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AN EXPERIMENTAL-COMPUTATIONAL SYSTEM FOR MATERIALS THERMAL PROPERTIES DETERMINATION AND ITS APPLICATION FOR SPACECRAFT STRUCTURES TESTING

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ABSTRACT

An experimental-computational system is presented for investigating the thermal properties of composite materials by methods of inverse heat transfer problems and which is developed at the Thermal Laboratory of Department Space Systems Engineering, of Moscow Aviation Institute (MAI). The system is aimed at investigating the materials in conditions of unsteady contact and/or radiation heating over a wide range of temperature changes and heating rates in a vacuum, air and inert gas medium. The paper considers the hardware components of the system, including the experiment facility and the automated system of control, measurement, data acquisition and processing, as well as the aspects of methodical support of thermal tests. In the next part the conception and realization of a computer code for experimental data processing to estimate the thermal and radiative properties of thermal-insulating materials are given. The most promising direction in further development of methods for non-destructive composite materials using the procedure of solving inverse problems is the simultaneous determination of a combination of their thermal and radiation properties. The general method of iterative regularization is concerned with application to the estimation of materials properties (as example: thermal conductivity $\lambda(T)$ and heat capacity $C(T)$. Such problems are of great practical importance in the study of material properties used as non-destructive surface shield in objects of space engineering, power engineering, etc. In the third part the results of practical implementation of hardware and software presented in previous two parts are given for the estimating of thermal properties of thermal-insulating materials. The main purpose of this study is: to confirm operability and effectiveness of the

1. INTRODUCTION

In space engineering we deal with structures operating in the conditions of intensive, often extreme thermal effects. The general tendency in the development of technology is connected with the increase of the number of responsible, thermally loaded engineering objects, with the toughening of conditions of their thermal loading by a simultaneous increase of reliability and safe life and a reduction of specific consumption of materials. For space vehicles and reusable transportation systems the support of thermal conditions is one of the most important aspects of design, determining the main design solutions. The distinctive features of modern heat-loaded structures in space engineering are non-stationarity, non-linearity, multidimensionality and conjugate nature of heat-and-mass transfer processes. These distinctions confine a possibility of using many traditional design-and-theory and experiment methods. So, in developing space and aerospace vehicles of different mission and type, traditionally there were both the development of new approaches and the improvement of available research techniques. Similar problems exist in other branches of industry. The main stream of new system development is the implementation of advanced thermal protective and insulating materials. The development of such materials and solving above mentioned problems of thermal design of systems assume broad application of mathematical and physical simulation methods. But mathematical simulation is impossible if there is no true information available on the characteristics (properties) of objects analyzed. In the majority of cases in practice the direct measurement of materials' thermophysical properties, especially of complex composition, is impossible. There is only one way which permits to overcome these complexities - the indirect measurement. Mathematically, such an approach is usually formulated as a solution of the Inverse Heat Transfer Problems (IHTP): through direct measurements of system's state (temperature, component concentration, etc.) define the properties of a system analyzed, for example, the materials' thermophysical characteristics.

Methods of IHTP were developed to increase the informativity of thermal experiments and tests, to improve the accuracy and reliability of experimental data processing and interpretation, and also to estimate the unknown parameters of the thermal systems [1]. In the majority of cases this methodology is used as optimal, but in a number of practical situations it is the sole technique available, as, for example, in measuring the transient heat fluxes and determining thermal properties of materials with a memory of heating/cooling conditions. Violation of cause-and-effect relations in the statement of these problems results in their correctness in mathematical sense (i.e., the absence of existence and/or uniqueness and/or stability of the solution). Hence to solve such problems we develop special methods usually called regularized. This methodology is based on the mathematical theory of ill-posed problems of mathematical physics. So, a successful implementation of IHTP methodology is possible only by a rational combination of physical simulation of heat transfer processes in the specimen, exact measurements of initial thermal parameters and correct mathematical processing of experimental data based on the solution of the IHTP.

The approaches to identification of materials' properties based on methods of ill-posed problem solving were widely analyzed in Russia and in other countries having displayed efficiency in the development and investigation of modern materials in rocket-space, aircraft and automotive industries, metallurgy, power engineering etc. A new system being developed for thermophysical metrology is a combinations of sufficiently accurate measurements of primary heat values in testing conditions to the maximum approximate to full-scale conditions and ultimately correct mathematical treatment of experimental data based on the theory of inverse problems.

