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PROBLEMS OF NUMERICAL MODELING OF THE TEMPERATURE AND STRESS FIELDS IN THE STRUCTURES OF SFRE NOZZLE BLOCKS

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Consideration is given to approaches to numerical modeling of the distribution of temperatures and mechanical stresses in both thermally loaded and power elements of the nozzle blocks (NBs) of solid-fuel rocket engines (SFREs) that are stipulated by the structural features and employed materials. A typical NB design is analyzed for the strength of its individual units and the structure of the needed software is studied. Calculation examples are presented.

The most important structural element of a solid-fuel rocket engine, which makes up a significant portion in the overall mass of the SFRE and determines its general efficiency, is a nozzle block. At the present time, SFREs of the sustainer propulsion stages of ballistic rockets most commonly use structural schemes of NBs with a single central all-rotatable nozzle partly buried in the combustion chamber of the engine and placed in a special hermetic unit of the suspension device [1, 2]. The distinctive features of SFREs are as follows: the intricate geometry of their components, each of which performs a certain thermal protective or force function; a combined thermal and power load from the side of a highly agressive flow of the combustion products, which is variable over the time of the engine operation and over the component surfaces and leads to a change in the geometry of the "fire" surface as a consequence of the entrainment of materials of the surface layers; wide use, in this connection, of nonmetallic composite materials; the need for considering the contact interaction of structural components made of unlike materials; unfeasibility of an adequate strength try-out of thermally loaded nozzle components; the need for simultaneous compliance with the conflicting demands for high strength reliability and minimum mass of the structure.

Figure 1 presents a block diagram of the SFRE NB employed for studying a thermally stressed state of its elements. The inserted part of the nozzle experiences the most intense loading during the engine operation. As a rule, it is formed by axisymmetric components of various materials, among which it is possible to name graphites, carbon-carbon composites (CCCs), and carbon plastics (CPs) with different, mainly axisymmetric, reinforcement schemes. Elements of refractory alloys, for example, tungsten alloys, are frequently employed in the composite inserts. The external action on the components of the inserted part of the nozzle can be regarded as axisymmetric. Marked difficulties in studying individual components of the inserted part are caused by the boundary conditions that must be specified for modeling the interaction of the considered component with discarded structural elements. Therefore it seems reasonable to calculate a thermally stressed state of this unit using a computational scheme that includes the maximum possible number of components of the inserted part. Naturally, this computational scheme must account for the contact interaction of individual components and the presence of structural clearances and glue joints. Evidently, this computational scheme can also incorporate a divergent part of the nozzle that consists, as a rule, of a carbon-plastic lining, protecting the metal frame of the nozzle, and a thin-walled nozzle head made of CCC or refractory metal alloys. The effect of a load, exerted on the rotatable nozzle by a steering drive, on the distribution of thermal stresses in the lining can be considered as insignificant as a result of the high rigidity of the unit of transmission of the guiding force that is stipulated by structural considerations. Sometimes the divergent part of the nozzle, especially in the region of the head, is subjected to an external nonaxisymmetric action caused by the surroundings or operating condi-

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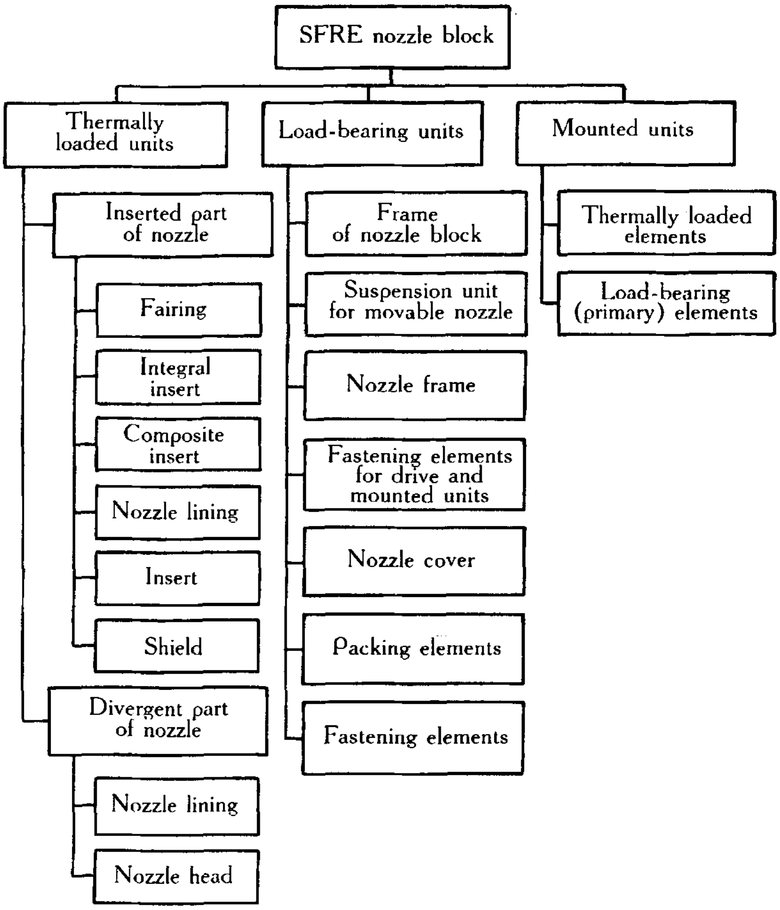


