

Defining Thermophysical Parameters of Electric Devices Based on Solution of Inverse Heat Transfer Problem

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Abstract

This paper describes application of the study methods based on the solution of inverse problems of mathematical physics to define thermophysical parameters of electric devices. The mathematical model of the device is developed based on equations of non-stationary heat conductivity. The algorithm to define thermophysical parameters is developed; this algorithm uses the finite element method to solve a direct heat transfer problem and the gradient method to minimize the objective function. Examples of the algorithm application are given. The problem to define an equivalent heat transfer coefficient of the solenoid area covered with heavy winding and a heat emission from its inside surface is considered. In the second example thermophysical parameters of electromagnetic valve actuator of an ICE (internal combustion engine) gas distribution mechanism are defined. The obtained results show that thermophysical parameters and temperature distribution in non-stationary and steady-state operating conditions of electrical devices may be evaluated with adequate efficiency based on the solution of inverse heat transfer problems.

Keywords: inverse problems, heat transfer, non-stationary heat conductivity, electrical device

1. Introduction

The need to save energy and resources leads to creation of technical units characterized by marginal operation, high thermal, electro-magnetic and mechanical loads on their materials and structures. All of these require a reliable identification of the study subjects i.e. parameters and characteristics of materials and structures used in mathematical modeling shall be defined with an adequate accuracy. At the same time some of the parameters and characteristics can not be directly defined. In such cases the only way to obtain necessary information is to use a study approach based on solving inverse problems of mathematical physics (Alifanov, 1994), (Bachvalov *et al.*, 2013), (Beck *et al.*, 1985), (Bui, 1994), (Grechikhin and Grecova, 2011), (Korovkin *et al.*, 2006), (Ozisik and Orlande, 2000), (Tikhonov and Arsenin, 1977), (Vatulyan, 2007). It is one of the main trends in studying physical processes and optimizing operating parameters of technical units and operating procedures.

Functioning of a number of technical units, including electric devices, is accompanied with heat transfer processes, which in their turn have an impact on the unit technical characteristics. Tougher tolerances are being established for temperature ranges of parts and devices, requirements to reliability in maintaining these ranges and reduction of material intensity of structures are getting tougher. Therefore thermophysical study of electric devices and calculation of their thermal rates becomes very important. Effectiveness of decisions made depends a lot on completeness and accuracy of heat transfer study. This justifies a necessity to conduct full-scale and modeling tests of devices (Grechikhin and Grecova, 2011). During the tests temperature $T_*(M_i, t)$ is measured in points M_i of the device on a bounded time interval $[0, t_e]$. Then, a thermal mathematical model of the device is adjusted by variation of a system of n thermophysical parameters x_1, x_2, \dots, x_n in such a way, that the values $T_*(M_i, t)$ of the device agree with $T(M_i, t)$ of the model on the interval $[0, t_e]$ with an adequate accuracy. Then, using the model, desired time to achieve the steady-state condition t_s and temperature distribution of the device in this condition are defined.

Heat transfer and heat conductivity coefficients which values either unknown or known but with low accuracy can be used as adjustable thermophysical parameters. It is known, that temperature measurement data remain the main source of inaccuracy in solving applied problems to define these parameters (Beck *et al.*, 1985). This is caused by performance features of temperature sensors. Therefore it is practical to identify heat transfer and heat

conductivity coefficients based on the solution of inverse heat transfer problems (Alifanov, 1994), (Beck *et al.*, 1985), (Ozisik and Orlande, 2000). This paper describes a mathematical model and an algorithm to define thermophysical parameters of electric devices using such an approach.

Two problems are solved. The first one determines an equivalent heat transfer coefficient for a solenoid heavy winding of a measuring system designed to define magnetization curves (B-H curves) and hysteresis loops for ferromagnetic materials as well as a heat transfer coefficient between the solenoid inside surface and the ambient air. The second problem defines thermophysical parameters of an electromagnetic valve actuator in an ICE gas distribution mechanism.

This paper shows the results of using thermal testing methods for the stated devices based on the solution of an inverse heat transfer problem resulting in essential decrease of testing time and power consumption.

2. Methodology

2.1 Statement of the Problem

The studied electric device together with the ambient environment are represented as a multiply connected domain V (Fig. 1), with subdomains V_i , and heat sources with volume density q_v .

