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Investigation of Thermomechanical Processes in Rods Made of Heat-resistant Material, Taking into Account the Presence of Local Thermal Insulation, Temperature, Heat Exchange and Internal Point Heat Sources

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ABSTRACT

The paper presents the developed methods for the formation of functionals characterizing the energy conservation laws, considering the presence of local thermal insulation, temperature, heat exchange and internal point heat sources in rods of heat-resistant materials. The methods developed are based on the application of the energy conservation law in the new formulation of the problem. Studies have been carried out on the application of the energy conservation law to determine the temperature field in a rod made of heat-resistant material with simultaneous exposure to local temperatures, heat exchanges, internal point heat sources and local thermal insulation. The nonlinear thermomechanical state of a rod made of a high-temperature alloy was studied considering the above conditions. At the end of the work, the technique for implementing the developed method was presented on the personal computer using Python program.

Keywords : Heat Exchange, Internal Point Heat Sources, Local Heat Insulation, Rod Made of Heat-Resistant Material, Thermomechanical Processes.

I. INTRODUCTION

This article is a continuation of the work published this year in the Indian International Journal of Engineering Research and Science [1]. In this paper, the authors considered methods and methodologies for studying rods from heat-resistant alloys, especially the study of the dependence of the coefficient of thermal expansion on temperature. Methods were developed for considering the presence of local surface heat exchanges, temperatures, and internal point heat sources in the study of rods of high-temperature alloys.

Considering that the general review of the state of the problem was described in [1], it was decided to skip this information and proceed immediately to the essential issues of this article. Below, a brief review of recent research carried out in recent years will be presented, which deals only with the subject matter of this article.

II. BRIEF OVERVIEW OF PREVIOUSLY STUDIED RESEARCHES

In work [2] optimization of a double-tubed spiral heat exchanger with various optimization parameters was carried out and its comparison with a tube with and a double tube was performed. At the same time, the authors used the ANSYS FLUENT 14 Computational Fluid Dynamics package for numerical studies. The optimization parameters were the shape of the cross section and the cone angles. Optimization was carried out to find the best shape of the cross-section of heat exchangers using rectangular, square, triangular and circular cross sections.

In work [3] the problem of non-stationary heat conductivity of a hollow orthotropic sphere with internal and external radii is considered, under the assumption that the material of the ball under consideration is orthotropic in terms of thermal properties and the main directions of thermal conductivity coincide with the main geometric directions.

The authors of the following paper obtained exact analytical solutions of nonstationary heat conduction problems by orthogonal methods for an infinite plate under symmetric boundary conditions of the first kind [4]. To obtain such results, the authors based on the joint application of previously known orthogonal methods of L.V. Kantarovich, Bubnov-Galerkin, and the integral method of heat balance.

The numerical solution of the nonlinear nonstationary heat conduction problem for determining the temperature field in a multilayer plate with internal heat sources is considered in the work [5]. In the proposed model, the author considers the dependence of the thermal conductivity on temperature, and simulates radiation at the boundaries of the plate. An implicit two-layer scheme for the sweep method is presented. The discretization of the nonstationary heat equation is carried out using a locally one-dimensional, absolutely stable scheme. At the end of the paper, the results of calculation using computer programs are presented.

An analysis of the results of research in this field of science over the past two years has shown their successful application in solving applied problems in engineering. For example, in the work [6] a numerical-analytical solution of the non-stationary heat conduction problem in building structures was obtained. The author of this work has constructed a discrete-continuum mathematical model of a non-stationary, heterogeneous thermal field on the basis of the theory of generalized and characteristic functions. A technique and algorithm for the numerical and analytical solution of the nonstationary heat conduction problem with approximation by spatial arguments using the method of finite differences, including, on an orthogonal discrete grid, on the basis of the positions of the theory of matrix functions, are also developed. Software implementation of the received decisions is carried out.
In the work of the authors of the St. Petersburg National Research University of Information Technologies, Mechanics and Optics, the formulation and solution of the combined (boundary and coefficient) inverse heat conduction problem are considered in order to simultaneously determine the thermos-physical characteristics of the material and the density of the heat flux entering the heat receiver [7]. The solution is based on the parameterization of this task and the use of Kalman's advanced digital filter. Results of simulation modeling of simultaneous heat flux recovery and heat conduction in one experiment on measuring surface temperature are presented. The work of the author [8] can be considered as the closest by the scientific and theoretical essence and by the results obtained, where a mathematical model was constructed that allows describing and determining heat fluxes and temperature fields of stationary and non-stationary thermal processes occurring in systems of curvilinear inhomogeneous contacting rods. On the basis of the studies carried out, solutions of stationary and nonstationary heat conduction equations are determined based on the simplest planar and spatial geometric graphs with boundary conditions of I, II, and III type by the Fourier method using the Beltrami-Berss formalism. Methods for constructing a heat conductivity matrix for an arbitrary system of rods are developed. The methodological basis of this work, as can be seen, is the application of graph theory.