Fig. 1. Diagram of the thermal strength analysis of an SFRE NB.

tions. In this case, an individual computational scheme different from an axisymmetric one must be used for this part of the nozzle [3].

By load-bearing units of SFPE NB we will understand those structural elements for which thermal loads are either absent or insignificant. As a rule, these are specially thermally protected components or assembly units not interacting directly with the flow of combustion products. The frame of the nozzle block is a metal or composite structural element of an axisymmetric shape that is sometimes locally reinforced and subjected mostly to axisymmetric loads. The NB frame is used for connecting the movable nozzle to the engine case and carries practically all mounted elements. When a solid-wound engine case of the "cocoon" type is used, the NB frame interacts immediately with an insertion element (IE), to which it is fastened via the dowel or another joint. Because the connection of the SFRE frame and IF is not rigid, the latter can shift from the frame during the engine operation, thus setting up an additional load on the NB frame and tending to open the joint, which, in turn, causes additional loading of the dowel. It seems reasonable to study the NB frame using a computational scheme that incorporates the insertion element, SFRE frame, and dowels and is capable of modeling the contact interaction of the considered components and of determining the additional load on the fastening elements.

One of the most complex structural elements of an NB from the standpoint of studying the stressed-strained state is a suspension unit of the movable nozzle of the Flexseal type. It consists of spherical metal or composite plates divided by elastomer layers. The structure is loaded by the intrachamber pressure, and also by the compressive force and bending moment from the side of the nozzle. This system of loads can cause a breakdown and loss of stability of the plates, and also scaling and separation of the elastomer layers. Evidently, the computational scheme for the suspension unit must account for features peculiar to the behavior of the

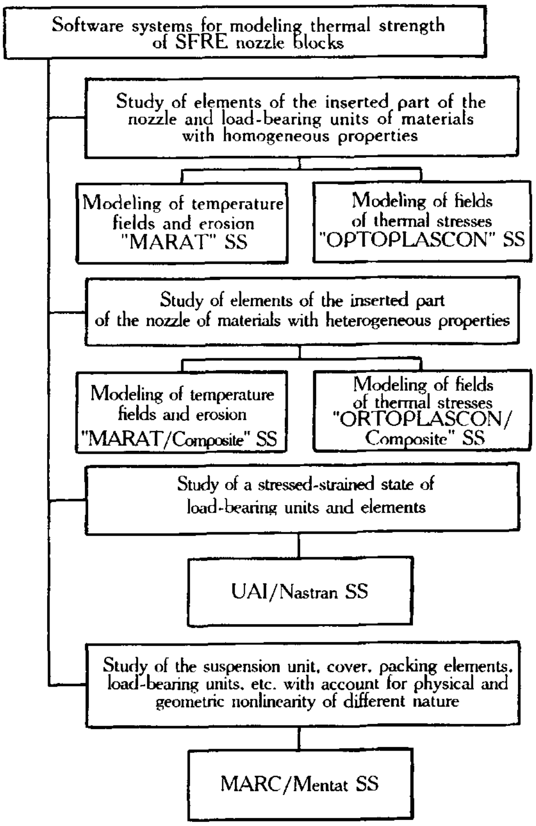


Fig. 2. Diagram of a specialized software.

material of the elastomer layers and geometric nonlinearity due to the great displacements and deviations from the initial unstrained configuration.