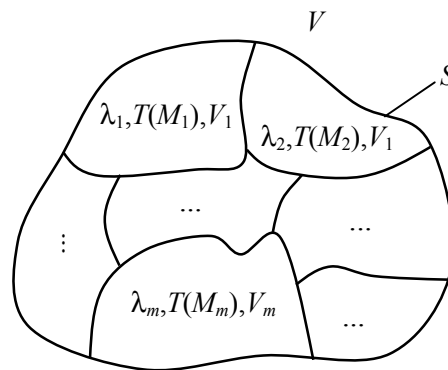


Figure 1. Multiply connected domain

Non-stationary temperature distribution in the domain V is described with a system of equations

$$\rho_i c_i \frac{\partial T_i(M_i)}{\partial t} = \text{div}(\lambda_i \text{grad} T_i(M_i)) + q_{v_i}; \quad i = 1, 2, \dots, m, \quad (1)$$

where $T(M_i)$ – temperature in the point $M_i \in V_i$; λ_i – heat transfer coefficient of the medium in V_i ; q_{v_i} –

volume density of the heat sources in a subdomain V_i ; ρ_i – density of the medium in V_i ; c_i – specific heat capacity of the medium in V_i ; m – number of bodies in the studied domain V .

Boundary conditions are added to the system of equations (1):

$$\lambda \frac{\partial T}{\partial n} = -\alpha(T - T_{\text{amb}}) \quad \text{on } S; \quad (2)$$

$$T(M_i) = T(M_{i+1}), \quad \lambda_i \frac{\partial T}{\partial n}(M_i) = \lambda_{i+1} \frac{\partial T}{\partial n}(M_{i+1}) \quad (3)$$

at interfaces of media with different λ_i . Here, α – heat emission coefficient, T_{amb} – ambient temperature.

Initial temperature distribution in the domain V at a point of time $t = 0$ is considered to be known:

$$T(M_i, 0) = T(M_i), \quad i = 1, 2, \dots, m. \quad (4)$$

Problem (1) – (4) describes heat transfer in linear and non-linear media. (1) – (4) forms a direct problem to find the function $T(M_i, t)$. Analytical (Polyanin *et al.*, 2005) and numerical (Samaraskii, 2001), (Zienkiewicz and Taylor, 2000) methods of solving this direct heat transfer problem are well known.

Let us consider an inverse problem where, for instance, in addition to $T(M_i, t)$, a heat transfer coefficient $\lambda(T)$ and a heat emission coefficient $\alpha(T)$ are unknown. The unknown coefficients shall be restored by solving the system (1) with conditions (2) – (4) and additional information

$$T_*(M^*, t) = \tilde{T}_M(t), \quad T_*(N^*, t) = \tilde{T}_N(t), \quad M^*, N^* \in V, \quad t \in [0, t_u]. \quad (5)$$

where M^*, N^* – fixed points, where temperature is measured with an error ΔT_* .

The formed problem belongs to inverse heat transfer problems of a mixed type (coefficient and boundary). The studies (Alifanov *et al.*, 1995), (Borukhov *et al.*, 2005) prove the existence and uniqueness of the solutions to such problems. Solution stability is ensured by selecting them in a class of functions with a bounded norm (Tikhonov's stability) (Tikhonov and Arsenin, 1977).

2.2 Computational Algorithm

To define thermophysical parameters of electric devices based on the solution of an inverse heat transfer problem we shall use a conjugate gradient method (Alifanov *et al.*, 1995), (Dinh and Reinhardt, 1998), (Rumyantsev, 1985). It is an iterative process of minimizing the objective function

$$J(\lambda, \alpha) = \int_0^{t_u} [T(N^*, t) - T_*(N^*, t)]^2 dt + \int_0^{t_u} [T(M^*, t) - T_*(M^*, t)]^2 dt. \quad (6)$$

Iterations, which define minimizing sequence of the function (5), are imposed with recursion

$$\lambda^{(n+1)} = \lambda^{(n)} - \rho \frac{\partial J^{(n)}}{\partial \lambda}, \quad n = 1, 2, \dots; \quad (7)$$

$$\alpha^{(n+1)} = \alpha^{(n)} - \rho \frac{\partial J^{(n)}}{\partial \alpha}, \quad n = 1, 2, \dots, \quad (8)$$

where $\lambda^{(n)}, \lambda^{(n+1)}$ – n and $(n+1)$ approximation for $\lambda(T)$; $\alpha^{(n)}, \alpha^{(n+1)}$ – n and $(n+1)$ approximation for $\alpha(T)$; $\frac{\partial J^{(n)}}{\partial \lambda}, \frac{\partial J^{(n)}}{\partial \alpha}$ – partial derivatives of the function (6).

