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CONJUGATE HEAT TRANSFER AND ESTIMATION OF THERMAL STATE OF ELEMENTS OF THE THERMAL PROTECTION SHIELD PACKAGE

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Abstract

This article presents the physical and computational models of heat transfer and the high-temperature flow path thermal protection with the use of radiation shields package. The analysis of the thermal insulating ability and temperature state of a multi-element radiation shields package was performed. It is shown that the distribution the temperature of the package elements is uneven, which can cause different thermal deformation of elements, the distortion of the shield, the possibility of mechanical contact of neighboring elements and the deterioration of the heat insulating ability

Keywords

Radiation heat transfer, radiation shield, emissivity, thermal protection

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Introduction. Ensuring the temperature mode of the construction of high-temperature technological, energy and propulsion systems is an important practical task, the relevance and importance of which increases with operating temperatures growth, which determines the energy efficiency of the structure. For thermal insulation of high-temperature technological equipment working area, for example, vacuum furnaces, or gas-dynamic flow paths of propulsion systems, the use of radiation shields is effective [1–3]. The heat insulating capacity of such thermal protection is mainly determined by the laws of radiative heat transfer in a package of shields, and its numerical estimates are most often limited by the conditions for setting temperatures or heat flux at the boundaries of a package of shields [4, 5]. At the same time, in a number of practical applications, the assignment of specific values of these parameters is difficult and it is necessary to take into account the mutual influence of the thermal state of insulation and heat exchange parameters at the boundaries, and this connection is enhanced with the transition to higher temperatures. This article analyzes the temperature state of the system elements, which includes the internal wall of combustion chamber heated by a high-temperature gas flow, separated from the enclosing wall (housing) by a package of radiation shields.

Problem formulation. We consider the heat transfer in the system is stationary (Fig. 1), system contains the internal wall of combustion chamber *1*, streamlined by high-temperature flow with V_p speed at T_p flow temperature. External (heated) and internal surfaces have emissivity $\varepsilon_1 = \varepsilon_1(T_1)$ and $\varepsilon_{12} = \varepsilon_{12}(T_1)$. The wall is considered to be thermally thin, its temperature state

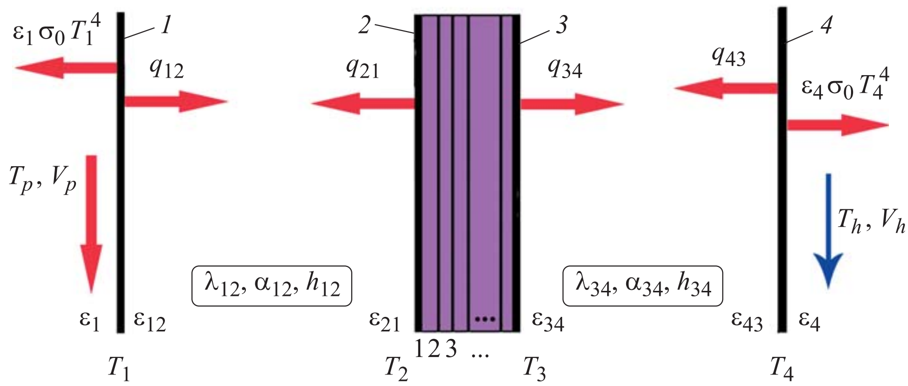


Fig. 1. Model of heat transfer in the flow path with a package of radiation shields: *1* is internal wall of combustion chamber; *2*, *3* are outer shields of package; *4* is outer housing

is characterized by temperature T_1; heat exchange between the gas flow and the internal wall surface facing it is due to convection and radiation and is characterized by an effective heat transfer coefficient $\alpha_p = \alpha_p(T_p, T_1)$. Between the internal wall and the casing wall there is a package of shields, the far left (*2*) and far right (*3*) shields have emissivity $\varepsilon_{21} = \varepsilon_{21}(T_2)$ and $\varepsilon_{34} = \varepsilon_{34}(T_3)$, and internal N_e shields have emissivity of each surface ε_i. We assume that the temperature state of the package is determined by the outer shields temperature T_2 and T_3, and in the internal gaps between the shields there is a heat exchange not only by radiation, but also by convection and due to the thermal conductivity of the gas, which will be taken into account by the generalized heat transfer coefficient of the package $\alpha_{pn} = \alpha_{pn}(T_2, T_3)$. Such a generalization is due to the fact that the screens in the package are almost always separated by heat-conducting distance elements [6], and if the gaps are not evacuated, then heat transfer occurs due to convection and thermal conductivity of the gas, which can be characterized by a generalized heat transfer coefficient of gaps in the package $\alpha_{pn,i}$.