The aforementioned nozzle frame represents a metal or composite shell mated with the reinforcement elements and loaded with concentrated guiding forces and distributed loads from the side of the flow of the combustion products.

The stressed-strained state of the nozzle cover should be studied taking into account the dynamic character of its loading and features stipulated by the selected mechanism of its removal. However, in most cases one or another type of symmetry can be used.

The elements for fastening the drive and the mounted units to the NB can be of a very diversified structure. Here it is possible to use fairly original and nonstandard designs that are specified by a close-packed arrangement of the article. Still, the study of the stressed-strained state of such units basically does not differ from the approaches generally accepted in mechanical engineering and is complicated only by their geometry and a spatial character of loading.

Carbon-based composites, which are employed in the SFRE NB structures and interact with the flow of the combustion products, have some important features of thermal strain. Carbon-carbon composites and CPs are characterized by a significant temperature dependence and a high degree of anisotropy of thermophysical and physicomechanical properties. At the same time, they have the capacity for inelastic (pseudoplastic) strain and a different capacity to resist tension and compression, which are most pronounced at elevated temperatures. The analysis of the structures of composite materials now leans most heavily on the approach that represents these materials as a continuous medium with some effective characteristics determined for specimens cut out of the actual structures. In an overwhelming majority of cases such approach seems justified; however, it cannot be denied that it totally leaves out of account and cannot take into account processes that are linked to differences in the characteristics of the composite components and occur at the microlevel of individual acts of breakdown of the material. This problem is critical to thermally loaded materials and, specifically, carbon plastics. The matter is, that, in a high-rate heating, thermally decomposing materials, to which, in particular, CPs belong, undergo pyrolysis [4] with the formation of a solid residue (coke) and gaseous products. In accordance with the established practice, thermophysical and physicomechanical characteristics are identified for specimens in a thermally stable state that stipulates holding at the test temperature during the time needed for a uniform heating. Naturally, in this time all transient processes determining the thermal strain of the material during the article operation have already been completed, and as a result of such test we obtain characteristics that only remotely resemble the actual ones and entirely disregard high-rate transient processes.

The foregoing features of the employed materials indicate that the thermally stressed state of the SFRE NB elements can be studied efficiently only by numerical methods, among which the finite-element method (FEM) has recently become the most commonly used. Here it is possible to achieve utmost success by applying sufficiently universal software products, namely, software systems (SSs) provided with a developed user interface and oriented toward the operation in an interactive mode.

Figure 2 presents a block diagram of the specialized software for numerical modeling of the thermally stressed state of an SFRE NB, which is used in the educational and scientific process of the N. E. Bauman Moscow State Technical University.

Below we consider in detail the features of numerical modeling of the fields of thermal stresses in elements of the inserted part of the NB and in some load-bearing units, for which purpose "MARAT" [5] and "ORTOPLASCON" [6] SSs are employed. The system of equations in this case includes:

the equation of unsteady heat conduction

$$c\rho\dot{T} = (\lambda_{ij} T_{,j})_{,i} , \tag{1}$$

the balance equations

$$\sigma_{ij,j} + R_i = 0 , \tag{2}$$

and the Cauchy relations

$$\varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}) , \tag{3}$$

which employ the rule of summation over double indices running through the values from 1 to 3. Relations (1)-(3) are completed with unambiguity conditions, which consist of the initial temperature distribution at each point of the structure

$$T(x_i, 0) = T_0 \tag{4}$$

and boundary conditions

on the S_T surface

$$\lambda_{ij} T_{,j} n_i + \overline{\alpha}(T - \widetilde{T}_\infty) + \widetilde{\varepsilon}\,\widetilde{\sigma}(T^4 - \widetilde{T}_f^4) + \rho V_n Q = 0 , \tag{5}$$

on the S_σ surface

$$\sigma_{ij} n_j = \widetilde{p}_{S_i} , \tag{6}$$

and on the S_u surface

$$u_i \nu_i = \widetilde{u}_\nu . \tag{7}$$

Moreover, consideration is given to the surface of a possible contact of two bodies A and B, on which the following boundary conditions are imposed:

$$u_n^A - u_n^B \le \delta_n, \quad \sigma_n^A \le 0, \quad |\sigma_r^A| \le -\mu\sigma_n^A. \tag{8}$$