The iterative process is terminated when the equation

$$\int_0^{t_u} [T^{(n)}(N^*, t) - T_*(N^*, t)]^2 dt + \int_0^{t_u} [T^{(n)}(M^*, t) - T_*(M^*, t)]^2 dt \leq \varepsilon \Delta T_* \quad (9)$$

is true,

where ε – given empirical parameter, defined using the criteria described in (Samarskii, 2001), (Tikhonov *et al.*, 1995), $T^{(n)}(N^*, t), T^{(n)}(M^*, t)$ – problem solution (2) – (4) when $\lambda(T) = \lambda^{(n)}(T)$ and $\alpha(T) = \alpha^{(n)}(T)$.

Considering (6) – (9) we shall present the sequence for solving the inverse problem (2) – (5). We shall select initial approximation $\lambda(T) = \lambda^{(0)}(T)$, $\alpha(T) = \alpha^{(0)}(T)$ and increments $\Delta \lambda$, $\Delta \alpha$, ρ and Δt .

Iteration loop of the algorithm for each $n = 0, 1, 2, \dots$ consists of the steps as follows:

1. We solve a direct problem (2) – (4) where $\lambda(T) = \lambda^{(n)}(T)$, $\alpha(T) = \alpha^{(n)}(T)$ and define a temperature field

including the values $T(N^*, t_j)$ and $T(M^*, t_j)$, $j = 1, 2, \dots, n$, at the time points t_j .

2. We find a value of the function (6).

3. We check the condition for termination of the calculations (9). If the condition (9) is satisfied, values

$\lambda(T) = \lambda^{(n)}(T)$, $\alpha(T) = \alpha^{(n)}(T)$ and $T^{(n)}(N^*, t), T^{(n)}(M^*, t)$ are considered to be the solution of the problem.

If the condition (4) is not satisfied, then go to 4.

4. We find the next values of the desired variables using a gradient method and the equations (7) and (8).

5. Go back to 1.

As a rule numerical implementation of this algorithm is based on the application of a finite element method (FEM) or a finite difference method.

3. Results and Discussion

3.1 Thermophysical Parameters of the Measuring System Solenoid

The applicable standards (IEC Standard 60404) for measuring static magnetic characteristics of soft magnetic materials are not adopted for testing under changing temperature and mechanical stresses. For instance, during operation the temperature of automobile starters and generators may reach 200 °C, their stress – 200 MPa. In cases like that it is practical to take measurements on an open magnetic circuit, using a solenoid to magnetize the material (Hall *et al.*, 2009).

Let us consider a problem of finding thermophysical parameters of a solenoid of a measuring system designed to define magnetization curves (B-H curves) and hysteresis loops for soft magnetic materials. They include an equivalent heat transfer coefficient λ_2 of area 2 of the solenoid, covered with heavy winding, and a heat emission coefficient α_1 between the solenoid inside surface with a radius r_1 and the ambient air (Fig. 2).

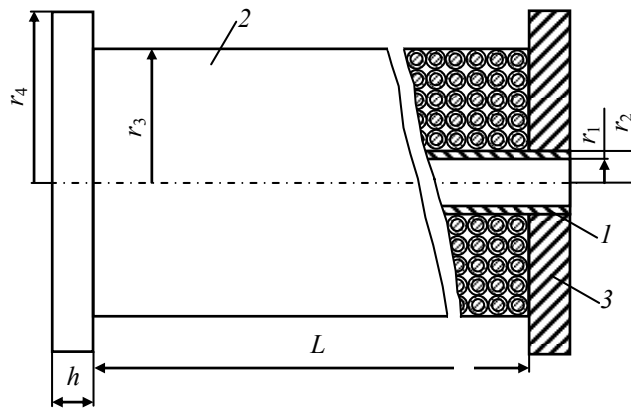


Figure 1. Sketch of a solenoid

Smallness of the radius r_1 makes it harder to measure thermophysical parameters inside the solenoid and allows for only one temperature sensor to be placed inside that area.

Considering axial symmetry of the solenoid, we will use a cylindrical coordinate system $r\theta z$.

In this case a system of equations (1) is

$$\rho_i c_i \frac{\partial T_i}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(\lambda_i r \frac{\partial T_i}{\partial r} \right) + \frac{\partial}{\partial z} \left(\lambda_i \frac{\partial T_i}{\partial z} \right) + q_{v_i}, i = 1, 2, \dots, m. \quad (10)$$

The initial temperature distribution in the solenoid at the point of time $t = 0$ $T(N_i, 0) = T(N_i)$, $i = 1, 2, 3$; and the ambient temperature T_{amb} are considered to be known.

