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METHOD OF PROTECTION AND DIAGNOSTICS OF THE COMBUSTION CHAMBER WALL ON EXPOSURE TO A HIGH-INTENSITY HEAT FLUX

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In the present work, consideration is given to the method of thermal protection of the walls of high-power installations (plasmatrons and gas-phase nuclear reactors), made of porous refractory materials, with the use of gas-dust protection. The algorithm for determining the mechanical, thermal, and thermophysical characteristics of the porous wall of a combustion chamber from the measured increase in the pressure on the exterior surface of the wall is given.

An efficient method of thermal protection of the walls of high-power installations is manufacturing the walls from porous refractory materials in combination with transpiration gas cooling.

In this work, a combined method is suggested to protect a porous wall of a hydrogen-fuel combustion chamber, exposed to a high-intensity convective-radiant heat flux, and to diagnose the thermomechanical state of the wall.

This method is based on the force feeding of cooling gaseous low-boiling compounds of refractory materials to the combustion chamber through the porous wall. On entering the combustion chamber, the reduction of these materials in the flow of a gaseous hydrogen fuel occurs; this reduction is accompanied by the formation, near the wall, of a gas-dust screen which shields the wall from heating by the radiant component of the heat flux.

Measuring the magnitude of the pressure increase of the gaseous compounds fed through the porous wall allows one to determine the thermophysical characteristics of the wall material and the thermal stresses in it from the analytical dependences obtained.

The method of thermal protection and diagnostics is considered for the chamber walls of high-power installations in which the level of the thermal state is determined mainly by the magnitude of the radiant component of the heat flux. These are power installations with temperatures of the heat flux of thousands of degrees. They include plasma installations [1] and gas-core nuclear engines of spacecraft [2]. In gas-core nuclear engines, hydrogen is used as the working body.

In a plasma reactor, radiation from the plasma arc at a temperature of 10,000 K and high pressures can efficiently be absorbed by argon or helium flows blackened with the particles of tungsten and carbon.

Spacecraft require an engine with a specific pulse of 5000 sec [2] and a ratio of the thrust to the engine weight close to 1. For this, it is necessary to heat the working body to 10,000 K. The temperature over the radius of the plasma nuclear volume changes from 10^5 near the axis to 10^4 K on the outer radius of the active volume, while the pressure reaches several megapascals. In the gas-core nuclear engine, the working body, apart from its prime objective must provide the confinement of the plasma of enriched uranium inside the cavity bounded by the moderator wall. To do this, one uses hydrogen, which is tangentially supplied to a cylindrical chamber through slots in the wall with simultaneous feed of blackening particles.

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The disadvantage of this method of blackening the working body of the engine is the nonuniformity of the distribution of particles near the wall and their coarsening in motion in the chamber [3, 4].

In order to efficiently protect the active volume with a temperature to 10,000 K from radiation, it is essential [5] that particles with a radius size of $0.005 < r < 0.1$ μm be present in the working flow. This can be achieved by manufacturing the chamber wall from a porous refractory metal or porous glass and by feeding low-boiling compounds of the WCl_6 and WF_6 type through the chamber wall. On arrival at the engine chamber, these compounds in the gaseous state interact with the working body and are reduced:

$$WCl_6 + 3H_2 = W + 6HCl \rightarrow W + 3H_2 + 6Cl\,, \quad WF_6 + 3H_2 = W + 6HF \rightarrow W + 3H_2 + 6F\,.$$

In the process of conglomeration, a gas-dust polydisperse screen with a great number of tungsten particles from an Angström to a micrometer in size is formed in the gas medium of the engine chamber. This degree of polydispersion of the tungsten particles that appear in the wall layer of the working medium of the engine ensures the shielding of thermal radiation in the ultraviolet region with a wavelength of $0.003 < \lambda < 0.03$ μm.