In development new thermal protection materials a large number of comparative thermal tests is carried out, the purpose of which is determining the thermal-protective properties of materials in different heating conditions corresponding as much as possible to real operation conditions. The experimental specimens for such tests are manufactured in the form of a flat plate. Owing to the structural version and uniform surface heating in specimens a one-dimensional heat transfer process is realized. As effective way to solving the given problem is to develop a problem-oriented scientific research system interconnecting the specially developed experimental equipment, computer-aided data processing and control system and the methodical support of the experiment based on IHTP. The experimental-computational system described in the present paper is the result of further development of investigations carried out in MAI and connected with the elaboration of the computer-aided research system of the thermal processes based on IHTP methodology [3,4]. The system is designed for laboratory and semi full-scale thermal testing in order to determine and investigate thermophysical, radiation-optical and physical-chemical properties of composite materials and members of structures designed on their basis. Testing can be performed in conditions of unsteady contact and/or radiation heating at a rate up to100°C/s in the range of temperatures from a room temperature to 1600 °C in air or in the inert gas medium at pressure up to 1.6 bar or in a vacuum as low as 2.5×10^{-8} bar. In addition, the system permits the following investigations to be conducted: selection testing for perspective thermal materials (flexible and multilayer, inclusive); design and development of new experimental-computational methods for identification of unsteady heat transfer processes in materials and structures; design and development of highly accurate thermal sensors and instrumentation.

2. THE EXPERIMENTAL-COMPUTATIONAL SYSTEM

The hardware equipment system includes: a high-temperature thermovacuum stand TVS-1M; special experimental modules (EM) for realization of heat transfer models in the testing of specimens; an automated system (AS) of heating control, experimental information measurement, collection and processing based on PC and PXI module system; hardware of local network providing interconnection of the system with distant workbenches of researchers; as well as special technological equipment for the preparation of experimental specimens, the manufacture of the thermosensors and their installation in composite materials.

Methodical support of experimental investigations include: the methods for preparation and conduction of thermal testing and experiment design [2]; an applied software for processing and interpretating experimental data based on the IHTP solution [1,5]; a special software of the information-measurement subsystem (IMS) based on integrated software LabVIEW.. The experimental system has been developed based on a high-temperature thermovacuum stand TVS-1M. This stand is an essentially modernized version of thermovacuum stand TVS-1. The general view of TVS-1M stand is shown in Fig.1. The stand includes a horizontal water-cooled vacuum chamber and the following systems: vacuuming, water cooling, electric power, control and monitoring. Fig. 2 illustrates a photo of the vacuum chamber with the installed experimental module. The control of heating is performed by AS using a specified program. As a feedback during the procedure there is an indication of the thermocouple mounted on the heating element or on the specimen's heated up face. The control devices and instrumentations of the stand are arranged in the monitoring and control rack.

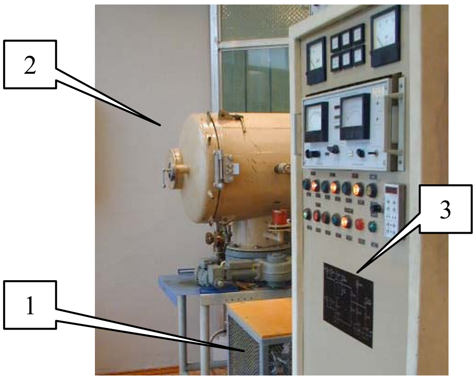


Fig. 1: General view of TVS-1M stand: 1 – power transformer; 2 – vacuum chamber; 3 – monitoring and control rack.

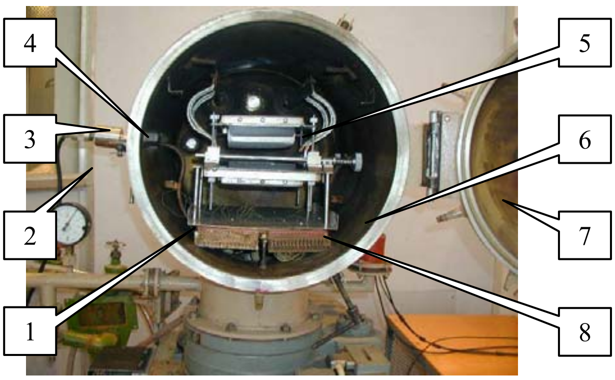


Fig. 2: Vacuum chamber of TVS-1M stand: 1 – vacuum chamber; 2 – communication cable with AS; 3 – connector; 4 – seal lead; 5 –experimental module; 6 – chamber's workbench; 7 – cover of vacuum chamber; 8– contact plate.

3. DEVELOPMENT AND MANUFACTURE OF SPECIMENS

The experimental specimen is a plate from the material under study in the form of a rectangular parallelepiped with the big edge thickness-to-length ratio not less than 1:5. Such a ratio of the specimen's dimensions, as well as the using of a symmetrical heating scheme of two identical specimens and the corresponding test procedure [2] provide in the course of testing a formation in the specimen a temperature distribution close to one-dimensional. Initially a uniform temperature distribution is realized in the specimen.

The type of boundary conditions and the number of temperature measurement points should satisfy the conditions of uniqueness of the inverse problem solution [3]. The conditions of uniqueness usually determine a minimum required number of measurements to be made in one experiment. For simultaneous determination of temperature dependences of thermal conductivity and volumetric heat capacity it is necessary firstly to measure a heat flux passing through the specimen which differs from zero at least at one its boundary and secondary to measure temperature not less than in two additional points (internal or on the surface with boundary conditions of second kind). Selection of a temperature-measuring scheme (location of thermocouples in specimen) is conditioned by the material features. Tested lightweight heat-insulating material is high-porous, brittle enough and electroconductive. This considerably complicates the internal installation of thermocouples in the specimen. With regard to these features of the material under study it is of little sense to install thermocouples inside the specimen.