A) Conclusions and statement of the problem

Analyzing the above small overview of the current state of research results in the field of non-stationary nonlinear thermomechanical processes in typical objects of various configurations, the following conclusions can be made:
- the methodology of modern research must necessarily include a numerically-analytical solution of the non-stationary problem with the use of mathematical modeling methods, as well as a program for implementing computer calculations based on the models developed;
- despite the relevance and novelty of the results of earlier studies carried out in recent years, studies on the application of the energy conservation law to determine the temperature field in rods of heat-resistant material, which should consider the simultaneous effects of local temperatures, heat exchanges, internal point heat sources and local thermal insulation has not been carried out by anybody. In this case, an investigation of the nonlinear thermomechanical state of a rod made of a high-temperature alloy taking into account the above-mentioned conditions is of independent interest.

III. THE METHOD OF SOLVING THE ASSIGNED PROBLEM AND DISCUSSION OF THE RESULTS

A) Determination of the temperature field in a rod made of heat-resistant material with simultaneous exposure to local temperatures, heat exchanges,

internal point heat sources and local thermal insulation

Consider a horizontal rod (Fig. 16) of limited length h $[cm]$ and a cross-sectional area F $[cm^2]$ that is constant along its length. The lateral surface of the test rod is partially insulated. For example, if you point the axis OX horizontally along the axis of the rod from left to right, then the lateral surface of the $0 \le x \le l = \frac{L}{2}$ rod section is thermally insulated. Through the lateral surface of the section $\frac{L}{2} \le x \le L$, and also through the cross-sectional area of the right end of the rod, heat exchange takes place from the environment surrounding these areas. At the same time, the heat transfer coefficient is ν $\left[\frac{W}{cm^{2\,0}C}\right]$, and the ambient temperature is T_a $[{}^0C]$. In addition, the temperature at the left end is set to be $T(x=0)=\bar{\bar{T}}_1$. Also internal heat sources are set inside the rod $T\left(x=\frac{l}{2}\right)=\bar{\bar{T}}_2$. Where $l=\frac{L}{2}$ $[cm]$.

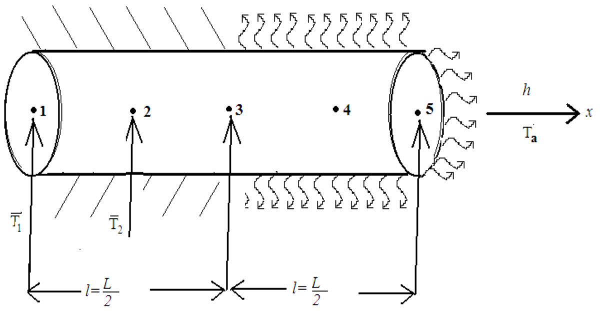

Figure 1. Calculation scheme for the rod at the half length of the occurring heat transfer

To form the functional characterizing the energy conservation laws, taking into account the simultaneous presence of heat sources in the investigated rod from a heat-resistant alloy, it is discretized by two elements of the same length l $[cm]$. In the first element, a predetermined external local temperature is $T(x=0)=\bar{\bar{T}}_1$, as well as inside the rod is $T\left(x=\frac{l}{2}\right)=\bar{\bar{T}}_2$. In addition, the lateral surface of this portion of the rod is thermally insulated. Therefore, no heat loss occurs through the lateral surface of this section of the rod. Now let's look at the second section of the rod $(\frac{l}{2} \le x \le L)$. Through the lateral surface of this section and through the cross-sectional area of the right end, heat exchange takes place with the surrounding medium. Given these steady processes, a functional that characterizes the energy conservation law is formulated. For the first segment of the rod
$(0 \le x \le l)$ such a functional has the following form:

$$J_1 = \int_{V_1} \frac{k_{xx}}{2}\left(\frac{\partial T}{\partial x}\right)^2 dv = \frac{Fk_{xx}}{6l}\begin{pmatrix} 7\bar{\bar{T}}_1^{\,2} - 16\bar{\bar{T}}_1\bar{\bar{T}}_2 + 2\bar{\bar{T}}_1 T_3 - \\ -16\bar{\bar{T}}_2 T_3 + 16\bar{\bar{T}}_2^{\,2} + 7T_3^2 \end{pmatrix},$$

$$0 \le x \le l \qquad (1)$$

where V_1 – the volume of the first discrete element of the test rod; T_3 - the value of the temperature t in the cross-section of the rod $(x=l)$. Its value is still unknown. Now let's pass to the second discrete element of the rod. This element differs from the first discrete element of the rod in that convective heat transfer occurs from the surrounding areas of the medium through the lateral surface and through the cross-sectional area of the right end. Given these steady-state heat transfer processes for the second discrete element of the rod under investigation, the functional expression that characterizes the energy conservation law will have the following form