Another problem under consideration is to determine the thermal state of the cylindrical porous wall of the engine, i.e., (a) the magnitude of the received heat flux; (b) surface temperatures; (c) thermal stresses; (d) boundaries of plastic zones in elastoplastic deformation; (e) the magnitude of the effective thermal conductivity.

In the present work, we describe a method of determining the thermal characteristics of cooled porous walls exposed to an intense heat flux.

This method is based on measuring the magnitude of the pressure increase of a cooling gas at the entrance to a porous wall. The gas is fed with a fixed mass flow rate. We measure the magnitudes of the gas pressure before the beginning of the heat-flux action on the wall and when its thermal state is steady. The thermal state of the porous wall can be determined from the difference in the measured quantities.

It is established that in the fine-mesh structure of the material wall, the coefficient of heat exchange between the cooling gas and the wall is infinitely large [6]. As a result, the gas acquires the temperature of the porous structure already at the entrance to the wall, in practice; a volumetric thermal expansion of the gas and an increase in the pressure of the coolant before the entrance are observed.

One shape of the combustion chamber of the engine is a cylinder with a wall made of a porous material. The greatest temperature drop over the wall thickness that determines the required flow rate of the coolant occurs under steady-state thermal operating conditions of the engine.

By solution of the equation describing the law of conservation of energy for unit length of the cylindrical wall in the steady temperature state, we obtain a dependence which characterizes the temperature distribution over the wall thickness without account for radiation from the exterior surface:

$$T = T_0 + (T_1 - T_0)\left(\frac{R_1}{r}\right)^{\gamma}, \tag{1}$$

where $\gamma = (mc_p)/(2\pi\lambda_w)$. From formula (1) we express the temperature T_1 in terms of the value of the temperature in the radius-average cross section of the porous wall $\overline{T}$. The temperature T_1 differs from the average integral temperature of the wall T_0 by no more than 2–3%, i.e.,

$$T_1 = T_0 + (\overline{T} - T_0)\left(\frac{R_1 + R_2}{2R_1}\right)^{\gamma}. \tag{2}$$

For the isothermal state of a porous permeable wall, its temperature, the coolant pressure, and the coefficient of hydraulic resistance are related to each other by the following dependence [7]:

$$\xi_T = \frac{P_1^2 - P_2^2}{\beta j^2 \overline{R}Th} \,. \tag{3}$$

In the absence of the coolant dissociation, the hydraulic resistance is virtually independent of the temperature conditions of flow. When gaseous helium flows through a tungsten porous nonisothermal wall, the correction factor for nonisothermicity is equal to ≈ 1.02. It can be taken that for $\overline{T} = T_{\text{isotherm}}$

$$\xi_{\overline{T}} \approx \xi_T \,. \tag{4}$$

The hydraulic resistance of porous metal-ceramic walls at temperatures lower than the dissociation temperature of the coolant changes by 10%. In this case, β is close to 1 and

$$\xi_{T_0} \approx \xi_{\overline{T}} \approx \frac{P_1^2 - P_2^2}{j^2 \overline{R}h\overline{T}} \,. \tag{5}$$

Dependence (1) with account for Eqs. (2)–(5) can be expressed in terms of the change in the coolant pressure caused by the heating of the porous wall:

$$T = T_0 \left[1 + \frac{P_1^2 - P_0^2}{P_0^2 - P_2^2} \left(\frac{R_1 + R_2}{2r} \right)^{\gamma} \right]. \tag{6}$$

By substituting expression (6) into the dependences [8] that relate the thermal stresses to the temperature distribution over the wall thickness, we obtain formulas for determining the thermal stresses in the wall under the thermal action on the interior surface.