Should one of the temperature measurements at the heating or back surface of the specimen be used as a boundary condition, the uniqueness of IHTP solution will be violated. It follows that it is of sense to provide experimental determination of the heat flux on the back face and use it as a boundary condition, together with temperature measurements on both surfaces of the plate as complementary information for solving the inverse problem. For the described scheme of experimentation and measurements, the data obtained in one test will be sufficient to determine two properties: coefficient of thermal conductivity $\lambda(T)$ and volumetric heat capacity $C(T)$. Finally, a scheme of temperature measurements has been chosen with thermosensors installed only on the heating and back surfaces of the specimen.

Based on the given physical model, a mathematical model of heat transfer process in the material's specimen (infinite plate of known thickness) can be presented as follows [4]:

$$C(T)\frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x}\left(\lambda(T)\frac{\partial T}{\partial x}\right), \quad x \in (X_0, X_1), \quad \tau \in (\tau_{\min}, \tau_{\max}] \tag{1}$$

$$T(x, \tau_{\min}) = T_0(x), \quad x \in [X_0, X_1] \tag{2}$$

$$-\lambda(T)\frac{\partial T(X_0, \tau)}{\partial x} = q_1(\tau), \quad \tau \in (\tau_{\min}, \tau_{\max}] \tag{3}$$

$$-\lambda(T)\frac{\partial T(X_1, \tau)}{\partial x} = q_2(\tau), \quad \tau \in (\tau_{\min}, \tau_{\max}] \tag{4}$$

Data on the material known properties are presented in Table 1.

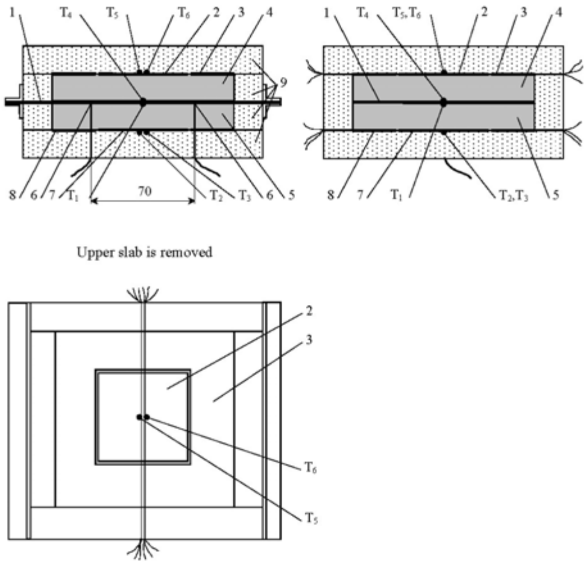


Fig. 3: A testing scheme for specimens: 1 – heating element of module EM-2; 2 – sensitive element (SE) of heat flux gage on the upper specimen (1a/2a); 3 – mask of the upper (SE); 4 – upper specimen (1a/2a); 5 – lower specimen (1a/2b); 6– voltage measuring points on the heating element; 7 – SE on lower specimen (1b/2b); 8 – mask of the lower SE; T_1, T_2, T_3 - thermocouples on the lower specimen (1b/2b); T_4, T_5, T_6 - thermocouples on the upper specimen (1a/2a).

Thermocouples are installed in specimens 1b/2b:

- T_4 at the heating surface;
- T_5 and T_6 on the copper sensitive element located on the back face (T_6 - stand-by thermocouple).

Type of material	Density, *kg/m*^{3}	Emis-sivity	Destruction tempera-ture, *K*
ETTI-CF-ULT	42	0.9	3000
ETTI-CF-ERG	48	0.9	3000

Table 1: Known properties of material.

To determine the heat flux on the specimens' back faces, the sensitive elements are installed there in the form of thin copper plates of 60×60×0.3 mm in size with guard masks (frames) from the same material, see Figure 3. Two identical specimens have been made for testing: 1a, 1b of the material ETTI-CF-ULT and 2a, 2b of the material ETTI-CF-ERG. A photograph of one of the specimens prior to installation of thermocouples and heat flux sensor is presented in Figure 4.

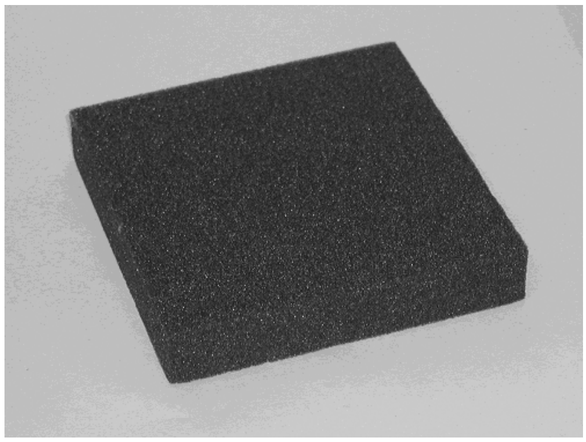


Fig. 4: A specimen of material.