If there is a glue layer at the boundary of contact interaction, boundary conditions (8) are completed with the expressions

$$u_i^A = u_i^B \text{ for } 0 < \sigma_n^A \le [\sigma^+_{\text{glue}}] \text{ and } [\sigma_\tau^A] \le |\tau_{\text{glue}}|. \tag{9}$$

For closing the solved system of equations (1)-(9), it must be completed with the relations for loading parameters

$$R_i = R_i(t), \tag{10}$$

$$\tilde{\alpha} = \tilde{\alpha}(x_i, p^*, \ldots), \tag{11}$$

$$\tilde{T}_\infty = \tilde{T}_\infty(x_i, p^*, \ldots), \tag{12}$$

$$\tilde{\varepsilon} = \tilde{\varepsilon}(x_i, p^*, \ldots), \tag{13}$$

$$\tilde{T}_f = \tilde{T}_f(x_i, p^*, \ldots), \tag{14}$$

$$V_n = V_n(x_i, p^*, \ldots), \tag{15}$$

$$\tilde{P}_{S_i} = \tilde{P}_{S_i}(x_i, p^*, \ldots), \tag{16}$$

$$p^* = p^*(t) \tag{17}$$

and with determining relations of the form

$$\sigma_{ij} = C^*_{ijpq}(\varepsilon_{pq} - \varepsilon^{(T)}_{pq} - \tilde{\varepsilon}^{(P)}_{pq}). \tag{18}$$

The components of the tensor of physical constants of the material are obtained according to the model of inelastic strain of anisotropic carbon-based materials with a different capacity to resist tension and compression, which was proposed in study [7]

$$C^*_{ijpq} = C^*_{ijpq}(\varepsilon_{ml}, \tilde{\varepsilon}^{(P)}_{ml}, I_{1\varepsilon}, T). \tag{19}$$

The "MARAT" and "ORTOPLASCON" software systems have a structure traditional for the systems of finite-element analysis. The first of them is designed for numerical modeling of unsteady temperature fields in axisymmetric and plane structures with allowance for the temperature dependence and anisotropy of thermophysical characteristics, and also for the geometric alterations of components as a result of the entrainment of the material of surface layers. The "ORTOPLASCON" SS permits numerical modeling of the fields of thermal stresses in axisymmetric and plane units, made of anisotropic inelastic materials with a different capacity to

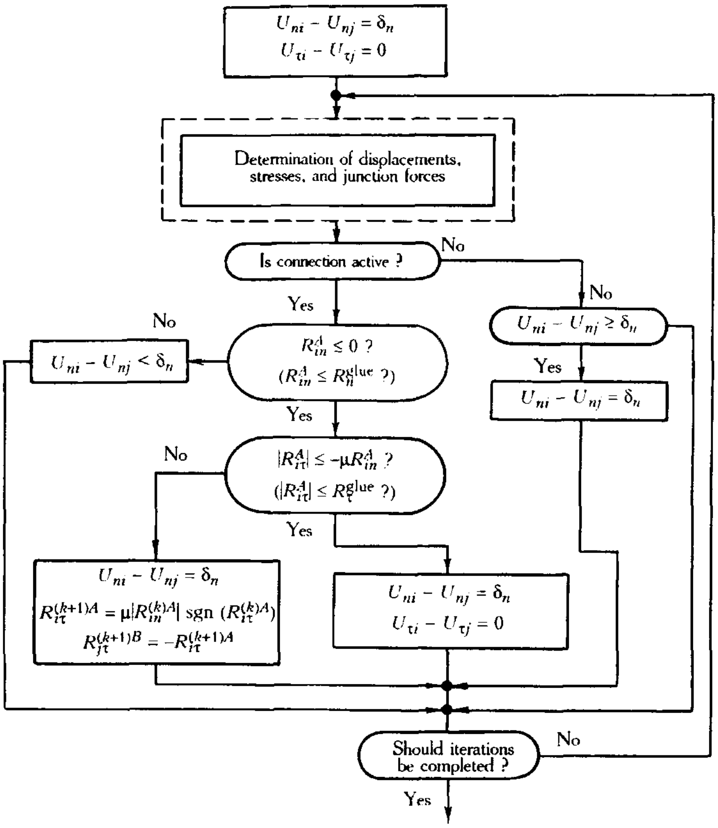


Fig. 3. Algorithm of solution of a contact problem.