Boundary conditions are:

- On the inside surface of solenoid area 1

$$\lambda_1 \frac{\partial T_1}{\partial n} \Big|_{r=r_1} = -\alpha_1 [T_1(r_1, t) - T_{amb}];$$

- On the outside surface of solenoid area 2

$$\lambda_2 \frac{\partial T_2}{\partial n} \Big|_{r=r_3} = -\alpha_2 [T_2(r_3, t) - T_{amb}];$$

- On the surfaces of area 3, which are in contact with the ambient environment:

$$\frac{\partial T_3}{\partial n} = 0;$$

- At the media interfaces

when $r = r_2$

$$T_1(r_2, t) = T_2(r_2, t); \quad \lambda_1 \frac{\partial T_1}{\partial n} \Big|_{r=r_2} = \lambda_2 \frac{\partial T_2}{\partial n} \Big|_{r=r_2};$$

- at the interfaces of areas 1 and 3

$$T_1(N, t) = T_3(N, t); \quad \lambda_1 \frac{\partial T_1}{\partial n} = \lambda_3 \frac{\partial T_3}{\partial n};$$

- at the interfaces of areas 2 and 3

$$T_2(N, t) = T_3(N, t); \quad \lambda_2 \frac{\partial T_2}{\partial n} = \lambda_3 \frac{\partial T_3}{\partial n},$$

where α_1, α_2 – heat emission coefficients between the inside and outside surfaces of the solenoid and the ambient air, respectively.

Computational domain is given in Fig. 3.

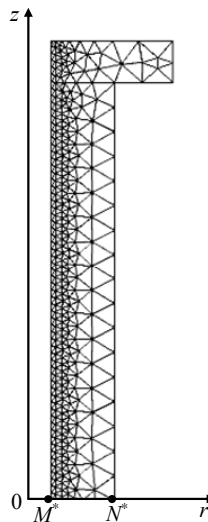


Figure 3. Computational domain with FEM mesh (709 elements)

M^*, N^* – points where temperature sensors are placed

Unknown values are λ_2, α_1 and $T_i = T(N_i, t), i = 1, 2, 3$.

We shall formulate a problem: it is required to define the equivalent heat transfer coefficient λ_2 of the area covered with the solenoid winding, the heat emission coefficient α_1 and the functions $T_i = T(N_i, t), i = 1, 2, 3$, which satisfy the system of equations (10) and the above given initial and boundary conditions; there are additional known data– functions $T_*(N^*, t)$ and $T_*(M^*, t)$, obtained by taking measurements in N^* and M^*

(Fig. 3) with error ΔT_* on the time interval $[0, t_e]$.

Let us convert the solution of this problem to the solution of a sequence of direct problems – a system of equations (10) with the above given initial and boundary conditions using the FEM.

We shall select initial approximation $\lambda_2^{(0)}, \alpha_1^{(0)}$ and increments $\Delta \lambda_2, \Delta \alpha_1, \rho_1, \rho_2$ and Δt .

Then, according to the algorithm, we shall solve a direct problem using the FEM when $\lambda_2 = \lambda_2^{(n)}$, $\alpha_1 = \alpha_1^{(n)}$ and define the temperature field, including $T(N^*, t_j)$ and $T(M^*, t_j)$, $j = 1, 2, \dots, n$, at the points of time t_j .

As in our case the functions $T_u(N^*, t)$ and $T_u(M^*, t)$ are represented as table data, instead of (6) we will use a function type

$$J^{(n)}(\lambda_2^{(n)}, \alpha_1^{(n)}) = \beta_1 \sum_{j=1}^p [T(N^*, t_j) - T_*(N^*, t_j)]^2 + \beta_2 \sum_{j=1}^p [T(M^*, t_j) - T_*(M^*, t_j)]^2,$$

where p – number of temperature measurements on the interval $[0, t_e]$; β_1, β_2 – weight factors, $\beta_1 = 1/3$; $\beta_2 = 2/3$.

According to (9), we shall check the condition for calculation termination. If the condition (9) is not satisfied we start calculating, similar to (7) and (8), the next values of the desired variables:

$$\lambda_2^{(n+1)} = \lambda_2^{(n)} - \rho_2 \frac{\partial J^{(n)}}{\partial \lambda_2};$$

$$\alpha_1^{(n+1)} = \alpha_1^{(n)} - \rho_1 \frac{\partial J^{(n)}}{\partial \alpha_1},$$

and solve the direct problem again using the FEM when $\lambda_2 = \lambda_2^{(n+1)}$, $\alpha_1 = \alpha_1^{(n+1)}$.