$$J_2 = \int_{v_2} \frac{k_{xx}}{2}\left(\frac{\partial T}{\partial x}\right)^2 dv + \int_{S_{2lsa}} \frac{h}{2}(T-T_a)^2 ds + \int_{S(x=L)} \frac{h}{2}(T-T_a)^2 ds =$$
$$= \frac{Fk_{xx}}{6l}\left(7T_3^2 - 16T_3T_4 + 2T_3T_5 - 16T_4T_5 + 16T_4^2 + 7T_5^2\right) +$$
$$+ \frac{Phl}{30}\begin{pmatrix} 2T_3^2 + 2T_3T_4 - T_3T_5 + 8T_4^2 + 2T_5^2 + 2T_4T_5 - 5T_3T_a - \\ -20T_4T_a - 5T_5T_a + T_a^2 \end{pmatrix} +$$
$$+ \frac{Fh}{2}(T_5 - T_a)^2, \quad l \le x \le L \qquad (2)$$

where V_1 – the volume of the second discrete element of the test rod; S_{2lsa}- the lateral surface area of the second discrete element of the rod; $S(x=0)$ - the cross-sectional area of the right end of the rod; P - perimeter of rod cross-section; T_3, T_4 и T_5 the values of the temperatures in the sections $\left(x=l, x=\frac{3l}{2}, x=L\right)$ respectively. Their values are still unknown. Then the general functional that characterizes the energy conservation law for the investigated rod as a whole has the following form:

$$J = J_1 + J_2 = \frac{Fk_{xx}}{6l}(7\overline{T}_1^2 - 16\overline{T}_1\overline{T}_2 + 2\overline{T}_1 T_3 - 16\overline{T}_2 T_3 +$$
$$+16\overline{T}_2^2 + 7T_3^2) + \frac{Fk_{xx}}{6l}(7T_3^2 - 16T_3T_4 + 2T_3T_5 - 16T_4T_5 +$$
$$+16T_4^2 + 7T_5^2) + \frac{Phl}{30}(2T_3^2 + 2T_3T_4 - T_3T_5 + 8T_4^2 + 2T_5^2 +$$
$$2T_4T_5 - 5T_3T_a - 20T_4T_a - 5T_5T_a + T_a^2) + +\frac{Fh}{l}(T_5 - T_a)^2 \quad (3)$$

Further minimizing J with respect to the unknown nodal temperature values T_3, T_4 and T_5 we obtain the following system of linear algebraic equations with natural boundary conditions

$$\frac{\partial J}{\partial T_3} = 0; \Rightarrow \frac{Fk_{xx}}{6l}(2\overline{T}_1 - 16\overline{T}_2 + 14T_3 + 14T_3 -$$
$$-16T_4 + 2T_5) + \frac{phl}{30}(4T_3 + 2T_4 - T_5 - 5T_a) = 0$$
$$\frac{\partial J}{\partial T_4} = 0; \Rightarrow \frac{Fk_{xx}}{6l}(-16T_3 - 16T_5 + 32T_4) + \frac{phl}{30}(2T_3 +$$
$$+16T_4 + 2T_5 - 20T_a) = 0$$

$$\frac{\partial J}{\partial T_5} = 0; \Rightarrow \frac{Fk_{xx}}{6l}(2T_3 - 16T_4 + 14T_5) + \frac{phl}{30}(-T_3 + 14T_5 +$$
$$+2T_4 - 5T_a) + FhT_5 - FhT_a = 0 \quad (4)$$

After a slight simplification from the latter system of equations:

$$\left.\begin{aligned}
&\left(14 + \frac{2phl^2}{5Fk_{xx}}\right)T_3 + \left(\frac{phl^2}{5Fk_{xx}} - 8\right)T_4 + \left(1 - \frac{phl^2}{10Fk_{xx}}\right)T_5 = \\
&= \frac{phl^2}{2Fk_{xx}}T_a - \overline{T}_1 + 8\overline{T}_2 \\
&\left(\frac{phl^2}{5Fk_{xx}} - 8\right)T_3 + \left(16 + \frac{8phl^2}{5Fk_{xx}}\right)T_4 + \left(\frac{phl^2}{5Fk_{xx}} - 8\right)T_5 = \\
&= \frac{2phl^2}{Fk_{xx}}T_a \\
&\left(1 - \frac{phl^2}{10Fk_{xx}}\right)T_3 + \left(\frac{phl^2}{5Fk_{xx}} - 8\right)T_4 + \left(7 + \frac{2phl^2}{5Fk_{xx}}\right)T_5 + \frac{phl}{k_{xx}}T_5 = \\
&= \left(\frac{phl^2}{2Fk_{xx}} + \frac{3hl}{k_{xx}}\right)T_a
\end{aligned}\right\} \quad (5$$