resist tension and compression, with account for the contact interaction of individual components, friction, clearances, glue joints, and the actual rigidity of the bolts or dowels. The software systems have a common "ZoneConnector" preprocessor, intended for interactive preparation of the initial data in the graphic mode, and "ResultViewer" postprocessor, which serves for graphic representation of the computation results. Another element common to these SSs is an information accumulation system (IAS), which is a set of databases (DBs) provided with a specialized management system (DBMS). The IAS includes:

"DVHAR.BAZ" DB, which contains information on the characteristics of solid rocket fuels and serves for determining, using the dimensionless relations [2, 8], the parameters of heat transfer in the nozzle (11)-(14) and the distribution of surface loads (16) as functions of the pressure variation in the combustion chamber (17). At the same stage of preparation of the initial data, the oxidation potential of combustion products is determined that is needed for calculating the rate of chemical erosion for the materials of surface layers (15);

"TEPLPHIS.BAZ" DB, which contains information on thermophysical characteristics of materials;

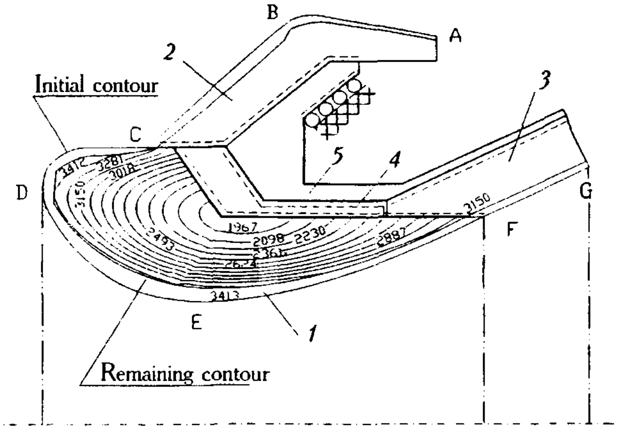
"PHISMECH.BAZ" DB, which contains information on physicomechanical characteristics of materials, including diagrams of strain under tension and compression in the principal directions of orthotropy that are needed for constructing model (19);

"POINT.BAZ" DB, which contains information on the "control point" needed for resuming an interrupted computation;

"TEPLREZ.BAZ" DB, which contains results in the form of temperature fields and structure geometry that are changed as a result of the entrainment;

"GRAPHREZ.BAZ" DB, which contains results for subsequent graphical processing via a postprocessor;

"PLAST.BAZ" DB, which contains results in the form of plastic strains accumulated at each step of integration over time.



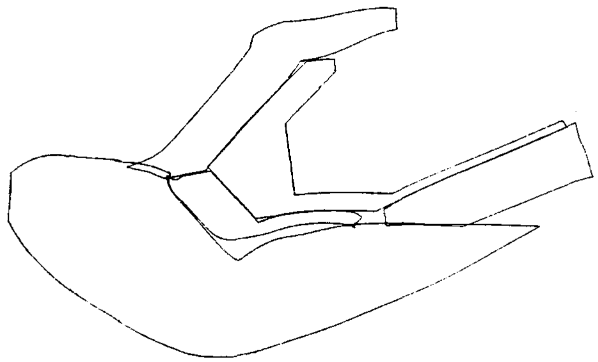


Fig. 4. Computational scheme and computation results for temperature fields, K.

Fig. 5. Strain of the structure.