When installed on the specimen's heating surfaces, the thermocouples were fixed on the surface by means of a special thermoresistant compound. The thermocouple junction relative to the specimen's surface was hence under control. The heat flux sensors with guard masks (frames) installed on the back faces of the specimens were also fixed on specimen's surface by means of a special thermoresistant compound. Prior to the thermocouple installation, the calibration and functional test was made.

A picture of the experimental module with installed specimens and removed upper plate of the heat-insulating holder is shown in Figure 5. The assembled experiment module was installed in the vacuum chamber of stand TVS-1.

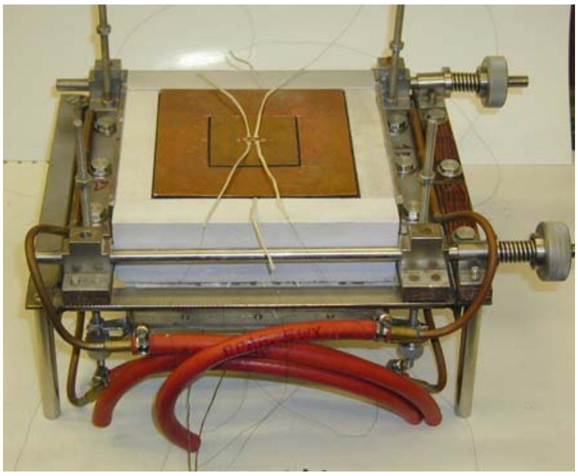


Fig. 5: The experiment module with installed specimens and removed upper plate of the heat-insulating holder.

4. TESTING

Since the number of specimens was limited (two specimens from material ETTI-CF-ULT and two from ETTI-CF-ERG), testing of each pair of specimens was conducted by the following program:
- a preliminary test with the pre-heating mode № 0 in the conditions of a vacuum when the material was warmed up in order to remove the absorbed water. To provide this it is necessary to warp up the materials till 430°C. The consequent conservation of specimens installed in the experimental module until the next test was made in conditions of vacuum (the experiment module with specimens remained in the vacuum chamber with a vacuum level ≤1x10^{-5} bars).

The heating mode № 0 (600 °C):
- the first segment: heating by a linear law at a rate of 4 °C/s from T_o = 15 °C to T_{max} = 600°C;
- the second segment: with uniform temperature *T (τ)* = 600 °C for 1800 s;
- the third segment: natural cooling from *T (τ)* = 600 °C.
- a test with the heating mode № 1 in conditions of a vacuum ≤1x10^{-7} bars. The conservation of specimens in conditions of a vacuum ≤1x10^{-5} bars until the next test.

The heating mode № 1 (300):
- the first segment: heating by a linear law at a rate of 4 °C/s from T_o = 18 °C to T_{max} = 300 °C;
- the second segment: with uniform temperature *T (τ)* = 290 °C for 1200 s;
- the third segment: natural cooling from *T* = 290 °C.
- a test with the heating mode № 2 in conditions of a vacuum ≤1x10^{-5} bars. The conservation of specimens in conditions of vacuum ≤1x10^{-5} until the next test.

The heating mode № 2 (550):
- the first segment: heating by a linear law at a rate of 4 °C/s from *T* = 290 °C to T_{max} = 550 °C;
- the second segment: with uniform temperature *T (τ)* = 550 °C for 1200 s;
- the third segment: natural cooling from *T* = 550 °C .
- a test with the heating mode № 3 in conditions of a vacuum ≤1x10^{-5} bars. The conservation of specimens in conditions of vacuum ≤1x10^{-5} until the next test.

The heating mode № 3 (800):
- the first segment: heating by a linear law at a rate of 4 °C/s from T_o = 12,2 °C to 800 °C;
- the second segment: with uniform temperature *T (τ)* = 800 °C for 1200 s;
- the third segment: natural cooling from *T* = 800 °C .
- a test with the heating mode № 4.

The heating mode № 4 (1000):
- the first segment: heating by a linear law at a rate of 4 °C/s from T_o = 14 °C to T_{max} = 1000 °C;
- the second segment: with uniform temperature *T (τ)* = 1000 °C for 1200 s;
- the third segment: natural cooling from *T* = 1000 °C

The experimental data of specimens 1a and 1b of the material ETTI-CF-ULT and 2a and 2b of the material ETTI-CF-ERG as $T_m\ (\tau)$, $0 \le \tau \le 3000$ s (for the heating modes №2 and №3 only) are presented in Figures 6-7. Since readings of the main thermocouple T_2 actually coincided with those of the standby thermocouple T_3, there are shown only the readings of the T_2. This remark is true also for the thermocouples T_5 and T_6. Tests carried out have shown that:

- After tests, the experiment module, including the heat-insulating holder, shows no signs of heating.