For the final solution of the system obtained, introducing the following designations:

$$a_{11} = \left(14 + \frac{2phl^2}{5Fk_{xx}}\right);\ a_{12} = \left(\frac{phl^2}{5Fk_{xx}} - 8\right);$$
$$a_{13} = \left(1 - \frac{phl^2}{10Fk_{xx}}\right);\ b_1 = \frac{phl^2}{2Fk_{xx}}T_a - \overline{T}_1 + 8\overline{T}_2;$$
$$a_{11} = \left(16 + \frac{8phl^2}{5Fk_{xx}}\right);\ b_2 = \frac{2phl^2}{Fk_{xx}}T_a;$$
$$a_{33} = \left(7 + \frac{2phl^2}{5Fk_{xx}}\right) + \frac{3hl}{k_{xx}};\ b_3 = \left(\frac{phl^2}{2Fk_{xx}} + \frac{3hl}{k_{xx}}\right)T_a;$$

$$\left.\begin{aligned}
a_{11}T_3 + a_{12}T_4 + a_{13}T_5 &= b_1 \\
a_{12}T_3 + a_{22}T_4 + a_{12}T_5 &= b_2 \\
a_{13}T_3 + a_{12}T_4 + a_{33}T_5 &= b_3
\end{aligned}\right\} \quad (6)$$

For the initial data, let's take:

$$l = 10cm;\ L = 2l = 20cm;$$
$$k_{xx} = 100\frac{W}{cm^0C};\ h = 10\frac{W}{cm^{2\,0}C};$$
$$T_a = 40^0C;\ \overline{T}_1 = 200^0C;\ \overline{T}_2 = 150^0C;$$
$$r = 1cm;\ F = \pi r^2 = \pi cm^2;\ p = 2\pi r = 2\pi cm.$$

With these initial data, the last system has the following form:

$$\begin{aligned}
22T_3 - 4T_4 - T_5 &= 2150 \\
T_3 - 12T_4 + T_5 &= -200 \\
T_3 + 4T_4 - 18T_5 &= -520 \quad (7)
\end{aligned}$$

Solving for (7) it is found that:

$$T_3 \approx 104.84℃; T_4 \approx 28.83℃, T_5 = 41.12℃$$

Then the law of the temperature distribution along the length of the first discrete element of the investigated rod is determined as follows:

$$T^{(I)}(x) = \varphi_i(x)\overline{T_1} + \varphi_j(x)\overline{T_2} + \varphi_k(x)\overline{T_3} =$$
$$= \frac{1}{l^2}[(2x^2 - 30x + 100)\cdot 200 +$$
$$+(40x - 4x^2)\cdot 150 + (2x^2 - 10x)\cdot 104.84] =$$
$$= \frac{1}{100}[(400 - 600 + 209.68)x^2 +$$
$$+(6000 - 6000 - 1048.4)x + 20000] =$$
$$= \frac{1}{100}(9.68x^2 - 1048.4x + 2000) =$$
$$= 0.0968x^2 - 10.484x + 20;\ 0 \le x \le l. \ (8)$$

Similarly, the law of temperature distribution along the length of the second part of the investigated rod is determined by the following equation:

$$T^{(II)}(x) = \varphi_i(x)T_3 + \varphi_j(x)T_4 + \varphi_k(x)T_5 =$$
$$= \frac{1}{l^2}[(2x^2 - 30x + 100)\cdot 104.84 +$$
$$+(40x - 4x^2)\cdot 28.83 + (2x^2 - 10x)\cdot 41.12] =$$
$$= \frac{1}{100}[(209.68 - 115.32 + 82.24)x^2 +$$
$$+(1153.2 - 3045.2) - 411.2)x + 10484] =$$

$$= \frac{1}{100}(176.6x^2 - 2303.2x + 10484) =$$
$$= 1{,}766x^2 - 23.032x + 104.84;$$
$$0 \le x \le l. \quad (9)$$

B) Investigation of the nonlinear thermomechanical state of a rod made from a heat-resistant alloy with simultaneous presence of local and internal point

temperatures of local heat insulation and heat transfer

In earlier studies [1] the first problem was solved. The purpose of which was to determine the temperature field along the length of the rod from the heat-resistant alloy with simultaneous presence of local and internal point sources of heat, local heat insulation and heat exchange. Now let's proceed to the solution of the second problem. If the left end of the test rod is rigidly clamped, and the right end is free, then it is lengthened because of the presence of dissimilar heat sources. The second task is to determine the elongation value of the test rod. It is determined in accordance with the fundamental laws of thermophysics:

$$\Delta l_T = \int_0^l \alpha T(x)dx.$$

In the general case, the values of α - for different materials and at different temperatures will be different. These dependences are determined experimentally. If the average value of α for the core of the heat-resistant alloy is taken as $\alpha = 125 \cdot 10^{-7} \frac{1}{℃}$, then for the temperature distribution laws found, the magnitude of the rod extension is determined as follows:

$$\Delta l_T = \int_0^l \alpha T^{(I)}(x)dx + \int_0^l \alpha T^{(II)}(x)dx = = \frac{\alpha l}{6}(T_1 + 4T_2 + T_3) + \frac{\alpha l}{6}(T_3 + 4T_4 + T_5) = = \frac{\alpha l}{6}(T_1 + 4T_2 + 2T_3 + 4T_4 + T_5) = = \frac{0.000125}{6}(200 + 4 \cdot 150 + 2 \cdot 104.84 + 4 \cdot 28.82 + 41.12) = \frac{0.000125}{6}(200 + 600 + +209.68 + 115.28 + 41.12) = \frac{0.000125}{6} \cdot \cdot 1166.08 = 0.024293\ cm. \quad (10)$$

Next, let's proceed to the solution of the third problem. Suppose that both ends of the rod under investigation are rigidly clamped. Then, because of the presence of dissimilar heat sources in the investigated rod of the heat-resistant material, there is an axial compressive force R [kg]. The calculation scheme of the third problem is given in Figure 17.

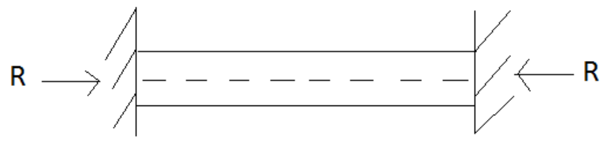

Figure 17. The calculations scheme of the problem for determining the compressive force

The magnitude of the resulting compressive force is determined from the solution of the corresponding statically indeterminate problem with the use of the compatibility condition of deformation.

$$\frac{RL}{EF} + \Delta l_T = 0; => R = -\frac{\Delta l_T EF}{\alpha} \qquad (11)$$

If it is considered that $F = \pi r^2 = \pi\ cm^2$; $E = 2 \cdot 10^6\ \frac{kg}{cm^2}$; $L = 20\ cm$, then for the considered problem the magnitude of the resulting axial compressive force is determined as follows:

$$R = -\frac{0.024293 \cdot 2 \cdot 10^6 \pi}{20} = -7628.002\ kg. \quad (12)$$

Obviously, this value is relatively large. Now the solution to the next fourth problem can be found. Its aim is to determine the field of the thermoelastic stress *σ (x)*. It is determined in accordance with the Hooke's law:

$$\sigma = \frac{R}{F} = \frac{\Delta l_T E}{\alpha} = -\frac{0.024293 \cdot 2 \cdot 10^6}{20} = -2429.3\ \frac{kg}{cm^2} \qquad (13)$$

Obviously, this value of the thermoelastic stress is not small. Then let's proceed to the solution of the fifth problem. Its purpose is to determine the distribution field of the thermoelastic strain *ε (x)* along the length of the investigated rod from the heat-resistant alloy. It is determined from the corresponding type of Hooke's law:

$$\sigma = E\varepsilon => \ \varepsilon = \frac{\sigma}{E} = -\frac{\Delta l_T}{\alpha} = -\frac{0.024293}{20} = -0.0012. \qquad (14)$$

It is seen from (13) and (14) that the character of σ and ε will be compressive, i.e. they are negative along the entire length of the investigated rod. Now let's turn to the solution of the sixth problem. This problem is about determining the field of the temperature component of the deformation along the length of the investigated rod from the heat-resistant alloy. It is determined from the fundamental relationships of thermophysics:

$$\varepsilon_T^{(I)}(x) = -\alpha T^{(I)}(x) = -\alpha(0.0968x^2 - -10.484x + 200), \quad 0 \le x \le l,$$

where $\alpha = 125 \cdot 10^{-7} \frac{1}{°C}$;

$$\varepsilon_T^{(II)}(x) = -\alpha T^{(II)}(x) = -\alpha(1.766x^2 - -24.032x + 104.84),\ 0 \le x \le l$$

or finally having that

$$\varepsilon_T^{(I)}(x) = -0.00000121x^2 + 0.00013105x - -0.00025, \quad 0 \le x \le l \quad (15)$$

$$\varepsilon_T^{(II)}(x) = -0.00002275x^2 + 0.0002879x - -0.0013105, \quad 0 \le x \le l.$$