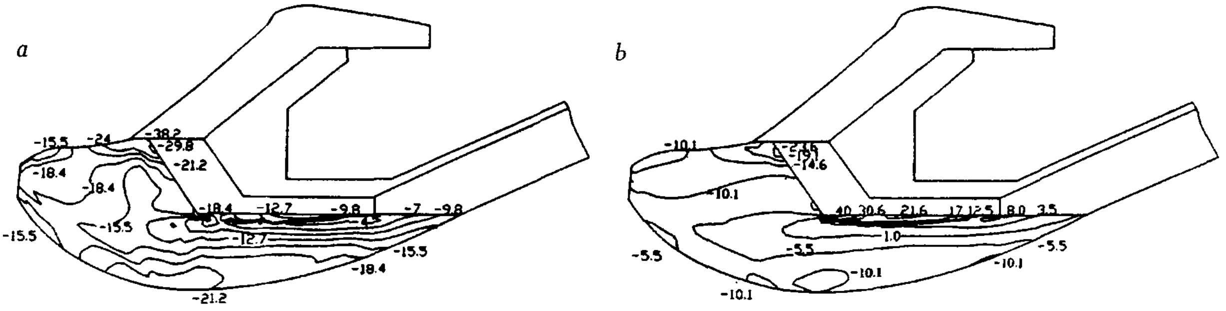


Fig. 6. Calculated circumferential (a) and axial (b) stresses, MPa.

When the "ORTOPLASCON" SS is operated, relation (16) is linearized with the aid of a version of the method of variable elasticity parameters [7]. The contact problem is also solved by the iteration method [9] via an algorithm, whose block diagram is presented in Fig. 3, where the active connection is the connection fulfilled in the form of an equality.

By way of example, we consider results of numerical modeling of the fields of thermal stresses in an integral insert of the SFRE nozzle of the Thiokol company performed with the aid of the "MARAT" and "ORTOPLASCON" SSs [10]. A computational scheme for the nozzle element is presented in Fig. 4, where item 1 marks an integral insert made of spatially reinforced CCC. Items 2 and 3 correspond to carbon-plastic fairing and lining, and item 4, to a glass-plastic band, which protects titanium load-bearing structure 5 against heating. The dashed line marks the surfaces, along which the conditions of contact interaction are specified or those unilateral, working in compression of the connection. Along the ABCDEFG surface, the construction interaction is specified with the flow of the combustion products, whose parameters, along with the characteristics of the materials, are given in [7]. The same figure presents results calculated for the temperature fields and erosion entrainment of the material at the 15th second of engine operation. The contact interaction of individual structural elements is displayed in the picture of exaggerated calculated strains (Fig. 5), and calculated distributions of circumferential and axial stresses are presented in Fig. 6.

The study of the thermally stressed state of composite elements of the inserted part with account for the difference in characteristics of their components is carried out with the aid of the "MARAT/Composite" and "ORTOPLASCON/Composite" SSs. The first of them can consider structures made of materials of three types simultaneously: traditional homogeneous materials (HM), sparially reinforced CCCs, and thermally decomposing CPs. The equation of unsteady heat conduction in the form (1) holds for components made of HM.

The assumption of the difference in temperatures of the matrix and filler of CCC components in this case makes it possible to write the equations of heat conduction for each component of the composite [11]

$$\rho_\alpha c_\alpha \dot{T}_\alpha = (\lambda_{ij_\alpha} T_{\alpha,j})_{,i} + \beta_{\alpha\gamma}(T_\gamma - T_\alpha)\,, \quad \alpha, \gamma = 1, 2\,, \quad \alpha \neq \gamma\,. \tag{20}$$

In analyzing CP components, of greatest interest is the pyrolysis zone of a thermoreactive binder, in which the material is regarded as two-component, consisting of a porous core and a gas phase contained in the pores. In this case, in lieu of Eq. (1) we write a system of equations that consists of the equation of unsteady heat conduction in the core and the equation of unsteady filtration of the gas phase [11]

$$\begin{gathered}\left[(1-\pi)\, c_\mathrm{k}\, \rho_\mathrm{k} + \pi c_\mathrm{g} \frac{p_\mathrm{g}}{R_\mathrm{g} T}\right] \dot{T} = (f \lambda_{kij} T_{,j})_{,i} + c_\mathrm{g}\, \pi\, K_{kij}\, p_{\mathrm{g},j} T_{,i} + (1-\pi)\, \rho_\mathrm{k}\, r_\mathrm{k}\,; \\ \frac{1}{R_\mathrm{g} T} \dot{p}_\mathrm{g} = (K_{kij}\, p_{\mathrm{g},j})_{,i} + \frac{\dot{T}}{R_\mathrm{g} T} p_\mathrm{g} + \frac{m_\mathrm{g}}{\pi}\,.\end{gathered} \tag{21}$$