-After a series of tests under different conditions, the material specimen surfaces have no observable signs of heating or destruction. The material only became more rigid (brittle) and easy to crumble.

- At all heating conditions, a more rapid cooling of the specimen's heating surfaces as against their back surfaces was observed. This can be explained by the cooling of the heating element depending on the cooling system operation of the experiment module.

- Peak temperature values on the heating surfaces of the specimens 1a and 1b measured in the course of the tests under prescribed heating conditions differ insignificantly from each other (up to 3%) (for specimens 2a and 2b from 0.2% at № 3(1000) and № 4(1000) up to 5% at others). By this, the temperature on the surface of the specimen 1a was higher than that on the face of specimen 1b (apart from conditions № 4 (1000) and temperature on the surface of the specimen 2a was higher than that on the surface of the specimen 2b (apart from modes № 4 (1000)).

- Peak temperature values on the back surfaces of specimens 1a and 1b realized in the course of the tests under prescribed heating conditions differ insignificantly (from 4.3% in № 1 (290) to 0.4% in № 4 (1000), as well as 2a and 2b). This together, with a previous remark taken into account, was allowed to count in favor of sufficient heating symmetry of specimens in the realized scheme of tests.

- At all heating conditions a peak temperature on the back face of the specimen 1b was higher than that on the back face of specimen 1a. Perhaps, this is because of a difference in the material thermal properties of specimens 1a and 1b (particularly, specimen 1b has a higher density).

- At all heating conditions for specimens 1a and 1b the difference in values of the peak temperature on the specimens' back surface and the peak temperature on the specimens' hot surface was within the limits of 128 °C for № 1 (290) until 163 °C for № 2 (550). A mean value of this difference for all conditions was about 143 °C. At all heating conditions for specimens 2a and 2b the difference in values of the peak temperature on specimens' back surface and peak temperature on specimens' heating surface was within the interval of 202.4 °C for № 2 (550) till 216.5 °C for № 4 (1000). A mean value of this difference for all conditions was about 209 °C.

Comparisons of the heating merits of specimens 2a and 2b of ETTI-CF-ERG and specimens 1a and 1b of ETTI-CF-ULR have shown, that for the same heating specimens of ETTI-CF-ULR there is significantly higher response at the back surfaces (about 50 °C or 25%).

5. ESTIMATION OF THE THERMAL PROPERTIES BY AN INVERSE METHOD

In models (1) – (4) the coefficients $C(T)$ and $\lambda(T)$ are unknown. The complimentary information needed for solving the inverse problem prescribed are the results of the temperature measurements

$$T^{\exp}(x_m,\tau)=f_m(\tau),\ \ m=\overline{1,2},\ \ x_1=X_0,\ x_2=X_1 \qquad (5)$$

Let us introduce in the interval $[T_{\min},T_{\max}]$ three uniform difference grids with the number of nodes N_i, $i=1,2,3,$ namely

$$\omega_i=\left\{T_k=T_{\min}+(k-1)\Delta T,\ k=\overline{1,N_i}\right\},\quad i=\overline{1,2} \qquad (6)$$

We now approximate the unknown functions on grids (6) using cubic B-splines as follows

$$C(T)=\sum_{k=1}^{N_1}C_k\varphi_k^1(T),\qquad \lambda(T)=\sum_{k=1}^{N_2}\lambda_k\varphi_k^2(T), \qquad (7)$$

where C_k, $k=1,N_1$, λ_k, $k=1,N_2$, are parameters. As a result of the approximation, the inverse problem is reduced to a search for the vector of unknown parameters $\overline{p}=\{p_k\}$, $k=1,N_p$, which has dimension $N_p=N_1+N_2$.

In the inverse problem (1) – (5) it is essential above all to indicate the domain of definition of the unknown functions in the form of the temperature interval, common for all experiments, $[T_{\min},T_{\max}]$, where the inverse problem under analysis has a unique solution. The initial temperature minimum value is taken for $T_{\min}$, the temperature maximum value obtained from the thermocouple located on the heating surface - for $T_{\max}$. The least- square residual of computational and measured temperatures at points of the thermocouple installation is given by [5]:

$$J(C(T),\lambda(T))=\sum_{m=1}^{2}\int_{\tau_{\min}}^{\tau_{\max}}\left(T(x_m,\tau)-f_m(\tau)\right)^2d\tau\,, \qquad (8)$$

where $T(x_m,\tau)$ is defined from a solution of the boundary-value problem (1) – (4).

Proceeding from the principle of iterative regularization [4], the unknown vector $\overline{p}$ can be determined through the minimization of the functional (8) by gradient methods of the first-order prior to the fulfillment of the condition:

$$J(\overline{p})\le\delta_f\,, \qquad (9)$$

where $\delta_f=\sum_{m=1}^{M}\int_{\tau_{\min}}^{\tau_{\max}}\sigma_m(\tau)d\tau$ is an integral error of the temperature measurements $f_m(\tau)$, $m=1,M$, and σ_m are the measurement variance.