Total thermal resistance R_{pn} of package gaps with the number of intermediate gaps N_e is determined by the relation

$$R_{pn} = \frac{1}{\alpha_{pn}} = \sum_{i=1}^{N_e+1} \frac{1}{\alpha_{pn,i}},$$

and the generalized heat transfer coefficient in the gaps $\alpha_{pn,i}$ we define through the effective thermal conductivity coefficient of the gap λ_i

$$\alpha_{pn,i}(T_{i+1} - T_i) = \lambda_i \frac{T_{i+1} - T_i}{h_i}.$$

From this we get

$$\alpha_{pn,i} = \frac{\lambda_i}{h_i},$$

then

$$\frac{1}{\alpha_{pn}} = \sum_{i=1}^{N_e+1} \frac{h_i}{\lambda_i},$$

where h_i is the size of the gaps in the package. Introducing the effective thermal conductivity coefficient of the package λ_{ef} as the relation

$$\alpha_{pn}(T_2 - T_3) = \sum_{i=1}^{N_e+1} \lambda_i \frac{T_{i+1} - T_i}{h_i} = \lambda_{ef} \left[(T_2 - T_3) \Big/ \sum_{i=1}^{N_e+1} h_i \right],$$

we get

$$\alpha_{pn} = \lambda_{ef} \Big/ \sum_{i=1}^{N_e+1} h_i.$$

If we assume

$$\lambda_{ef} = 0,5\left[\lambda(T_2) + \lambda(T_3)\right],$$

then

$$\alpha_{pn} = \alpha_{pn}(T_2, T_3) = \frac{\lambda(T_2) + \lambda(T_3)}{2(N_e+1)h_i}.$$

The wall of the housing *4* is also considered thermally thin, is characterized by temperature T_4, has an emissivity of the internal surface $\varepsilon_{43} = \varepsilon_{43}(T_4)$, and external (facing the environment) has an $\varepsilon_4 = \varepsilon_4(T_4)$. The gas stream flows around the outer surface at a rate of V_h and temperature T_h; convective heat exchange with the external environment is characterized by a heat transfer coefficient $\alpha_h = \alpha_h(T_4, T_h)$.

Generally, we will assume that in the gap between the internal wall of combustion chamber and the package of shields (h_{12}) there is heat exchange by radiation, and also heat transfer is allowed due to convection with a heat transfer coefficient $\alpha_{12} = \alpha_{12}(T_1, T_2)$ and thermal conductivity of gas with thermal conductivity coefficient $\lambda_{12} = \lambda_{12}(T_1, T_2)$. Similarly, in the gap between the screen package and the housing (h_{34}) there is heat exchange by radiation and also there can be heat transfer by convection and heat conduction with appropriate heat transfer coefficient $\alpha_{34} = \alpha_{34}(T_3, T_4)$ and thermal conductivity coefficient $\lambda_{34} = \lambda_{34}(T_3, T_4)$. We can note that in narrow gaps without forced flow of gas, the effect of convection may be insignificant, less than thermal conductivity, but the decisive role in the studied temperature range $(T \approx 1000-2000\,\text{K})$ belongs to radiation, and the indicated molecular mechanisms of heat transfer are included in the mentioned model in order of generalizing the numerical algorithm to the regimes in which the influence of these factors can be significant.

Further, in order to simplify mathematical expressions, unless otherwise stated, the functional dependence of the heat transfer parameters from temperature will not be given.

Mathematical model and solution method. Effective radiation fluxes in the gaps q_{ij} and in a package of shields q_{pn} are determined by the relations that follow from the problem solution of radiation heat transfer in a system of flat surfaces for a diathermisches medium:

$$q_{12} = \frac{\varepsilon_{p1}}{\varepsilon_{21}} \sigma_0 T_1^4 + \frac{\varepsilon_{p1}}{\varepsilon_{12}} (1-\varepsilon_{12}) \sigma_0 T_2^4; \tag{1}$$

$$q_{21} = \frac{\varepsilon_{p1}}{\varepsilon_{21}} (1-\varepsilon_{21}) \sigma_0 T_1^4 + \frac{\varepsilon_{p1}}{\varepsilon_{12}} \sigma_0 T_2^4; \tag{2}$$

$$q_{34} = \frac{\varepsilon_{p2}}{\varepsilon_{43}} \sigma_0 T_3^4 + \frac{\varepsilon_{p2}}{\varepsilon_{34}} (1-\varepsilon_{34}) \sigma_0 T_4^4; \tag{3}$$

$$q_{43} = \frac{\varepsilon_{p2}}{\varepsilon_{43}} (1-\varepsilon_{43}) \sigma_0 T_3^4 + \frac{\varepsilon_{p2}}{\varepsilon_{34}} \sigma_0 T_4^4; \tag{4}$$

$$q_{pn} = \varepsilon_{pn} \sigma_0 \left(T_2^4 - T_3^4 \right), \tag{5}$$

where

$$\varepsilon_{p1} = \frac{1}{\dfrac{1}{\varepsilon_{12}} + \dfrac{1}{\varepsilon_{21}} - 1}; \quad \varepsilon_{p2} = \frac{1}{\dfrac{1}{\varepsilon_{43}} + \dfrac{1}{\varepsilon_{34}} - 1};$$

$$\varepsilon_{pn} = \left[\frac{1}{\varepsilon_{21}} + \frac{1}{\varepsilon_{34}} - 1 + N_e \left(\frac{2}{\varepsilon_i} - 1 \right) \right]^{-1}$$

are reduced emissivity of surface systems, in which radiation heat exchange takes place; N_e is number of intermediate shields of the package.