Now using (15) the solution of the seventh problem can be found. Its aim is to determine the field of distribution of the temperature component of the stress $\sigma_T(x)$ along the length of the investigated rod, it is determined proceeding from the corresponding Hooke's law:

$$\sigma_T^{(I)}(x) = E\varepsilon_T^{(I)}(x) = (-2.42x^2 + 262.1x - -500), \left[\frac{kg}{cm^2}\right],\ 0 \le x \le l \quad (16)$$

$$\sigma_T^{(II)}(x) = E\varepsilon_T^{(II)}(x) = (-44.15x^2 + 575.8x - -2621), \left[\frac{kg}{cm^2}\right],\ 0 \le x \le l.$$

Next, proceeding to the solution of the eighth problem of determining the distribution field of the elastic component of the strain $\varepsilon_x(x)$ along the length of the investigated rod of the high-temperature alloy. It is determined from the fundamental theory of thermomechanics.

$$\varepsilon_x^{(I)}(x) = \varepsilon - \varepsilon_T^{(I)}(x) = -0.00145 + +0.00000121x^2 - 0.00013105x,\ 0 \le x \le l$$

$$\varepsilon_x^{(II)}(x) = -0.0025105 + 0.000022075x^2 - -0.0002879x, \quad 0 \le x \le l. \quad (16^*)$$

After this solution for the next ninth problem is found. Its aim is to determine the distribution field of the elastic component of stress $\sigma_x(x)$ along the length of the investigated rod. It is determined on the basis of the corresponding Hooke's law $\sigma_x(x) = E\varepsilon_x$. Then we have:

$$\sigma_x{}^{(I)}(x) = E\varepsilon_x{}^{(I)}(x) = -2900 + 2.42x^2 - -262.1x,\ 0 \le x \le l$$

$$\sigma_x{}^{(II)}(x) = E\varepsilon_x{}^{(II)}(x) = -5021 + 44.15x^2 - -575.8x,\ 0 \le x \le l \quad (17)$$

Finally, let's proceed to the solution of the last tenth problem of determining the displacement field along the length of the investigated rod from a heat-resistant alloy. It is determined from the general Cauchy relations

$$\varepsilon_x = \frac{\partial u}{\partial x}; => u = \int \varepsilon_x dx.$$

From here is follows that:

$$u^{(I)}(x) = \int \varepsilon_x{}^{(I)}(x)dx = \int[-0.00145 + +0.00000121x^2 - 0.00013105x]dx = = -0.00145x + 0.00000121\frac{x^3}{3} - -0.00013105\frac{x^2}{2} + C,\ 0 \le x \le l\ . \quad (18)$$

Here C is the integration constant. It is determined from the boundary condition $U(x=0)$. Since the left and right ends of the test rod are rigidly clamped, then $U(x=0)=0$. So we have

$$u^{(I)}(x=0) = -0.00145 \cdot 0 + = +0.00000125 \cdot \frac{0}{3} - 0.00013105 \cdot \frac{0}{2} + C = 0.$$

From here is found that $C = 0$. Then

$$u^{(I)}(x) = -0.00145x + 0.00000125\frac{x^3}{3} - -0.00013105\frac{x^2}{2};\ 0 \le x \le l\ . \quad (19)$$

Now let's proceed to the second section of the rod:

$$u^{(II)}(x) = \int \varepsilon_x{}^{(II)}(x)dx = \int[-0.0025105 + +0.000022075x^2 - 0.0002879x]dx = -0.0025105 + 0.000022075\frac{x^3}{3} - -0.0002879\frac{x^2}{2} + C.$$

Here the integration constant C is determined from the condition of continuity of the displacement during the transition from the first section to the second section of the rod, that is:

$$u^{(I)}(x=l) = u^{(II)}(x=0).$$

$$u^{(I)} = -0.0145 + 0.000416 - 0.0065525 = C.$$

It follows that

$$C = -0.0206358.$$

Then the law of distribution of displacement along the length of the second section of the rod will be determined by the following formula:

$$u^{(II)}(x) = -0{,}0206358 - 0{,}0025105x + +0{,}000022075\frac{x^3}{3} - 0{,}0002879\frac{x^2}{2}, \quad 0 \le x \le l\ . \quad (20)$$

C) Implementation of the developed method for the formation of functionals that characterize the law of conservation of energy, taking into account the simultaneous presence of local thermal insulation, temperatures, heat exchanges and internal heat sources on the personal computer using the Python programs

The programming package developed in the Python language made it possible to show the distribution laws of the following functions along the length of the rod of the heat-resistant alloy clamped by two ends of the heat-resistant alloy: temperature (Figure 2), stresses (Figure 19), elastic, temperature and thermos-elastic deformation components (Figure 20), and displacement (Figure 3). These laws are presented in the form of graphs. Each of these graphs shows the corresponding Python program, which is implemented on a personal computer. From the obtained graphs it is clear that they correspond to the formulation of the problem. From them one can judge the nonlinear thermos-physical processes that arise in the investigated rod. From these graphs, one can also assess the adequacy of the developed model.