Here, the mass production is defined by an expression of Arrhenius type

$$m_\mathrm{g} = -D\,(\rho - \rho_\mathrm{c})^n \exp\left(-\frac{E}{RT}\right),$$

whose coefficients are determined via mathematical processing of the experimental derivatograms at different heating rates. The thermal effect of the reaction of thermal decomposition can be calculated based on information on the makeup of the products of thermal decomposition

$$\rho_\mathrm{k} r_\mathrm{k} = -\left\{ \sum_{i=1}^{l} \xi_i \left[\Delta H_i^0 + c_{pt}\,(T - T_{298})\right] - \Delta H_\mathrm{cp}^0 \right\} A\,(\rho - \rho_\mathrm{c})^n \exp\left(-\frac{E}{RT}\right).$$

The degree of CP destruction at each instant of time is determined by the expression

$$e = \frac{\rho_0 - \rho}{\rho_0 - \rho_\mathrm{c}}\,.$$

With a gas phase present inside a porous core, the balance equation (2) should be recast in the form

$$(1-\pi)\, \sigma_{ij,j} + \pi \delta_{ij}\, p_{\mathrm{g},j} + \left[\rho_\mathrm{k}\,(1-\pi) + \frac{\pi p_\mathrm{g}}{R_\mathrm{g} T}\right] R_i = 0\,.$$

Speaking about determining relations, we will consider spatially reinforced CCCs as two-component materials that consist of an isotropic, plastically deformable matrix (α) and elastic reinforcing elements (γ) oriented in several directions. In this case, Eqs. (18) will take the form [12]

$$\sigma_{ij} = (C_{ijpq}^{*\alpha} + C_{ijpq}^{\gamma})\, \varepsilon_{pq} - C_{ijpq}^{*\alpha}\, \varepsilon_{pq}^{(T)\alpha} - C_{ijpq}^{\gamma}\, \varepsilon_{pq}^{(T)\gamma}\,.$$

A serious problem for CCCs is the experimental determination of the physicomechanical characteristics of components that do not exist outside the composite. For this end, work [13] suggests an approach to identifying properties of the composite components based on standard tests of specimens cut out of the structural components in several directions.

For an approximate account for the dependence of thermophysical and physicomechanical properties of CP on the heating rate, the following relation is proposed:

$$\rho\chi = e\chi_c \rho_c + (1 - e)\chi_0 \rho_0 ,$$

where χ is any thermophysical or physicomechanical characteristic of a thermally decomposing CP.

Because the systems of equations (20) and (21) are similar, in the process of finite-element discretization for all the three above-considered types of materials it is possible to write a unified system of nonlinear differential equations of the first order

$$\overline{C}_{rs} \dot{X}_s + \overline{K}_{rs} X_s = \overline{F}_r , \quad r, s = 1, \dots , 2S , \tag{22}$$

where

$$X_r = \{T_\alpha, T_\gamma\}^T \text{ for CCC} ; \; X_r = \{T, p_g\}^T \text{ for CP and } X_r = \{T, 0\}^T \text{ for HM} .$$

Evidently, for mating the zones or components made of unlike materials, expression (22) should be completed with the joining conditions

$$L_{rs} X_s = 0 ,$$

where the form of the L_{ij} matrix is specified by the type of mated components.

Such are the features of numerical modeling for the fields of thermal stresses in the structure of the inserted part of the SFRE nozzle. For studying the remaining structural elements of the engine, which admit a detail-by-detail consideration, it is possible to successfully apply widely used and commonly accessible systems of finite-element analysis, as is shown in Fig. 2. An isothermal analysis of the stressed-strained state of geometrically intricate spatial structures of the SFRE NB load-bearing units, such as brackets and locally loaded reinforced casings of the nozzle frame, is conveniently performed via the UAI/Nastran SS in a linear formulation, sometimes using the method of substructures. On the other hand, physical and geometrically nonlinear and unsteady problems, which arise in the numerical modeling of the suspension unit of the nozzle, elastomer elements of the construction, and devices like high-temperature regulators and valves, are successfully solved using the "MARC/Mentat" SS.