We write the heat balance equations for all boundary surfaces of the system:

$$\alpha_p(T_p - T_1) + \varepsilon_{12}q_{21} - \varepsilon_1\sigma_0 T_1^4 - \varepsilon_{12}\sigma_0 T_1^4 - \left(\alpha_{12} + \frac{\lambda_{12}}{h_{12}}\right)(T_1 - T_2) = 0; \quad (6)$$

$$\varepsilon_{21}q_1 - \varepsilon_{21}\sigma_0 T_2^4 + \alpha_{12}(T_1 - T_2) + \frac{\lambda_{12}}{h_{12}}(T_1 - T_2) - q_{pn} - \alpha_{pn}(T_2 - T_3) = 0; \quad (7)$$

$$q_{pn} + \alpha_{pn}(T_2 - T_3) - \varepsilon_{34}q_3 - \varepsilon_{34}\sigma_0 T_3^4 - a_{34}(T_3 - T_4) = 0; \quad (8)$$

$$\varepsilon_{43}q_{34} + \alpha_{34}(T_3 - T_4) + \frac{\lambda_{34}}{h_{34}}(T_3 - T_4) - \varepsilon_{43}\sigma_0 T_4^4 - \varepsilon_4\sigma_0 T_4^3 - \alpha_h(T_4 - T_h) = 0. \quad (9)$$

Taking into account expressions (1)–(5), after transformations, the system of equations (6)–(9) can be written as a system of nonlinear algebraic equations referred to temperatures T_1, T_2, T_3, T_4:

$$z_1 = b_{11}T_1^4 + b_{12}T_2^4 + b_{13}T_3^4 + b_{14}T_4^4 + d_{11}T_1 + d_{12}T_2 + d_{13}T_3 + d_{14}T_4 + c_1 = 0; \quad (10)$$

$$z_2 = b_{21}T_1^4 + b_{22}T_2^4 + b_{23}T_3^4 + b_{24}T_4^4 + d_{21}T_1 + d_{22}T_2 + d_{23}T_3 + d_{24}T_4 + c_2 = 0; \quad (11)$$

$$z_3 = b_{31}T_1^4 + b_{32}T_2^4 + b_{33}T_3^4 + b_{34}T_4^4 + d_{31}T_1 + d_{32}T_2 + d_{33}T_3 + d_{34}T_4 + c_3 = 0; \quad (12)$$

$$z_4 = b_{41}T_1^4 + b_{42}T_2^4 + b_{43}T_3^4 + b_{44}T_4^4 + d_{41}T_1 + d_{42}T_2 + d_{43}T_3 + d_{44}T_4 + c_4 = 0. \quad (13)$$

Coefficients b_{ij}, d_{ij} are determined by the relations:

$$b_{11} = \frac{E_1}{\varepsilon_{p1}},\ b_{12} = -1,\ b_{13} = 0,\ b_{14} = 0;$$

$$d_{11} = \frac{\alpha_p + a_{12}}{\varepsilon_{p1}\sigma_0},\ d_{12} = -\frac{a_{12}}{\varepsilon_{p1}\sigma_0},\ d_{13} = 0,\ d_{14} = 0;\ c_1 = -\frac{\alpha_p T_p}{\varepsilon_{p1}\sigma_0};$$

$$b_{21} = 1,\ b_{22} = \frac{E_{21}}{\varepsilon_{p1}},\ b_{23} = \frac{\varepsilon_{pn}}{\varepsilon_{p1}},\ b_{24} = 0;$$

$$d_{21} = 0,\ d_{22} = -\frac{a_{12} + \alpha_{pn}}{\varepsilon_{p1}\sigma_0},\ d_{23} = \frac{\alpha_{pn}}{\varepsilon_{p1}\sigma_0},\ d_{24} = 0;\ c_2 = 0;$$

$$b_{31} = 0,\ b_{32} = \varepsilon_{pn},\ b_{33} = E_{23},\ b_{34} = -\varepsilon_{p2};$$

$$d_{31}=0,\quad d_{32}=\frac{\alpha_{pn}}{\sigma_0},\quad d_{33}=-\frac{\alpha_{pn}+a_{34}}{\sigma_0},\quad d_{34}=\frac{a_{34}}{\sigma_0};\quad c_3=0;$$

