric (herein after GFRP) for the spacecraft wing [9] by numerical simulation validated by experimental data. GFRP was chosen to test the developing approach as this material is well-studied and can be additionally validated by known data.
2. Numerical modeling of GFRP thermal properties in MSC Digimat for the wing skin

Traditionally the process of obtaining of composite materials properties with a complex microstructure has been carried out by only experimental methods that is an expensive and time consuming process. Nowadays, the situation has being changed and there are a number of software for determination of the thermal behavior of materials via multi-scale modeling tools [24]. Through this tools realized in such software one can find the effective properties of considered materials with complex woven microstructure, inclusions, coatings, defects, etc., and use it as an input to in-depth analysis of structures. In this case the composite constituent material is considered based on homogenization procedure ignoring of internal boundaries and generation of representative volume element (RVE) model of a composite. The behavior of RVE can be considered as the basis for macro-level analysis by taking the effective properties obtained using homogenization process [25, 26].

![Figure 2. Geometric model of RVE of GFRP generated using Digimat-FE (matrix is hidden for clarity)](image)

In this research a special attention was paid to commercial software MSC Digimat. The approach of obtaining GFRP properties includes the generation of a RVE, the application of a heat load to its faces, and the subsequent calculation the values of the thermal conductivity coefficients via finite element analysis. The geometric model RVE of GFRP is depicted in Figure 2. Herewith the glass fiber and epoxy matrix were assumed as isotropic, and perfect thermal contact on their coupled boundaries was performed. The porosity factor was equal to 0. Due to these assumptions in the result of numerical modeling the upper estimate of thermal conductivity was obtained.

The initial data for modeling the thermal properties were the coefficients of thermal conductivity, density and heat capacity of individual components [8, 11]. It was believed that monofilaments have the shape of an infinitely elongated cylinder, and their volume content in the matrix is 50%. The results of modeling the coefficients of thermal conductivity in different directions of GFRP are given in Table 1.

| Property                                      | Value  |
|----------------------------------------------|--------|
| Thermal conductivity in-plane (x direction), W/(m·K) | 0.554  |
| Thermal conductivity in-plane (y direction), W/(m·K) | 0.547  |
| Thermal conductivity through plane, W/(m·K)     | 0.513  |

It is shown that the thermal conductivity of GFRP, especially in-plane, weakly depends on the direction. The results show a mismatch value of no more than 0.5%.

3. Experimental study for determination GFRP thermal properties for the wing skin

![Figure 3. GFRP samples for experimental](image)
To confirm the reliability of the numerical modeling results, its validation by comparison with the data obtained by experimental studies was conducted. For this purpose, two types of samples were produced (Figure 3). The first sample type was cylindrical with a diameter of $\varnothing 12.5$ mm and a thickness of 2 mm and used for investigation of thermal conductivity through plane ($\lambda_\perp$). The second type was produced in a form of plate and was applied to get data about thermal conductivity in-plane ($\lambda_{II}$).

### 3.1 Experimental measurement of the $\lambda_\perp$ via Laser Flash method

An array of methods has been developed for determination of $\lambda_\perp$ [27]. Among the most advanced and reliable is the laser flash method, which is implemented in the Laser Flash Apparatus (NETZSCH, Germany) [28] (Figure 4). In current study this apparatus was used to measure $\lambda_\perp$.

![Laser Flash Apparatus LFA 457 MicroFlash](image)

**Figure 4.** (a) Laser Flash Apparatus LFA 457 MicroFlash (NETZSCH, Germany); (b) measuring methodology for determination $\lambda_\perp$ [28]

As the result of measurement the temperature dependence $\lambda_\perp$ of the GFRP in the range from 25°C to 150°C (Figure 5) was revealed that showed satisfactory compliance with the modeling data.

![Temperature dependence of $\lambda_\perp$](image)

**Figure 5.** Temperature dependence of $\lambda_\perp$ (the red point related to $\lambda_\perp$ calculated in MSC Digimat)

### 3.2 Experimental measurement of the $\lambda_{II}$

The obtaining of $\lambda_{II}$ is a complicated scientific and technical task. Nowadays, there are no standard methods for determination of $\lambda_{II}$ [27, 29]. However, for this purpose in the Bauman University developed a
specialized experimental heating equipment [30]. The equipment (Figure 6) includes two heaters (2) that are covered with thermal insulation (5) and are fixed between copper plates for temperature equalization across the width of the sample (3). The sample is made in the form of a plate with dimensions 25x150 mm and thickness of 2 mm (3). To measure the temperature on the sample surface at test points, a Fluke Ti-400 infrared camera was used [31]. It was assumed that GFRP is quasi-isotropic and the experiment was aimed only on one parameter estimation.

![Figure 6](image_url)

**Figure 6.** Equipment for $\lambda_{II}$ measurement: 1 – steel console; 2 – heaters with copper plates; 3 – sample; 4 – aluminum plates; 5 – heat insulation

The measured by infrared camera time dependences of surface temperature of the GFRP sample center and at a distance of 5, 10 and 15 mm (Figure 6b) from the center were used as source data to solve the inverse heat conduction problem and determine $\lambda_{II}$ (Figure 6a). For this purpose, a three-dimensional geometric model of the heating equipment was developed for subsequent simulation of the transient process of radiation-conductive heat transfer. The heaters temperature was set constant in its volume and in accordance with experimentally determined dependencies. It was assumed that free convection on the sample surface as well as release of radiation energy from the surface sample were occurred. Parameter estimation problem was assumed the determination of $\lambda_{II}$ that provides a minimum of the residual functional of the experimental and calculated temperatures at the test points was considered. Based on the inverse problem solution only temperature dependence of $\lambda_{II}$ has been found, the other thermal properties were determined by the rule of the mixture as well as $\lambda_{\perp}$ were appropriated from an experimental study via the laser flash method described in paragraph 3.1.

![Graph](image_url)

(a)
Figure 7. (a) experimental temperature dependencies for GFRP sample; (b) images made by infrared camera (1 – temperature in the sample center; 2, 3, 4 – at a distance of 5, 10 and 15 mm from the center respectively)

As the result of the inverse problem solution, $\lambda_{II}$ was obtained for GFRP sample. Results analysis showed a good agreement between the experimental data and numerical modeling obtained in MSC Digimat (Table 2).

Table 2. Results comparison of the numerical modeling of GFRP mechanical properties and experimental data on $\lambda_{II}$ measurement

| Property | Value 
|----------|----------|
| $\lambda_{II}$ results of numerical modeling in MSC Digimat, W/(m·K): | 0.51 |
| $\lambda_{II}$ obtained through solution of inverse heat conduction problem, W/(m·K) | 0.49 |

4. Conclusion
Summing up, the comprehensive approach for determination of thermal properties of GFRP used in the hybrid composite wing skin of the tourist class reusable space vehicle was developed. The numerical modeling of epoxy-based GFRP thermal properties demonstrated good agreement with the experimental results. Also, manufactured two types of experimental samples of GFRP allowed to obtain the temperature dependence of $\lambda_{II}$ via laser flash method and $\lambda_{II}$ using heating equipment developed in Bauman University and subsequent inverse problem solution. In both experiments on thermal conductivity determination the difference between the experimental and analytical calculations was less than 4% that validates the numerical modeling results.

In future this approach can be applied for determination thermal properties of other materials that used in the wing skin of the tourist class reusable space vehicle.

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