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INVESTIGATION OF ACTIVE AND PASSIVE THERMAL HEAT PROTECTION SYSTEMS COMBINED USAGE FOR HYPERSONIC VEHICLE

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According to [1] equally with passive thermal heat protection systems (PTHPS) the active heat protection systems (ATHPS) take place. A combined usage's characteristics of ATHPS and PTHPS for three dimensional hypersonic flows around spherically blunted cone at atmosphere entry by using into account conjugate heat and mass transfer were studied. This body consists of a spherical blunted porous part from Fe or Cu materials and conical part from graphite material. The hypersonic entry of blunting body with velocity less than first cosmic one are considered. For heights below 30 km within shock layer the model of chemically equilibrium air [2] consisting from 6 components O, O_2, N, N_2, NO, Ar are used. A chemically no equilibrium boundary layer equations system are known from [3]. It takes into account next system of no equilibrium homogeneous chemical reactions:

$$1)\, N_2 + M \leftrightarrow 2N + M\,,\ 2)\, O_2 + M \leftrightarrow 2O + M\,,\ 3)\, NO + M \leftrightarrow N + O + M\,,$$
$$4)\, C_2 + M \leftrightarrow 2C_1 + M\,,\ 5)\, C_3 + M \leftrightarrow C_1 + C_2 + M\,,\ 6)\, CO + M \leftrightarrow C_1 + O + M\,,$$
$$7)\, CO_2 + M \leftrightarrow CO + O + M\,,\ 8)\, CN + M \leftrightarrow C_1 + N + M\,,$$
$$9)\, NO + O \leftrightarrow O_2 + N\,,\ 10)\, N_2 + O \leftrightarrow NO + N\,,\ 11)\, CO + O \leftrightarrow O_2 + C_1\,,$$
$$12)\, CO + N \leftrightarrow C_1 + NO,\ 13)\, CO + C_2 \leftrightarrow C_3 + O\,,\ 14)\, C_3 + C_1 \leftrightarrow 2C_2\,,$$
$$15)\, CO + C_1 \leftrightarrow C_2 + O,\ 16)\, N_2 + CO \leftrightarrow CN + NO,\ 17)\, NO + CO \leftrightarrow CN + O_2,$$
$$18)\, CN + CO \leftrightarrow C_2 + NO,\ 19)\, CO + N \leftrightarrow CN + O,\ 20)\, CN + O \leftrightarrow C_1 + NO\,,$$
$$21)\, N_2 + C_1 \leftrightarrow CN + N\,,\ 22)\, CN + C_1 \leftrightarrow C_2 + N\,,\ 23)\, 2CO \leftrightarrow CO_2 + C_1\,,$$
$$24)\, CO_2 + O \leftrightarrow O_2 + CO,\ 25)\, CO + NO \leftrightarrow N + CO_2,\ 26)\, 2CO \leftrightarrow C_2 + O_2$$

For porous spherical blunting an equation [4] are considered. It takes into account one dimensional filtration flow of refrigerating air on normal to body surface from internal cavity by using a nonlinear Darcy law [5] and pressure's assignment for air cavity. An integration of gas movement's equation for pores results in next dependence for refrigerating air outflow [6]:

$$(\rho v)_{1w} = \left[-A\int_0^L \mu T_1\, r_w/(H_1 r_1)\,dn_1 + \right.$$
$$\left. + \left(A^2 \left(\int_0^L \mu T_1\, r_w/(H_1 r_1)\,dn_1 \right) + 2B\frac{P_k^2 - P_e^2}{R/m}\int_0^L T_1\, r_w/(H_1 r_1)\,dn_1 \right)^{0.5} \right] /$$
$$/ \left[2B\int_0^L T_1 (r_w/(H_1 r_1))^2\,dn_1 \right] \qquad (1)$$

For conical part a three dimensional equation [7,8] are considered. It takes into account next system of nonequilibrium heterogeneous chemical reactions [8,9]:

$$1)\, C+O_2 \rightarrow CO_2,\, 2)\, 2C+O_2 \rightarrow 2CO,\, 3)\, C+O \rightarrow CO,\, 4)\, C+CO_2 \rightarrow 2CO,$$
$$5)\, C+O_2 \rightarrow CO+O,\, 6)\, O+O+C \rightarrow O_2+C,\, 7)\, N+N+C \rightarrow N_2+C,$$
$$8)\, 2NO+C \rightarrow N_2+O_2+C,\, 9)\, C \leftrightarrow C_1,\, 10)\, C \leftrightarrow C_2,\, 11)\, C \leftrightarrow C_3$$

Initial and boundary conditions [3,9] were used. For description of turbulent flow around body Cebeci–Smith turbulent model [10] were applied. Above mentioned systems of equations by using numerical methods [11-12] are calculated. Flow calculations around spherically blunted 10° cone at 5° incidence are performed for designed trajectory. Thermal physical characteristics for graphite [13,14] were used. The porosity coefficient $\varphi_1 = 0.34$, coefficients $\varepsilon_1 = \varepsilon_2 = 0.85$ are used. Initial shell's depth $L_0 = 2 \cdot 10^{-2}$ m, radius of spherical blunting $R_N = 0.1$ m. Thermal physical characteristics for Cu and Fe according to [1,5,15] were used. Distributions of blowing rate around spherical blunting are calculated by using formula (1) by setting the pressure P_k for inner gas cavity. Initial temperature for condense phase is equal 1000 K. Initial temperature of freezing gas was 300 K. The aim was to provide with above described ATPHS and PTHPS nonvolatile regimes for material of spherical blunting at hypersonic atmosphere entry.