$$b_{41}=0,\quad b_{42}=0,\quad b_{43}=\varepsilon_{p2},\quad b_{44}=E_3;$$

$$d_{41}=0,\quad d_{42}=0,\quad d_{43}=a_{34},\quad d_{44}=-(a_{34}+\alpha_h);\quad c_4=\alpha_h T_h;$$

$$a_{12}=\alpha_{12}+\lambda_{12}/h_{12},\quad \alpha_{34}=\lambda_{34}/h_{34};$$

where

$$E_1=(\varepsilon_1+\varepsilon_{12})-\frac{\varepsilon_{12}\varepsilon_{p1}(1-\varepsilon_{21})}{\varepsilon_{21}};$$

$$E_{21}=\frac{\varepsilon_{21}\varepsilon_{p1}(1-\varepsilon_{12})}{\varepsilon_{12}}-(\varepsilon_{21}+\varepsilon_{pn});$$

$$E_{23}=(\varepsilon_{pn}+\varepsilon_{34})-\frac{\varepsilon_{34}\varepsilon_{p2}(1-\varepsilon_{43})}{\varepsilon_{43}};$$

$$E_3=\frac{\varepsilon_{p2}\varepsilon_{43}(1-\varepsilon_{34})}{\varepsilon_{34}}-(\varepsilon_{43}+\varepsilon_4).$$

To solve the nonlinear system of equations (10)–(13), the iteration method was used.

Let us introduce a vector function

$$\boldsymbol{Z}=\begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \end{bmatrix} \qquad (14)$$

and the vector of unknown temperatures

$$\boldsymbol{T}=\begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \end{bmatrix}. \qquad (15)$$

Then the system of equations (10)–(13) can be written as

$$\boldsymbol{Z}(\boldsymbol{T})=0 \qquad (16)$$

and an iterative algorithm for solving it as

$$\boldsymbol{T}^{(n+1)}=\boldsymbol{T}^{(n)}-W^{-1}(\boldsymbol{T}^{(n)})\boldsymbol{Z}(\boldsymbol{T}^{(n)}), \qquad (17)$$

where n is approximation order;

$$W(\boldsymbol{T}) = \begin{bmatrix} \frac{\partial z_1}{\partial T_1} & \frac{\partial z_1}{\partial T_2} & \frac{\partial z_1}{\partial T_3} & \frac{\partial z_1}{\partial T_4} \\ \frac{\partial z_2}{\partial T_1} & \frac{\partial z_2}{\partial T_2} & \frac{\partial z_2}{\partial T_3} & \frac{\partial z_2}{\partial T_4} \\ \frac{\partial z_3}{\partial T_1} & \frac{\partial z_3}{\partial T_2} & \frac{\partial z_3}{\partial T_3} & \frac{\partial z_3}{\partial T_4} \\ \frac{\partial z_4}{\partial T_1} & \frac{\partial z_4}{\partial T_2} & \frac{\partial z_4}{\partial T_3} & \frac{\partial z_4}{\partial T_4} \end{bmatrix} \qquad (18)$$

is Jacobi matrix; $W^{-1}(\boldsymbol{T})$ is inverse matrix.

Termination condition of the iterative process has the form

$$\left\| \boldsymbol{b}^{(n)} \right\| = \left\| W^{-1}(\boldsymbol{T}^{(n)})\boldsymbol{Z}(\boldsymbol{T}^{(n)}) \right\| \lesssim \delta_{er}, \qquad (19)$$

where $\boldsymbol{b}^{(n)} = \boldsymbol{T}^{(n+1)} - \boldsymbol{T}^{(n)}$ is residual vector; $||\boldsymbol{b}||$ is norm of the residual vector; δ_{er} is the absolute allowable error of temperature calculation.

In the implemented algorithm it is accepted that

$$||\boldsymbol{b}|| = \sqrt{\sum_i \left(T_i^{(n+1)} - T_i^{(n)}\right)^2} =$$

$$= \sqrt{\left[T_1^{(n+1)} - T_1^{(n)}\right]^2 + \left[T_2^{(n+1)} - T_2^{(n)}\right]^2 + \left[T_3^{(n+1)} - T_3^{(n)}\right]^2 + \left[T_4^{(n+1)} - T_4^{(n)}\right]^2}.$$

A solution of an auxiliary system of equations describing heat transfer in a system with one equivalent intermediate shield [7] was used as an initial approximation to the equations system solution (16)

$$\tilde{\boldsymbol{Z}}(\tilde{\boldsymbol{T}}) = 0, \qquad (20)$$

where $\tilde{\boldsymbol{T}}$ is the solution to this system of equations — incomplete temperature vector of the initial approximation of the equations system (16) corresponding to the temperature of the internal wall of combustion chamber $\tilde{T}_1 = T_1^{(0)}$, equivalent intermediate screen $\tilde{T}_2 = T_2^{(0)}$ with reduced emissivity

$$\varepsilon_E = \frac{2}{(2N_e)/\varepsilon_i - (N_e - 1)}$$

and casing temperature $\tilde{T}_3 = T_4^{(0)}$. The initial approximation for the temperature of the right wall of the screen package $T_3^{(0)}$ is calculated as

$$T_3^{(0)} = \sqrt[4]{\frac{\left(T_2^{(0)}\right)^4 + \left(T_4^{(0)}\right)^4}{2}}.$$

Such an approach ensures fast convergence of the equations system solution (16).