For the deformed state of a porous permeable wall the relations obtained are of the form

$$\sigma_r^T = \frac{\alpha E A T_0}{r^2 (1-\mu)(2-\gamma)} \left(\frac{R_1 + R_2}{2} \right)^{\gamma} \left[\frac{R_2^{2-\gamma}(r^2 - R_1^2) - R_1^{2-\gamma}(r^2 - R_2^2)}{R_2^2 - R_1^2} - r^{2-\gamma} \right], \tag{7}$$

$$\sigma_\vartheta^T = \frac{\alpha E A T_0}{r^2 (1-\mu)(2-\gamma)} \left(\frac{R_1 + R_2}{2} \right)^{\gamma} \left[\frac{R_2^{2-\gamma}(r^2 + R_1^2) - R_1^{2-\gamma}(r^2 + R_2^2)}{R_2^2 - R_1^2} - r^{2-\gamma}(1-\gamma) \right], \tag{8}$$

$$\sigma_z^T = \frac{\alpha E T_0}{1-\mu} \left[A \left(\frac{R_1 + R_2}{2} \right)^{\gamma} \left(\frac{2\mu}{2-\gamma} \frac{R_2^{2-\gamma} - R_1^{2-\gamma}}{R_2^2 - R_1^2} - r^{-\gamma} \right) - 1 + \mu \right], \tag{9}$$

whereas when the load on the end surfaces is absent, these dependences are as follows:

$$\sigma_z^T = \frac{\alpha E A T_0}{(1-\mu)(2-\gamma)} \left(\frac{R_1 + R_2}{2} \right)^{\gamma} \left[\frac{2(R_2^{2-\gamma} - R_1^{2-\gamma})}{R_2^2 - R_1^2} - r^{-\gamma}(2-\gamma) \right]. \tag{10}$$

In determining the thermal stresses from Eqs. (7)–(10), we use the tabulated values of the coefficients of thermal conductivity, linear expansion, elastic modulus, and the Poisson ratio of the porous wall material at a temperature determined from the expression

$$T = \frac{P_1^2 - P_2^2}{P_0^2 - P_2^2} T_0 . \tag{11}$$

For porous walls whose hydraulic resistance is temperature-dependent, we use the tabulated values for the coefficients α, E, μ, and λ at the average temperature of the wall that is determined, for example, from the condition of linear variation in the quantity $(P_1^2 - P_2^2)/\overline{T}$ characterizing the hydraulic resistance of the wall as a function of the temperature:

$$\frac{P_1^2 - P_2^2}{\overline{T}} = k\,(\overline{T} - T_0) + \frac{P_0^2 - P_2^2}{T_0} , \tag{12}$$

whence

$$\overline{T} = \frac{kT_0^2 - P_0^2 + P_0^2 \pm \sqrt{(kT_0^2 - P_0^2 + P_2^2)^2 + 4kT_0^2\,(P_1^2 - P_2^2)}}{2kT_0} . \tag{13}$$

From the analysis of dependences (5) and (7)–(11) it is evident that

$$A = \frac{kT_0^2 - P_0^2 + P_0^2 \pm \sqrt{(kT_0^2 - P_0^2 + P_2^2)^2 + 4kT_0^2\,(P_1^2 - P_2^2)}}{2kT_0^2} - 1 . \tag{14}$$

The coefficient k is determined from the dependence that describes the nature of change in ξ_T with temperature. If the dependence $\xi_T = f(T)$ is of a linear nature, in this case the coefficient k can be found from expression (12) according to the results of measurement of $(P_1^2 - P_2^2)/\overline{T}$ at any two temperatures of the wall for the given flow rate of the coolant.