Above and below u, v, w – velocity vector's components in natural coordinate system (s, n, η), t – time, P, ρ, T, m – pressure, density, temperature and total molar mass, R – universal gas constant, H_1 – metric coefficient, R_N – radius of spherical blunting, $\varepsilon_i, i = \overline{1,2}$ – coefficients of radiative capacity for body's surface, μ – dynamic viscosity coefficient, $(\rho v)_{1w}$ – freezing gas rate, φ_1 – spherical blunting material's porosity, L – shell's depth, ξ – burning intensity, A, B – viscous and accelerative coefficients for Darcey's equation. Lower indices e, w, к fit to values on outer edge of boundary layer, fit to body's surface and to internal cavity with freezing gas, lower indices 1 и 2 fit to condense phases, lower index 0 fits to initial conditions. Inner normal to body's surface n_1 are led to inside body.

A trajectory parameters as flight height (fig. 1) and flight velocity (fig. 2) as time function are illustrated.

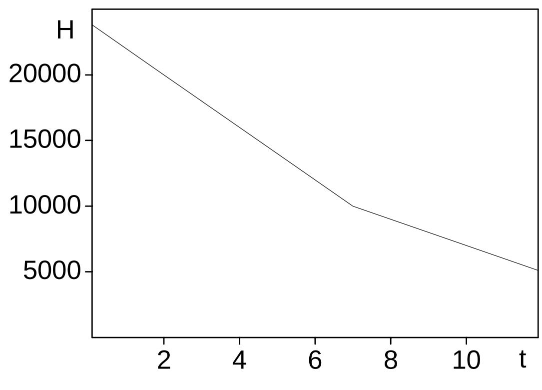

Fig. 1. Flight height H (m) against time t (s)

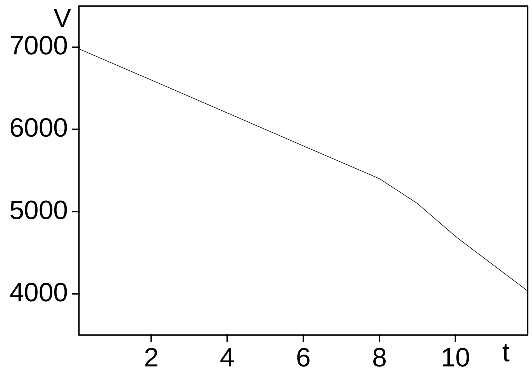

Fig. 2. Flight velocity V (m/s) against time t (s)

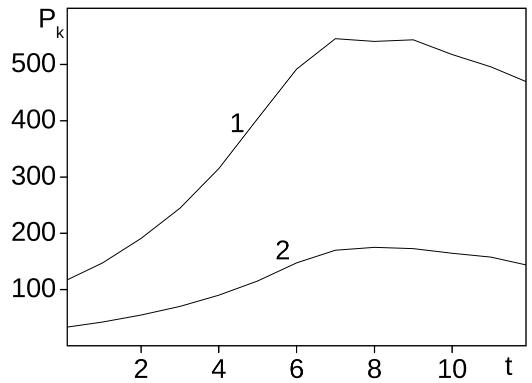

Fig. 3. Pressure in internal gas cavity P_k (Atm) against time t (s)

Line 1 on Fig. 3 corresponds to internal cavity's pressure P_k for spherical blunting form Cu, line 2 corresponds to one from Fe. It takes more intensive blowing rates of freezing air for Cu material than for Fe material. A reason is difference in thermal physical characteristics and in Darcey's coefficients for different materials.