Temperature of i-th $(i = 1, 2, \ldots, N_e)$ intermediate shield of package is determined by solving a nonlinear equation

$$\Phi(T_i) = \varepsilon_{pn}\sigma_0 \left(T_2^4 - T_3^4\right) + \alpha_{pn}(T_2 - T_3) -$$

$$-\varepsilon_{pi}\sigma_0 \left(T_2^4 - T_i^4\right) - \alpha_{pi}(T_2 - T_i) = 0, \qquad (21)$$

including the constancy of the resulting heat flux in the package of shields. Here

$$\varepsilon_{pi} = \left[\frac{1}{\varepsilon_{21}} + \frac{1}{\varepsilon_i} - 1 + (i-1)\left(\frac{2}{\varepsilon_i} - 1\right)\right]^{-1}$$

is the reduced emissivity of the package part containing i intermediate shields;

$$\alpha_{pi} = \alpha_{pn}(N_e + 1)/i$$

is generalized heat transfer coefficient of i gaps of the package.

The temperature mode of the structural elements of the flow path and thermal protection is determined by thermal and gas-dynamic flow parameters. The following are the calculation results for the flow of lithium hydride combustion products in the air flow at a stoichiometric ratio of components. The composition of the combustion products and thermophysical characteristics are taken appropriate to the temperature $T_p = 2500$ K and pressure $p = 0,5$ MPa. The heat transfer coefficient in the flow path is calculated according to the common practice criterion formula [8]

$$\mathrm{Nu} = 0,0296\,\mathrm{Re}^{0,8}\,\mathrm{Pr}^{0,46}\left(\frac{T_w}{T_e}\right)^{0,39}\left(\frac{T_e}{T_p}\right)^{0,11}, \qquad (22)$$

where Nu, Re, Pr are Nusselt, Reynolds and Prandtl criteria; T_w is surface temperature; T_p is gas flow temperature; $T_e = T_p\left(1 + ((k-1)/2) r\,\mathrm{M}^2\right)$ is recovery temperature, $r = \mathrm{Pr}^n$ is recovery coefficient, $n = 1/2$ for laminar and $n = 1/3$ for the turbulent flow mode, $k = c_p / c_v$ is adiabatic constant, c_p and c_v are heat capacity at constant pressure and volume respectively. The physical properties of the flow were calculated at the determining temperature $T_{def} = T_p + 0,5(T_w - T_p) + 0,22(T_e - T_p)$. By definition, heat transfer coefficient is $\alpha_p = \mathrm{Nu}\,\lambda / d_x$, where d_x is characteristic size (in the examples was taken $d_x = 0.1\,\mathrm{m}$). Ambient temperature and heat transfer coefficient were taken $T_h = 300$ K and $\alpha_h = 20$ W / (m$^2 \cdot$K).

The most important characteristic that determines the temperature mode of the radiation heat shield is the emissivity of its structural elements. For heat-resistant materials, this value is extremely uncertain and the data given in the literature (see, for example, [9]) have a large scatter. In this regard, in the main series of calculations, the emissivity values are taken from the characteristic range for heat-resistant materials in the high-temperature region: $\varepsilon_1 = \varepsilon_{12} = \varepsilon_4 = 0,9$; $\varepsilon_{21} = \varepsilon_{34} = \varepsilon_{43} = \varepsilon_i = 0,3$.

Fig. 2 shows the temperature dependences of the internal wall of combustion chamber T_1 and the outer housing T_4, and Fig. 3 shows the corresponding dependences of the temperature of the “hot” (facing the internal wall) surface of the radiation shields package T_2 on the gas flow rate taking into account only heat transfer by radiation in the system under consideration (assessment of the role of heat transfer in the gaps between the internal wall of combustion chamber, radiation shield and the housing by molecular mechanisms is given in work [7]).

An increase in the number of shield package elements leads to an unambiguous decrease of the casing temperature T_4, to an increase in the temperatures of the internal wall T_1 and the “hot” surface of the shield package T_2. Moreover, the degree of increase in the temperature of the shields package “hot” surface with an increase in the number of elements is significantly greater (by 3–3.5 times) than in the temperature of the internal wall surface.