Regardless of their intrinsic universality, each of the aforementioned software systems has preferable spheres of application in analyzing the SFRE NB structures. Therefore, the software should be used in thermal stability calculations in such a manner that the numerical modeling is close to optimal from the standpoint of a "cost–efficiency" criterion.

NOTATION

c, specific heat; ρ, density of material; T, temperature; λ_{ij}, heat conduction tensor; σ_{ij}, stress tensor; R_i, vector of mass loads; the dot above the symbol denotes partial derivative with respect to time; $(\ )_{,i}$, partial derivative with respect to spatial coordinate; ε_{ij}, strain tensor; u_i, displacement vector; S_T, S_σ, and S_u, surfaces, on which the conditions of heat transfer, pressure, and displacement, respectively, are imposed; n_i, vector of outward normal to surface; $\tilde{\alpha}$, coefficient of heat transfer from flow of combustion products; $\tilde{T}_\infty$, temperature of flow of combustion products; $\tilde{\varepsilon}$, coefficient of radiation from flow of combustion products; $\tilde{\sigma}$, Stefan–Boltzmann constant; $\tilde{T}_f$, temperature of radiation from flow of combustion products; V_n, velocity of entrainment of material of surface layer normally to surface; Q, thermal effect of entrainment of material of surface layer; $\tilde{p}_{S_i}$, vector of surface load; v_i, vector specifying a certain direction; t, time; $\tilde{u}_v$, assigned displacement along the v_t direction; u_n^A, vector projection on outward normal to boundary of the A body; δ_n, clearance normal to contact surface clearance of roll; σ_n^A and σ_τ^A, normal and tangential stresses on contact surface; μ, friction factor; $[\sigma_{\text{glue}}^+]$ and $[\tau_{\text{glue}}]$, limit characteristics of glue layer for separation and shear; p^*, pressure in SFRE NB combustion chamber; $\varepsilon_{ij}^{(T)}$, tensor of thermal strain; $\varepsilon_{ij}^{(P)}$, tensor of accumulated inelastic strain; $I_{1\varepsilon}$, first invariant of strain tensor; u_{ni}, u_{nj} and $u_{\tau i}$, $u_{\tau j}$, displacements at finite-element nodes i and j, belonging to the A and B

bodies normal and tangential to contact surface; R_n^{glue} and R_τ^{glue}, normal and tangential limit forces of glue joint in separation and shear; $\beta_{\alpha\gamma}$, coefficient of intercomponent heat transfer; π and f, volume and surface porosities; p, pressure of gas phase; R, gas constant; K_{ij}, tensor of permeability by viscous gas phase; r, specific heat release; m, specific mass production; D, preexponential factor; n, order of reaction; E, activation energy; ρ_{c}, density of coke residue; l, number of components of thermal decomposition for CP; ξ_t, volume fraction of the tth component of thermal decomposition; ΔH_t^0, enthalpy of formation of the tth component of thermal decomposition; c_{pt}, specific heat of the tth component of thermal decomposition; T_{298}, temperature of standard state; χ, any thermophysical or physicomechanical characteristic; ΔH_{cp}, enthalpy of formation of carbon plastic; e, degree of destruction; δ_{ij}, Kronecker tensor; $\overline{C}_{rs}$, matrix of specific heat; $\overline{K}_{rs}$, matrix of thermal conductivity; $\overline{F}_r$, vector of thermal load; S, total number of nodes of computational scheme. Subscripts: i, j, p, q, m, l, ordinal numbers of unit vectors of system of coordinates; α, γ, numbers of components of composite; k, parameters of porous core; g, parameters of gas phase; 0, initial value of parameter; c, coke parameter; n, parameter normal to boundary; τ, parameter tangential to boundary; r, s, ordinal numbers of unknown nodal values; T, σ, u, boundary surfaces on which heat transfer, pressure, and displacement conditions are imposed; ∞, f, recovery and radiation temperatures; glue, glue joint; S, surface parameter; t, thermal decomposition; CP, carbon plastic, k, number of iteration. Superscripts: A, B, contacting bodies; *, variable quantity; (T) and (P), thermal and plastic strains, respectively; α, γ, numbers of components of composite; glue, glue joint; 0, initial value of parameter; +, parameter defining separation characteristics of glue joint; n, exponent; T, transposition.

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