To construct the iterative algorithm for this inverse problem, the solution of a conjugate gradient method is used. A successive approximation process is constructed as follows:

(i) *a-priori* an initial approximation of the unknown parameter vector $\overline{p}^0$ are set, and

(ii) a value of the unknown vector at the next iteration are calculated as follows:

$$\begin{aligned} \overline{p}^{s+1} &= \overline{p}^{s} + \gamma^s \overline{g}^{s} \\ \overline{g}^{s} &= -\overline{J'}^{s} + \beta^s \overline{g}^{s-1} \end{aligned} \tag{10}$$

$$\beta^0 = 0, \quad \beta^s = \left\langle \left(\overline{J_p'^{(s)}} - \overline{J_p'^{(s-1)}} \right), J_p'^{(s)} \right\rangle_{R^{N_p}} \Big/ \left\| J_p'^{(s)} \right\|_{R^{N_p}},$$

where $J_p'^{(s)}$ is the value of the functional gradient at the current iteration.

An analytical form for the minimized functional gradient is given by

$$J'_{C_k} = -\int_{\tau_{\min}}^{\tau_{\max}} \int_{X_0}^{X_1} \psi(x,\tau) \cdot \varphi_k^1(T) \frac{\partial T}{\partial \tau} \, dx d\tau \tag{11}$$

$$\begin{aligned} J'_{\Lambda_k} = &-\int_{\phi_{\min}}^{\phi_{\max}} \int_{X_0}^{X_1} u(x,\phi) \cdot \left(\frac{\partial^2 T}{\partial x^2} \cdot \varphi_k^2(T) + \left(\frac{\partial T}{\partial x} \right)^2 \cdot \frac{\partial \varphi_k^2}{\partial T} \right) dx d\phi - \\ &- \mathit{в}_1 \int_{\phi_{\min}}^{\phi_{\max}} u(X_0,\phi) \frac{\partial T}{\partial x}(X_0,\phi) \varphi_k^2(T(X_0,\phi)) \, d\phi + \\ &+ \mathit{в}_2 \int_{\phi_{\min}}^{\phi_{\max}} u(X_1,\phi) \frac{\partial T}{\partial x}(X_1,\phi) \varphi_k^2(T(X_1,\phi)) \, d\phi , \end{aligned}$$

$$k = \overline{1,N_i}, \quad i=1,2, \tag{12}$$

where $\psi(x,\tau)$ is the solution of a boundary-value problem adjoint to a linearized form of the initial problem (1)-(4).

The authors started a prototype of the computer code, intended for the development of algorithms for the estimating of materials thermal properties, in 1990. Developed software is the set of problem-oriented blocks for numerical solving various inverse problems in the processing of transient thermal experiments, data processing and of optimal experiment design with respect to different optimality criterion. The software consists of individual modules and has multi-level structure. Software is made of the segments "Task", "Data", "Core", "Model coefficient", "Logistics" (Figure 6).

The presented structure is stipulated by the need to adjust the software to new problems to be solved and the role by each segment in the iterative procedure. The "Task" segment is intended for the following operations: to allocate required resources, to configure the software version to be used, namely to define the titles of subprograms, shaping the mathematical model and dimensions of the used arrays (mesh nodes, approximation parameters). "Task" segment is made of a set of commands and basis programs, which define the model to be used, allocate resources and control the operations by the "Model coefficient" segment. The "Data" segment modules are the sets of the input data to be used by other segments. The structure of input data is a very important question for users, and data input module generates a data description table, their basis characteristics as well as tables of connection with heat transfer mathematical model (Figure 7). Entire information is piled together in a singe data array. Individual modules are united into so-called segments.

The "Core" segment does not depend on the considered problem, that is achieved through the special procedure of input data processing and the system of interconnections among individual program modules. In this segment are realized the algorithms: optimization, one-dimensional and multi-dimensional search, statistic identification, etc. A particular problem is defined at the computation of the model coefficients. Programs, used for coefficients computing, make up the segment "Model coefficients". Modules, realizing conventional mathematical methods to be used by all programs, are united into the segment "Logistics". Software structure is an open-end one and can be enhanced or modified if needed. Software is realized into FORTRAN and C++ programming language.