Further we study the temperature state of the shields package. Figures 4 and 5 show the temperature distribution between the elements of the flow path and the radiation shields package for a number of emissivity values of the package elements (the value $\varepsilon = 0.05$ should be considered as hypothetical).

The emissivity of package elements has a weak effect on the temperature of intermediate elements. Thus, for a seven-element shield package, a change of ε_i from 0.5 to 0.05 results in a change in the temperature of the leftmost shield (i.e., T_2) from 2045 to 2069 K and from 1056 to 998 K for the right-most shield (i.e., T_3). However, in this case, the difference in temperatures between adjacent elements of the package changes significantly. So, if for the “hot” side of the package it is ~ 80 K, then for the “cold” it increases to 350–400 K (Fig. 4*b*). It should be noted that with a decrease in the number of elements of the shields package (Fig. 5), the manifestation of this factor becomes more noticeable.

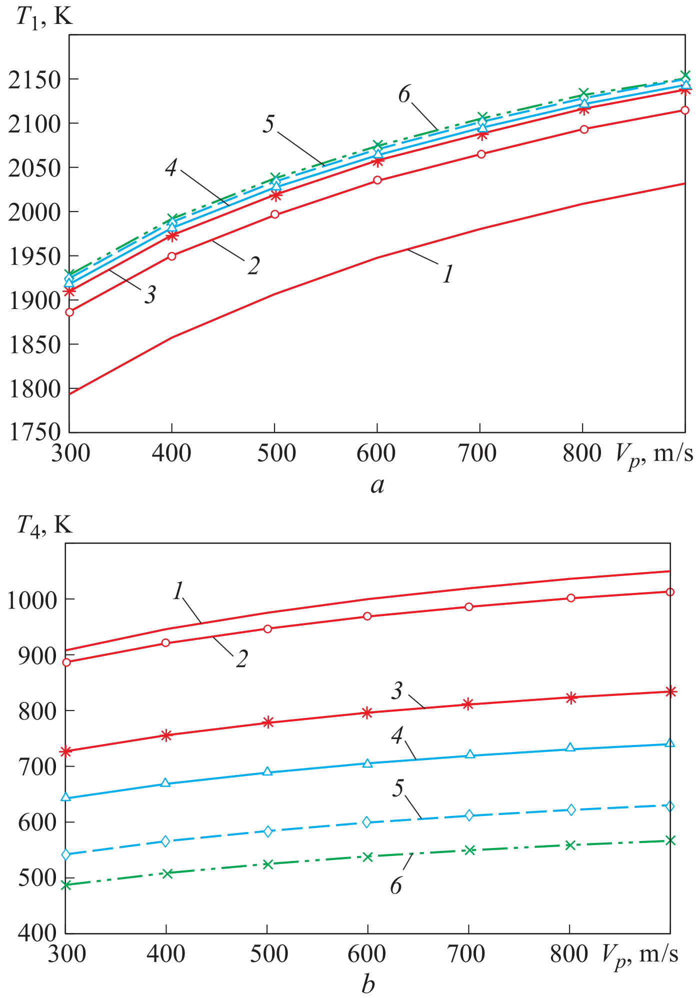


Fig. 2. Dependence of the internal wall temperature T_1 (*a*) and the housing temperature T_4 (*b*) on the gas flow rate for different radiation shields: *1* is no shield; *2, 3, 4, 5, 6* are one-, two-, three-, five- and seven-element shield package

Nonuniform heating of the radiation shields package elements can lead to distination deformation of the neighboring elements of the package, their mechanical contact and additional heat transfer due to contact heat conduction, i.e., deterioration of the heat insulating properties.

Multi-element radiation shield is a package of thin reflective shields, separated by distance elements. Their role can be performed by pads, backfilling, riffing or corrugations of shield elements, rods or grids [3, 6], but in any case, due to the thermal conductivity of the spacer elements, the heat shield properties of the multiscreen insulation deteriorate. Fig. 6 shows the temperature values of the flow path elements with the emissivity $\varepsilon_{21} = \varepsilon_{34} = \varepsilon_{43} = \varepsilon_i = \varepsilon = 0.3$ and different thermal conductivities of the spacer

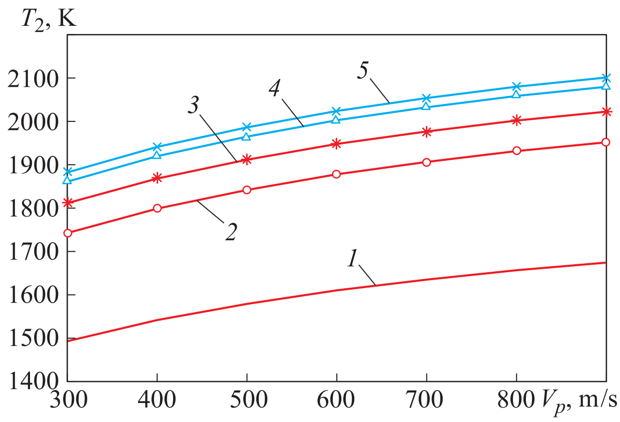


Fig. 3. Dependence of the internal wall "hot" surface temperature on the gas flow rate:
1, 2, 3, 4, 5 are one-, two-, three-, five- and seven-element shield package