Let us consider using the algorithm to define the heat emission coefficient α_1 and the equivalent heat transfer coefficient λ_2 of the solenoid area, covered with heavy winding of a copper wire with the following parameters:

$$r_1 = 12 \cdot 10^{-3} \text{ m}; \quad r_2 = 15 \cdot 10^{-3} \text{ m}; \quad r_3 = 50 \cdot 10^{-3} \text{ m}; \quad r_4 = 85 \cdot 10^{-3} \text{ m}; \quad h = 25 \cdot 10^{-3} \text{ m}; \quad L = 505 \cdot 10^{-3} \text{ m};$$

$\lambda_1 = \lambda_3 = 0.3 \text{ W/(m}\cdot\text{K)}$ (material – textolite); specific heat capacity of copper $c_{Cu} = 385 \text{ J/(kg}\cdot\text{K)}$; density of copper $\rho_{Cu} = 8.9 \cdot 10^3 \text{ kg/m}^3$; number of turns $w = 2514$; wire diameter (copper only) $2.1 \cdot 10^{-3} \text{ m}$; insulation thickness $0.2 \cdot 10^{-3} \text{ m}$; volume of copper $V_{Cu} = 1.02 \cdot 10^{-3} \text{ m}^3$; we shall consider that specific heat capacity and density values of other materials equal to zero; test time $t_e = 30 \text{ min}$.

Table 1 gives measurements of the temperature $T_*(N^*, t)$ and $T_*(M^*, t)$ in the points N^* and M^* , the heat flux density q_* , from the surface of area 2, the ambient temperature T_{amb} measured with ITP–MG4.03/3(1) Potok heat flux density and temperature measuring device with the solenoid winding powered from d.c. power source with voltage $U = 18.75 \text{ V}$, current $I = 7.53 \text{ A}$. The instrument error: $\pm 6 \%$ relative error for heat flux density, and $\pm 0.2 \text{ }^\circ\text{C}$ absolute error for temperature.

Table 1. Experimental data

$t, \text{ min}$	0	5	10	15	20	25	30
$T_*(N^*, t), \text{ }^\circ\text{C}$	22	25.5	29.2	32.0	34.6	37.7	40.1
$T_*(M^*, t), \text{ }^\circ\text{C}$	22	24.5	29.3	33.8	38.6	43.2	47.8
$q_*, \text{ W/m}^2$	0	43.1	77.2	106.1	137.1	165.6	188.7

$T_{amb}, ^\circ\text{C}$	22	22	22	22	22	22	22
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Using data from Table 1, we shall define the mean value of the heat emission coefficient from the solenoid surface

$$\alpha_2 = \frac{q^*}{T_*(N^*, t) - T_{amb}} = 11,1 \text{ W}/(\text{m}^2 \cdot \text{K}).$$

Now we shall find other solenoid parameters, reduced to the volume of area 2 (solenoid winding) V_2 :

$$V_2 = \pi(r_3^2 - r_2^2)L = 3,1416 \left[(50 \cdot 10^{-3})^2 - (15 \cdot 10^{-3})^2 \right] \cdot 505 \cdot 10^{-3} = 3.61 \cdot 10^{-3} \text{ m}^3;$$

$$q_{V_2} = \frac{UI}{V_2} = \frac{18.75 \cdot 7.53}{3.61 \cdot 10^{-3}} = 39122 \text{ W}/\text{m}^3;$$

$$\rho_2 c_2 = \rho_{Cu} c_{Cu} \frac{V_{Cu}}{V_2} = 8.9 \cdot 10^3 \cdot 385 \cdot \frac{1.02 \cdot 10^{-3}}{3.61 \cdot 10^{-3}} = 1.64 \cdot 10^6 \text{ J}/(\text{kg} \cdot \text{K}).$$

We consider that $\lambda_2^{(0)} = 0.01 \text{ W}/(\text{m} \cdot \text{K})$, $\Delta\lambda = 0.003 \text{ W}/(\text{m} \cdot \text{K})$, $\varepsilon = 10^{-4}$, $\alpha_1^{(0)} = 5 \text{ W}/(\text{m}^2 \cdot \text{K})$,

$$\Delta\alpha_1 = 0.5 \text{ W}/(\text{m}^2 \cdot \text{K}), \Delta t = 5 \text{ min}.$$

Computational domain (Fig. 2) is covered with the FEM mesh which consists of 709 triangles. Using the above algorithm, the fifth iteration gives us $\lambda_2 = 0.027 \text{ W}/(\text{m} \cdot \text{K})$, $\alpha_1 = 6.5 \text{ W}/(\text{m}^2 \cdot \text{K})$.