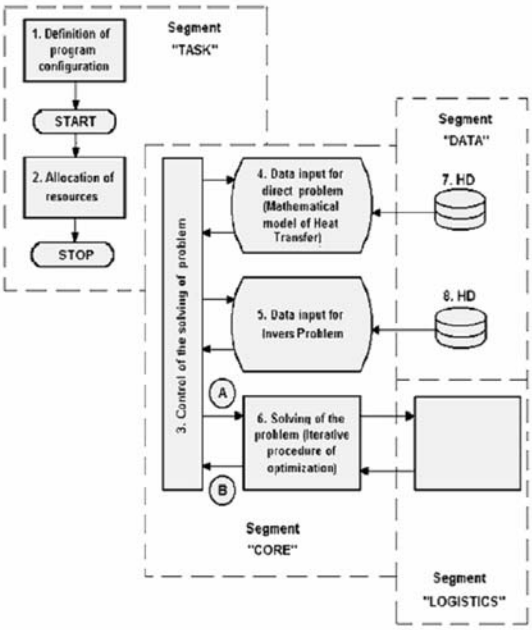
The segment "Logistics" includes the following functions:

- Linear/spline interpolation;
- Approximation/basis functions (B-splines with free and natural boundary conditions, polynoms);
- Calculation of matrix eigenvalues and eigenvectors;
- Various simulators of random values;
- Solving systems of linear algebraic equations and non-linear algebraic equations.

Programs of the "Model Coefficients" segment defined by the type of heat conduction equation:

- Programs to compute coefficients of heat transfer direct problem;
- Programs to compute coefficients of the adjoint problem,
- Programs to compute coefficients of the problem of temperature variations.

The "Core" programs are universal for the class of problem, considered here.



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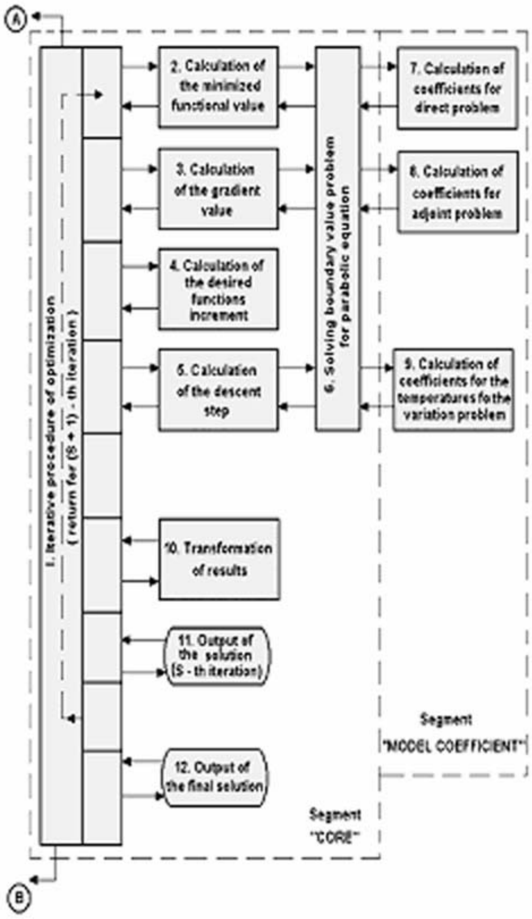

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Fig. 6: Software structure.

The change of heat transfer mathematical model demands the modifications of the problems, making up the second “Model Coefficients” segment (all these programs make up less then 2% of total software).

This approach reduces software maintenance cost and simplifies its modification, even general one.

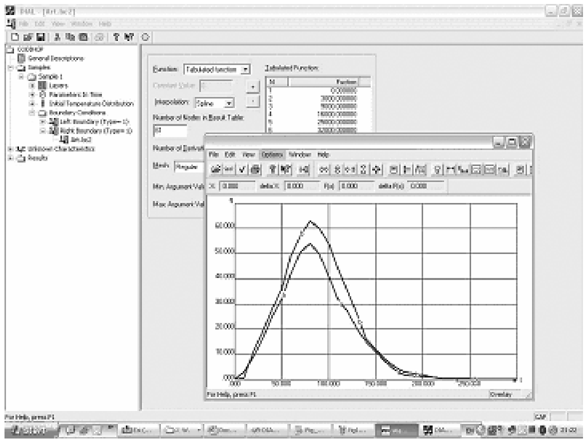

Fig. 7: Data input: right boundary conditions (heat flux as a function of time: 1- the first experiment, 2 - the second experiment).

The heat flux at the heating surface $q_2(\tau),\ 0 \le \tau \le \tau_n$ can be defined by electric power $W(\tau)$ of the heating element based on the measurements of the active voltage $U(\tau)$ at the boundaries of the heating element operating zone with area A and active current intensity $I(\tau)$ in the scheme of the heating element:

$$q_2(\tau) = W(\tau) / (2 * A), \quad 0 \le \tau \le \tau_m \qquad (19)$$

where τ - time, τ_n - measurement termination time. The experimental data obtained from testing, presented in the previous subsection has been used to determine the thermal properties of the analyzed materials. To solve the inverse problem in the presented version the software developed and presented above was used.

Comparisons of the calculated and measured temperatures on the specimens’ surfaces for materials ETTI-CF-ULT and ETTI-CF-ERG are presented in Figures 8 and 9. The result of estimating the functions $\lambda(T)$ and $c(T)$ for material ETTI-CF-ULT and ETTI-CF-ERG are presented in Fig. 10 and 11. Table 2 includes the obtained values of the least squares and the maximum deviation of the calculated temperatures from that measured in the experiments.