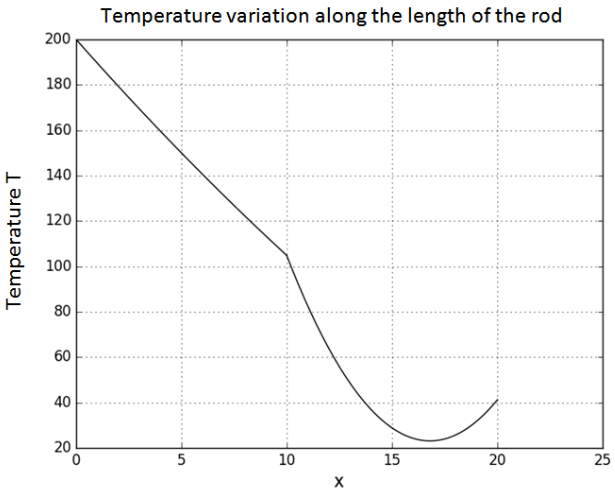

Figure 2. Temperature variation along the length of the rod with simultaneous
availability of heterogeneous heat sources

1) Temperature for 2 intervals

```
import matplotlib.pyplot as plt
import numpy as np
lag1=0.01
lag2=0.01
x1 = np.arange(0.0, 10+lag1, lag1)
x2 = np.arange(10, 20+lag2, lag2)
def func1(x):
return  0.0968*x*x-10.484*x+200
def func2(x):
return -24.03*(x-10)+1.766*(x-10)*(x-10)+104.84
fig = plt.figure()
plt.plot(x1, func1(x1),x2,func2(x2),color="k")
plt.title(u" Temperature variation along the length of the rod",{'fontname':'Arial','fontsize':16})
plt.ylabel(u"Temperature T",{'fontname':'Arial','fontsize':16})
plt.xlabel(u" x ",{'fontname':'Arial','fontsize':16})
plt.grid(True)
plt.show()
```

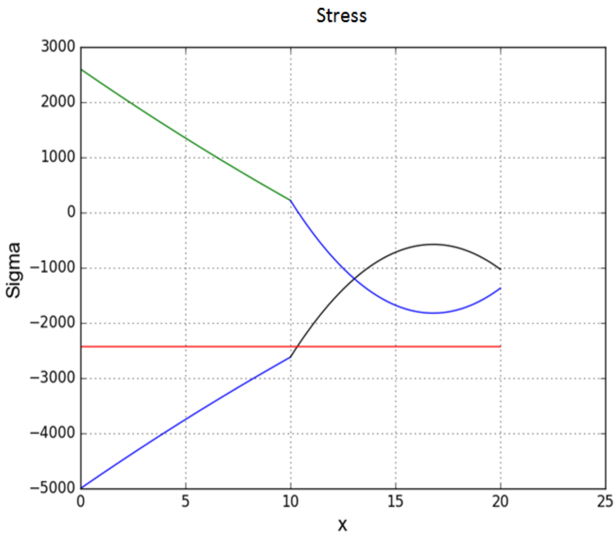

Figure 3. Stress variation with simultaneous presence of dissimilar heat sources

2) Stress for the 2 intervals

```
import matplotlib.pyplot as plt
import numpy as np
lag1=0.01
lag2=0.01
x1 = np.arange(0.0, 10+lag1, lag1)
x2 = np.arange(10, 20+lag2, lag2)
x3 = np.arange(0, 20+lag2, lag2)
def func1(x):
return  -2.42*x*x+262.1*x-5000
def func2(x):
return -44.15*(x-10)*(x-10)+600.8*(x-10)-2621
def func3(x):
return -2429.3*(x-x+1)
def func4(x):
return  2.42*x*x-262.1*x+2600
def func5(x):
return 44.15*(x-10)*(x-10)-600.8*(x-10)+221
fig = plt.figure()
plt.plot(x1, func1(x1),x2,func2(x2),'k',
x1, func4(x1),x2,func5(x2),'b',
x3,func3(x3),'r')
plt.title(u"Stress",{'fontname':'Arial','fontsize':16})
plt.ylabel(u"Sigma",{'fontname':'Arial','fontsize':16)
plt.xlabel(u" x ",{'fontname':'Arial','fontsize':16})
plt.grid(True)
plt.show()
```