Relative error of λ_2 and α_1 is not more than 3 % for the method used.

The standard deviation $T(M^*, t)$ of $T_*(M^*, t)$ with the found values λ_2 and α_1 on the interval $[0, 30 \text{ min}]$

was $1.3 \text{ }^\circ\text{C}$ (Fig. 3), which is acceptable. The same deviation is in the point N^* .

The developed mathematical model and the algorithm allowed defining temperature distribution in the solenoid in the steady-state condition (Fig. 4), which was reached within 12 h, as well as dependences $T(M^*, t)$,

$T(N^*, t)$ (Fig. 5) and the steady-state temperatures $T_{st}(M^*) = 173.4 \text{ }^\circ\text{C}$, $T_{st}(N^*) = 80.9 \text{ }^\circ\text{C}$.

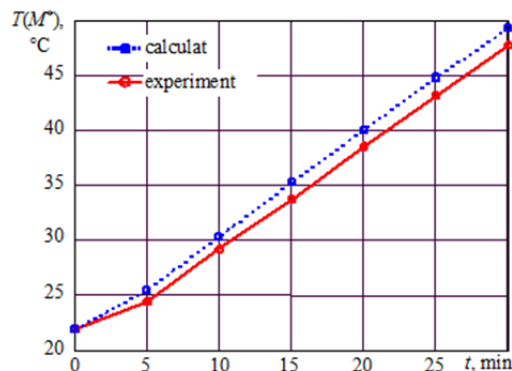


Figure 4. Results of measurements and temperature calculation in the point M^*

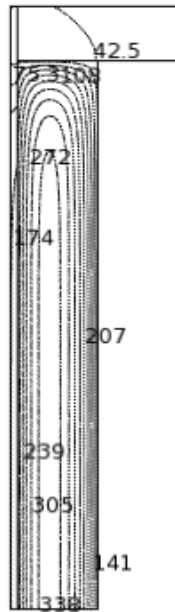


Figure 5. Temperature distribution in the solenoid cross-section in the steady-state condition

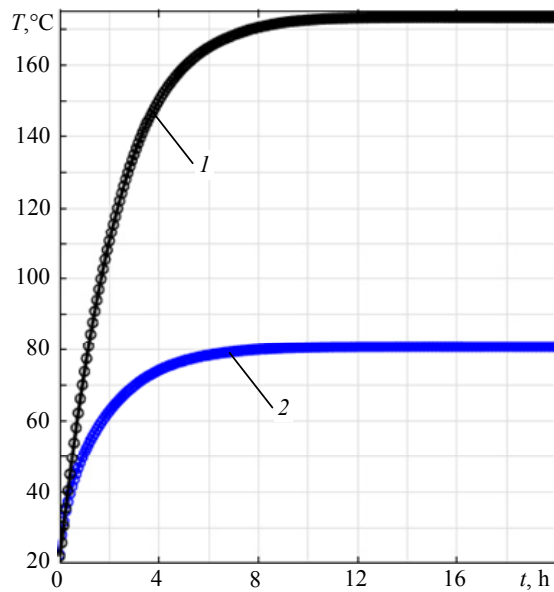


Figure 6. Temperature-time curve in the points M^* and N^* : 1 – $T(M^*, t)$; 2 – $T(N^*, t)$

Let us check if the first law of thermodynamics is satisfied in the reached steady-state (temperature T_{st}) – the capacity supplied to the solenoid winding shall be equal to the sum of heat energy radiated from the solenoid surface to the ambient environment:

$$UI = \alpha_1 S_{int} [T_{st}(M^*) - T_{amb}] + \alpha_2 S_{ext} [T_{st}(N^*) - T_{amb}], \tag{11}$$

Where $S_{int} = \pi \cdot 2r_1 L = 3.14 \cdot 24 \cdot 10^{-3} \cdot 505 \cdot 10^{-3} = 0.0384 \text{ m}^2$, $S_{ext} = \pi \cdot 2r_3 L = 3.14 \cdot 0.1 \cdot 505 \cdot 10^{-3} = 0.1586 \text{ m}^2$.