Material	Least-squares temperature deviation, K	Maximum temperature deviation, K
ETTI-CF-ULT	5.64	17.5
ETTI-CF-ERG	5.64	17.5

Table 2: The deviation of the calculated temperatures.

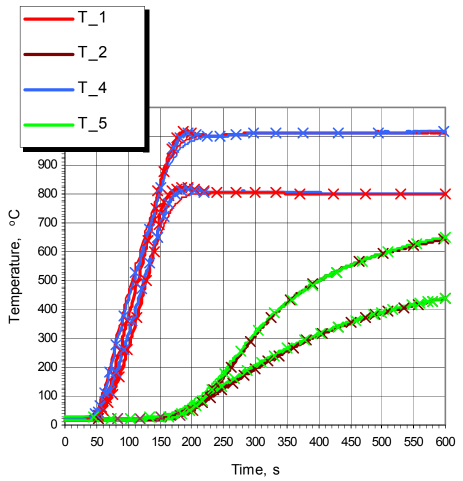

Fig. 8: Comparison the calculated (T_1 and T_2) and measured (T_3 and T_4) temperatures for material ETTI-CF-ULT

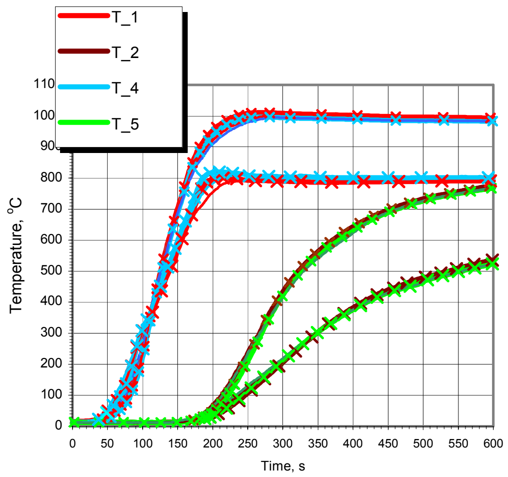

Fig. 9: Comparison the calculated (T_1 and T_2) and measured (T_3 and T_4) temperatures for material ETTI-CF-ERG

6. CONCLUSIONS

The executed thermal testing provided the solving of the above formulated problems to study the heat transfer in the specimens and to estimate the thermal properties of the lightweight porous materials.

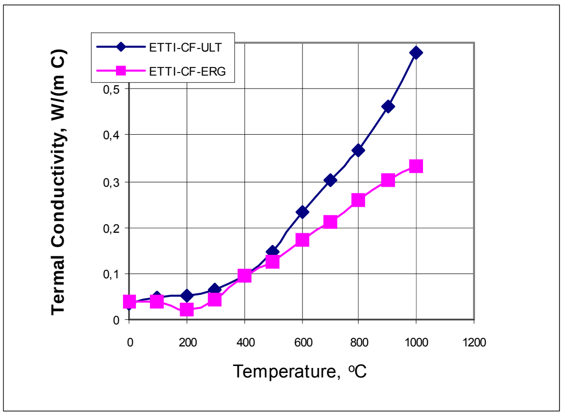

Fig. 10: Estimated value of the thermal conductivity for material ETTI-CF-ERG and ETTI-CF-ULT.

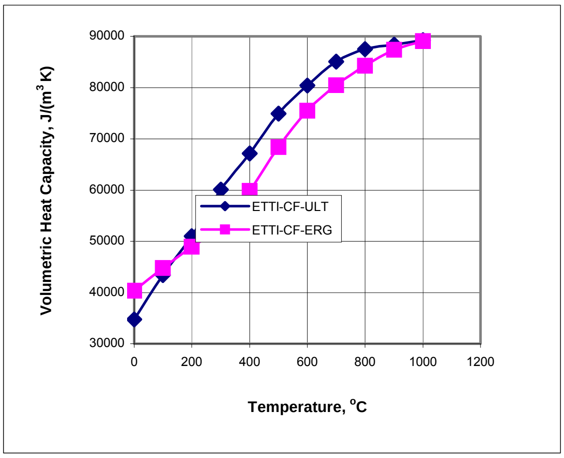

Fig. 11: Estimated value of the volumetric heat capacity for material ETTI-CF-ERG and ETTI-CF-ULT.

The operating opportunity and effectiveness of the developed methodology for preparing and carrying out the thermal testing of high porous, electrical conductive thermal insulating materials on the high temperature vacuum stand TVS-1 was approved (including the technology of specimen and thermosensors manufacture and installation).

The operating opportunity and effectiveness of developed hardware for the thermal testing of the above-mentioned materials was approved (including experimental module EM-2 and automatic system for heating, control, experimental data collection and processing).

The deviations of the calculated temperatures (using thermal property estimations) from the temperature measured in the experiments are insignificant showing sufficient accuracy in the estimations of thermal properties of analyzed materials.

7. ACKNOWLEDGEMENT

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