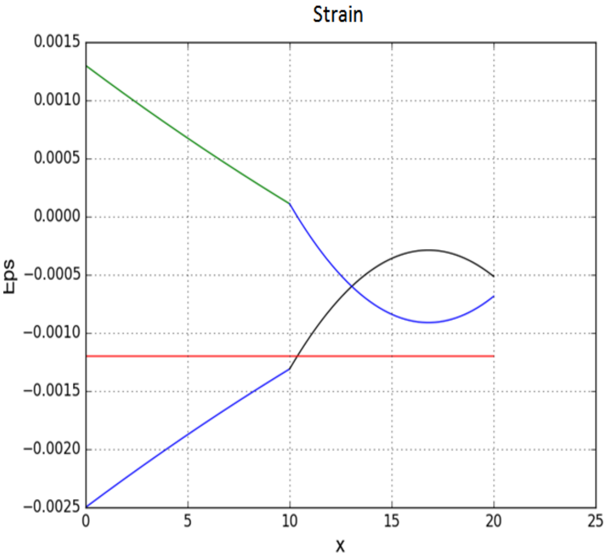

Figure 4. Strain variation with simultaneous presence of dissimilar heat sources

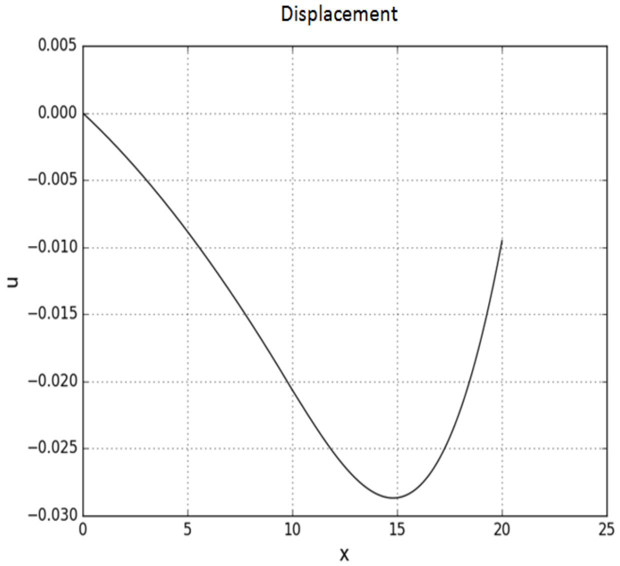

Figure 5. Displacement variation with simultaneous presence of heterogeneous heat sources

3) Strain for 2 intervals

```
import matplotlib.pyplot as plt
import numpy as np
lag1=0.01
lag2=0.01
x1 = np.arange(0.0, 10+lag1, lag1)
x2 = np.arange(10, 20+lag2, lag2)
x3 = np.arange(0, 20+lag2, lag2)
def func1(x):
return -0.00000121*x*x+0.00013105*x-0.0025
def func2(x):
return -0.000022075*(x-10)*(x-10)+0.0003004*(x-10)-
0.0013105
def func3(x):
return -0.0012*(x-x+1)
def func4(x):
return 0.0013+0.00000121*x*x-0.00013105*x
def func5(x):
return 0.0001105+0.000022075*(x-10)*(x-10)-
0.0003004*(x-10)
fig = plt.figure()
plt.plot(x1, func1(x1),x2,func2(x2),'k',
x1, func4(x1),x2,func5(x2),'b',
x3,func3(x3),'r')
plt.title(u"Strain",{'fontname':'Arial','fontsize':16})
plt.ylabel(u"Eps",{'fontname':'Arial','fontsize':16})
plt.xlabel(u" x ",{'fontname':'Arial','fontsize':16})
plt.grid(True)
plt.show()
```

4) Displacement for 2 intervals

```
import matplotlib.pyplot as plt
import numpy as np
lag1=0.01
lag2=0.01
x1 = np.arange(0.0, 10+lag1, lag1)
x2 = np.arange(10, 20+lag2, lag2)
def func1(x):
return-0.00145*x-
0.00013105*x*x/2+0.00000125*x*x*x/3
def func2(x):
return -0.0025105*(x-10)+0.000022075*(x-10)*(x-
10)*(x-10)/3+0.00002879*(x-10)*(x-10)*(x-10)-
0.0206358
fig = plt.figure()
plt.plot(x1, func1(x1),x2,func2(x2),color="k")
plt.title(u"Displacement",{'fontname':'Arial','fontsize':16
})
plt.ylabel(u"u",{'fontname':'Arial','fontsize':16})
plt.xlabel(u" x ",{'fontname':'Arial','fontsize':16})
plt.grid(True)
plt.show()
```

IV. CONCLUSION

Methods for the formation of functionals characterizing the energy conservation laws, taking into account the simultaneous presence of local thermal insulation, temperature, heat exchange and internal point heat sources in a rod of a heat-resistant alloy, limited in length, have been developed; A package of programs in the PYTHON language was developed allowing investigating the arising nonlinear thermo-physical state of the investigated rod; With the help of the developed programming package, graphs of the laws of temperature distribution, constituting stress and strain, as well as displacement along the length of the investigated rod are plotted; The obtained results can be the basis for further research of thermal processes inside a core of heat-resistant alloys, namely, for the development of a physic-mathematical model of the thermos-physical state of bodies in the presence of local thermal surface insulation.

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