Based on (11) we have:

$$18.75 \cdot 7.53 = 6.5 \cdot 0.0381 \cdot (173.4 - 22) + 11.1 \cdot 0.1586 \cdot (80.9 - 22) \text{ or } 141.2 \approx 141.17.$$

Consequently, heat transfer and heat emission coefficients of the test unit and temperature distribution in it can

be evaluated with an adequate accuracy based on the solution of the inverse heat transfer problems.

3.2 Thermophysical parameters of an Electromagnetic Valve Actuator of an ICE Gas Distribution Mechanism

Quick-action electromagnetic actuators are used as basic parts in many fuel delivery and air/gas mixing assemblies of ICES. They are used for gas distribution mechanisms with individual valve actuators, blow off valves, gas recirculation systems and other devices, which improve energy, economic and environmental performance indicators of motors (Bolshenko, (2013), Dresner and Barkan, (1989). The actuators work under conditions of excessive power loads, which makes it necessary to study heat parameters of the equipment operation.

A mathematic model represented by a system of equations (10) with boundary conditions on the outside surface of the actuator (2) is used to analyze heat transfer processes in the valve actuator of the ICE gas distribution mechanism (Figure 7).

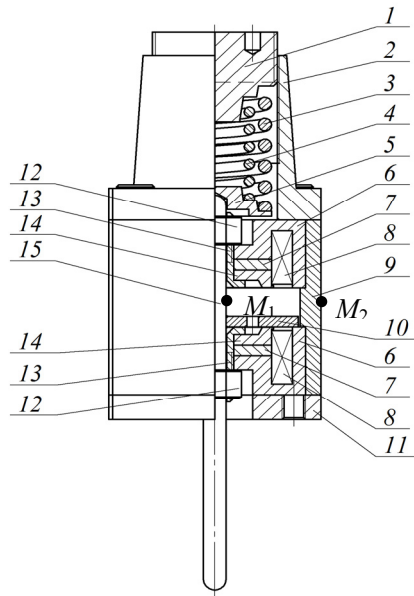


Figure 7. Electromagnetic valve actuator of a gas distribution mechanism

1 –adjusting screw; 2 – upper flange; 3 – external valve spring; 4 – internal valve spring; 5 – stop; 6 – solenoid mounting plate; 7 – constant magnet; 8 – coil; 9 – housing; 10 – anchor; 11 – lower flange; 12 – nut; 13 – bush; 14 – hub; 15 – rod

Unknown parameters in our case are equivalent coefficients of heat transfer λ_{eq} , specific heat capacity c_{eq} and equivalent density ρ_{eq} of the coils 8, as well as a heat emission coefficient α of the housing 9. Other parameters are known.

To solve an inverse heat transfer problem on a trial actuator and the time interval $[0, t_e]$ functions $T_*(M_1, t)$ in the point M_1 with the relative error $\delta(T_*(M_1))$ and heat flux density $q_*(M_2, t)$ in the M_2 with the relative error $\delta(q_*(M_2))$ are measured (Figure 7).

The inverse problem shall be solved using the following algorithm. We shall select initial values $\lambda_{eq}^{(0)}$, $c_{eq}^{(0)}$,

$\rho_{eq}^{(0)}$. Then, we solve the system (10), (12) and find the function to be minimized:

$$J^{(n)} = \sum_{j=1}^p \beta_1 \left(\frac{T_j^{(n)}(M_1) - T_{j*}(M_1)}{T_{j*}(M_1)} \right)^2 + \beta_2 \left(\frac{q_j^{(n)}(M_2) - q_{j*}(M_2)}{q_{j*}(M_2)} \right)^2, \quad (12)$$

where β_1, β_2 – weight factors, $\beta_1 = 1/3$; $\beta_2 = 2/3$; $T_j^{(n)}(M_1) = T^{(n)}(M_1, t_j)$; $q_j^{(n)}(M_2) = q^{(n)}(M_2, t_j)$; $T_{j*}(M_1) = T_*(M_1, t_j)$; $q_{j*}(M_2) = q_*(M_2, t_j)$; t_j – point of time on the interval $[0, t_e]$; p – number of j^{th} points on the interval $[0, t_e]$.

Then, we shall check the condition

$$J^{(n)} \leq \delta_{\max}^2, \quad (13)$$

where $\delta_{\max} = \max[\delta(T_*(M_1)), \delta(q_*(M_2))]$.

If the condition (13) is satisfied, the problem is solved. If not, then new values of the desired variables shall be found using a gradient method of minimizing the function (12), and we shall go to the start of the algorithm.