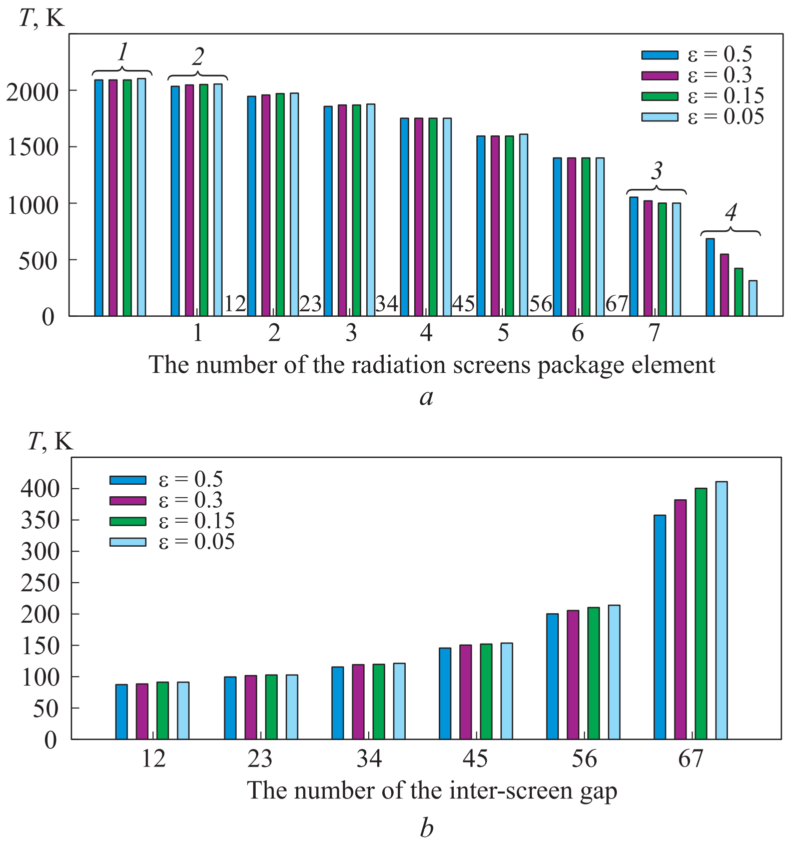
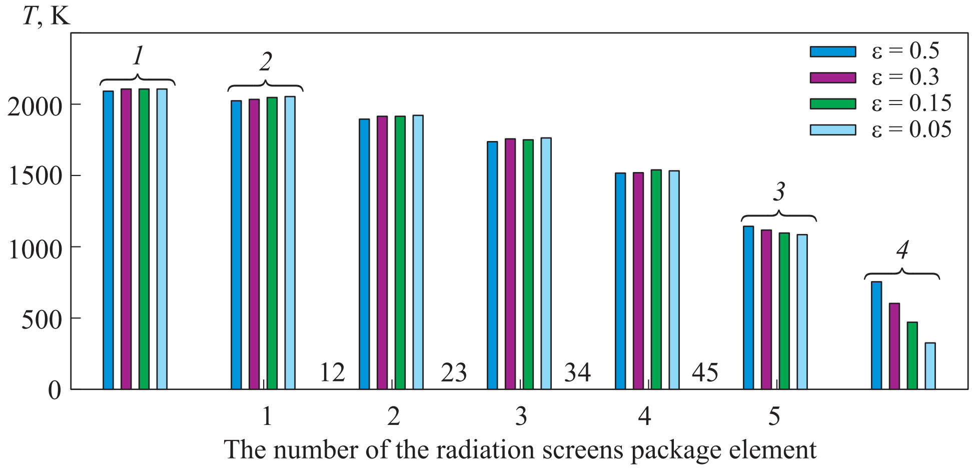
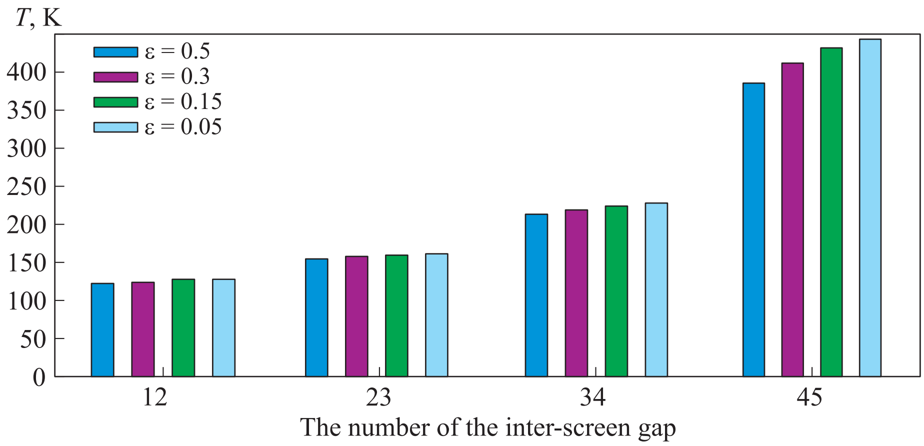