The material of the wall can be in the elastic or elastoplastic state. With increase in the mechanical loads or the temperature factors, the zones of plastic deformations over the wall thickness will increase. With allowance for the investigations carried out in [9, 10], the boundaries of the plastic zones in the steady thermal state of a wall of the permeable cylinder with porous cooling are determined from the expression

$$r_{\mathrm{c}} = r_{\mathrm{d}} = \left[\frac{R_2^{2-\gamma} - R_1^{2-\gamma}}{(1-\gamma)\,(R_2^2 - R_1^2)} \pm \frac{\sigma_T\,(T)\,(1-\mu)\,(2R_1R_2)^{\gamma}}{\alpha EA\,(R_1 + R_2)^{\gamma}}\right]^{-1/\gamma} . \tag{15}$$

From the condition of heat balance of the interior surface of the wall under steady-state conditions of its heating and disregarding the radiation from the exterior surface, in conformity with [11] we determine the received heat flux using the dependence

$$q_{\mathrm{w}} = \frac{mc_p}{2\pi R_1}\,(T_1 - T_0) . \tag{16}$$

With account for expression (6), the magnitude of the heat flux will be determined from the formula

$$q_w = \frac{mc_p T_0 \,(P_1^2 - P_2^2)}{2\pi R_1 \,(P_0^2 - P_2^2)} \left(\frac{R_1 + R_2}{2R_1} \right)^{\gamma} . \quad (17)$$

The dependences proposed hold for permeable cylinders with a porosity no higher than 30% in which $l \geq 2.4\sqrt{R_1(R_2 - R_1)}$ and $(R_1 + R_2)/(2h) \geq 10$. The mechanical characteristics of the material change only slightly with temperature (materials of the porous tungsten and molybdenum type).

Based on the method suggested to determine q_w, we developed the design of a sensor for determining intense radiative heat fluxes [12]. A plane porous plate blackened on the side of the heat flux is used as the thermally sensitive element. Through this plate the cooling gas is fed toward the heat flux. In this case, the magnitude of the heat flux is determined from the formula

$$q_w = \frac{c_p}{m\bar{R}\xi} \exp \left(\frac{mc_p h}{2\lambda_w} \right) \Delta p \,(\Delta p + 2P_0) . \quad (18)$$

We obtained analytically and confirmed experimentally the dependence of the pressure increase on the exterior surface of the porous wall Δp in passage of the gas through it on the effective thermal-conductivity coefficient of the porous material [13]. The dependence has the form

$$\lambda_w = \frac{mc_p}{\ln \left[\frac{q_w}{c_p} \frac{m\bar{R}\xi}{\Delta p \,(\Delta p + 2P_0)} \right]} . \quad (19)$$

By the method proposed one can measure the effective thermal conductivity of porous materials up to temperatures which do not cause structural changes in the materials.

NOTATION

T_0, wall temperature before thermal loading, K; T_1, temperature of the interior surface of the porous wall, K; l, h, R_1, and R_2, length, thickness, and inner and outer radii of the porous wall, m; r, running radius, m; j, specific flow rate of the coolant per second, kg/(m^2·sec); m, flow rate of the coolant per unit length, kg/(m·sec); c_p, heat capacity of the coolant, J/(kg·deg); P, pressure, N/m^2; P_0 and P_1, pressure of the coolant in front of the porous wall in the cold and hot state, N/m^2; P_2, pressure of the coolant at the exit from the porous wall, N/m^2; Δp, pressure jump in passage of the gas through the porous wall, N/m^2; λ_w, coefficient of thermal conductivity of the wall material, W/(m·deg); α, coefficient of linear expansion, 1/deg; ξ, coefficient of hydraulic resistance; β, inertial coefficient, m^{-1}; E, Young modulus, kgf/mm^2; μ, Poisson ratio; $\sigma_T(T)$, yield stress, kgf/mm^2; σ_r^T, σ_θ^T, and σ_z^T, radial, tangential, and axial temperature stresses, kgf/mm^2; A, hydraulic resistance of the wall without thermal action; $\bar{R}$, gas constant, J/(kg·deg); k, coefficient of proportionality in the linear dependence (12). Subscripts and superscripts: w, wall; T, temperature; p, pressure; r, θ, z, axes in a cylindrical coordinate system; c and d, internal and external plastic zones, respectively; 0, without thermal action; 1 and 2, interior and exterior surfaces of the porous wall.

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