Let us consider using the described algorithm to solve an inverse heat transfer problem for the given actuator, (Figure 8): $D_{\text{ext}} = 56$ mm; $h_{\text{em}} = 49$ mm; $h = 65$ mm; $H = 108.5$ mm.

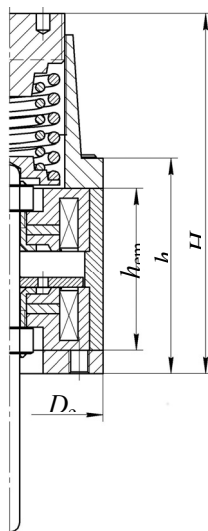


Figure 8. Main dimensions of the actuator

Design of the actuator, its dimensions, properties of the accessories (ρ, c, λ – density, specific heat capacity, heat transfer coefficient), except for the same parameters of the coils δ , relative errors of the temperature measurement $\delta(T_*(M_1))$ and the heat flux density $\delta(q_*(M_2))$ are known.

The actuator parts: 1 – 6, 10 – 12, 14, 15 are made from steel (grade 1010); 7 – NdFe35; 8 – copper; 9 – aluminum; 13 – brass.

Testo 922 is used to measure temperature, relative error of the temperature measurement $\delta(T_*(M_1)) = 1\%$, ITP–MG4.03/3(1) Potok is used to measure heat flux density, relative error $\delta(q_*(M_2)) = 6\%$.

As the result of the solution of the inverse heat transfer problem the following parameters are defined:

$\lambda_{\text{eq}} = 0.03$ W/(m·K); $c_{\text{eq}} = 164$ J/(kg·K); $\rho_{\text{eq}} = 6800$ kg/(m³); $\alpha = 18$ W/(m²·K). Figures 8 and 9 show the

functions on the time interval $[0.3 \times 10^3 \text{ s}]$: 1 – experimental data; 2 – data received from the calculation using

λ_{eq} , c_{eq} , ρ_{eq} and α . The standard deviation $T_*(M_1, t)$ of experimental data is 2.7 %. The standard deviation $q_*(M_2, t)$ of experimental data is 5.7 %.

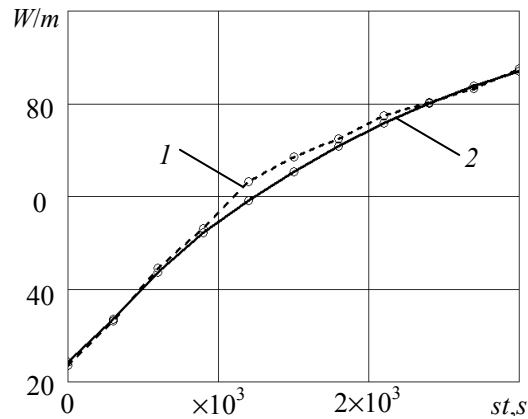


Figure 9. Results of temperature measurement and calculation in the point M_1

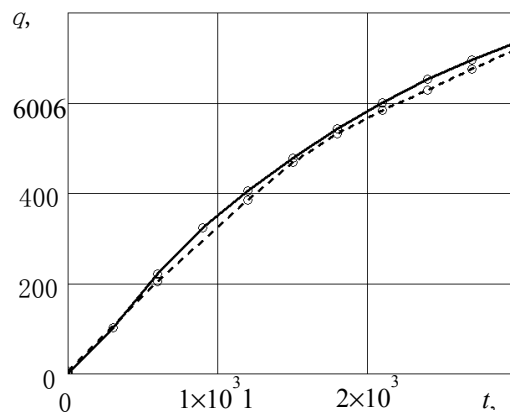


Figure 10. Results of heat flux density measurement and calculation in the point M_2

The undertaken studies of the heat transfer processes in the actuator using the developed model showed that at the ambient temperature of 150 °C, actuating pulses with the duration of 0.5 ms, the pulse period of 9.5 ms and the maximum current amplitude of 116 A, the temperature of the actuator winding in the steady-state is 196 °C and the temperature limit for such insulation class is 200 °C.

4. Conclusions

The results of the conducted study show that thermophysical parameters and temperature distribution in non-stationary and steady-state operating conditions of electrical devices may be evaluated with adequate efficiency based on the solution of inverse heat transfer problems.

The developed model and algorithm allow defining maximum temperature of a device as well decreasing time on thermal testing and electric power consumption.

It is planned that further studies will consider internal convection in a heat transfer model, and will help optimize the structure and the operating parameters of electric devices based on the obtained results.

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