Fig. 4. The temperature of the flow path elements (*a*) and the temperature difference $T_i - T_{i+1}$, $i = 1, 2, \ldots, 7$, between the elements of the seven-element radiation shield (*b*) with the emissivity of the package elements $\varepsilon_{21} = \varepsilon_{34} = \varepsilon_{43} = \varepsilon_i = \varepsilon$ and the combustion products flow rate $V_p = 700$ m/s:

1 is internal wall of combustion chamber (T_1); *2* is "hot" shield surface (T_2); *3* is "cold" shield surface (T_3); *4* is housing (T_4)



a



b

Fig. 5. The temperature of the flow path elements (*a*) and the temperature difference $T_i - T_{i+1},\ i = 1, 2, \ldots, 5$, between the elements of the five-element radiation shield (*b*) with the emissivity of the package elements $\varepsilon_{21} = \varepsilon_{34} = \varepsilon_{43} = \varepsilon_i = \varepsilon$ and the combustion products flow rate $V_p = 700$ m / s:

1 is internal wall of combustion chamber (T_1); *2* is "hot" shield surface (T_2); *3* is "cold" shield surface (T_3); *4* is housing (T_4)

elements with their thickness of 1 mm. With increasing thermal conductivity, the temperature difference between the shield elements decreases and the temperature of the protected surface increases, i.e., the heat insulating properties of the shield deteriorate. For example, in the example above, the use of a niobium grid, which occupies 5 % of the screen element area, leads to an increase in body temperature by ~ 400 K.

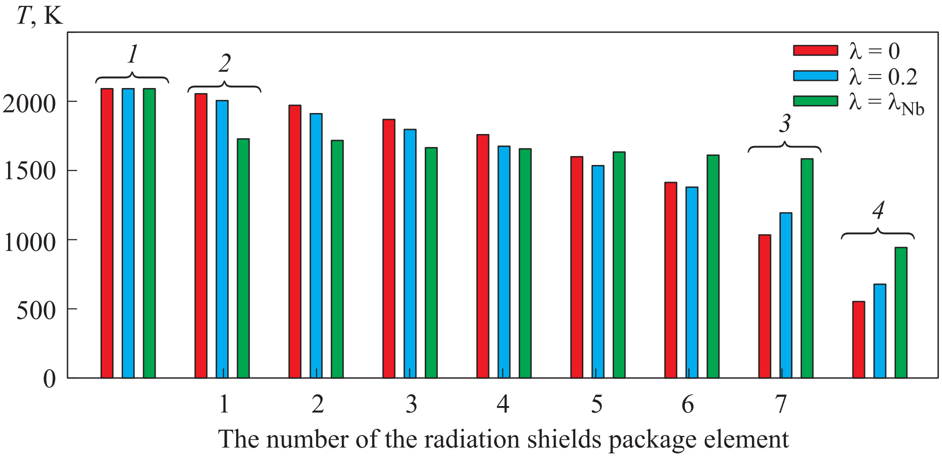


Fig. 6. The temperature of the flow path elements with five-element radiation shield with the emissivity of the package elements $\varepsilon_{21} = \varepsilon_{34} = \varepsilon_{43} = \varepsilon_i = \varepsilon = 0.3$ and the combustion products flow rate $V_p = 700$ m / s with different thermal conductivity of 1 mm thick spacer pads:

1 is internal wall of combustion chamber (T_1); *2* is “hot” shield surface (T_2); *3* is “cold” shield surface (T_3); *4* is housing (T_4); red color is no thermal conductivity distination; blue color is $\lambda = 0{,}2$ W / (m · K); green color is niobium mesh

Conclusion. On the basis of the developed model, the analysis of the heat insulating ability and the temperature state of the multi-element package of radiation shields was carried out. Such multi-element radiation shields are effective heat-shielding means of high-temperature devices. It is shown that the temperature distribution over the shield elements is uneven, which can lead to different thermal deformations of the elements, causing distortion of the shield, the possibility of mechanical contact of neighboring elements and the deterioration of thermal insulating ability.

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