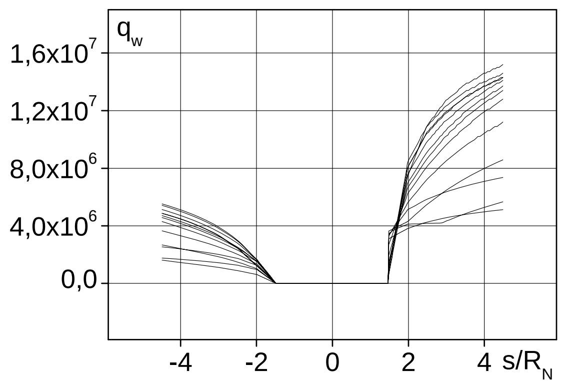

Fig. 4, *a* Convective heat flows in symmetry plane q_w (W/m^2) against dimensionless s/R_N for Cu

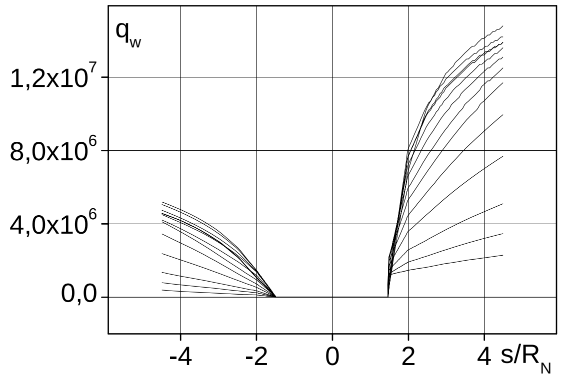

Fig. 4, *b* Convective heat flows in symmetry plane q_w (W/m^2) against dimensionless s/R_N for Fe

Upper curves on Fig. 4, *a*, *b* correspond to initial time. Freezing gas blowing is shielded convective heat flow. Conical part takes places in zone of thermal curtain which shows a decrease down-stream of flow. This effect implies monotonic increase at time of outer surface and internal surface temperatures (Fig. 5, 6). By body proceeds its trajectory convective heat flows monotonically decrease as a consequence of freezing air's rate growth (Fig. 7).

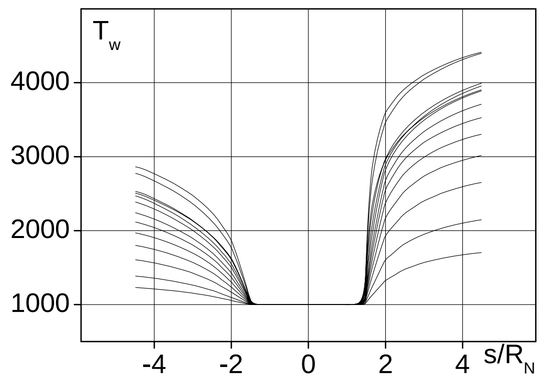

Fig. 5, *a* Outer surface temperature in symmetry plane T_w (K) against dimensionless s/R_N for Cu

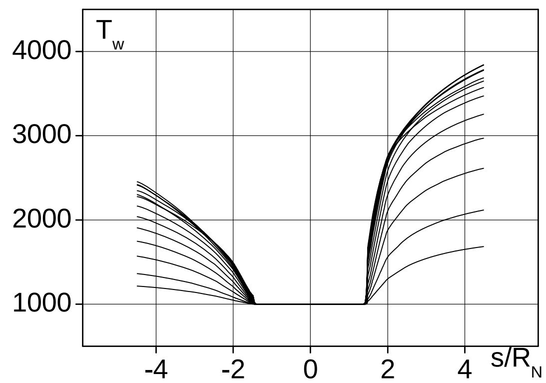

Fig. 5, *b* Outer surface temperature in symmetry plane T_w (K) against dimensionless s/R_N for Fe

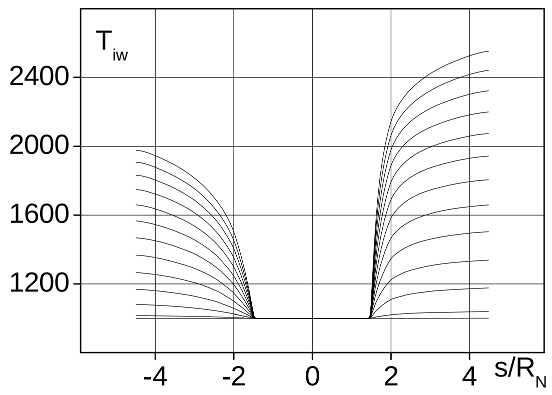

Fig. 6, *a* Internal surface temperature in symmetry plane T_w (K) against dimensionless s/R_N for Cu

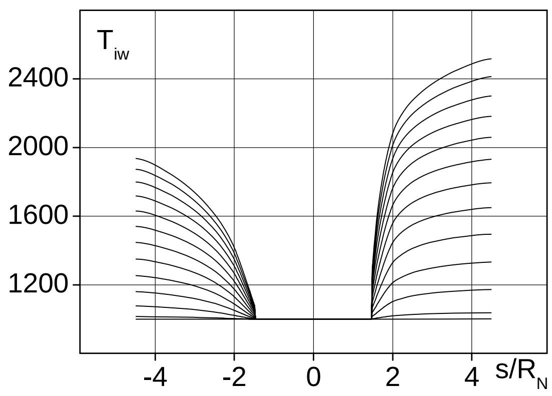

Fig. 6, *b* Internal surface temperature in symmetry plane T_w (K) against dimensionless s/R_N for Fe

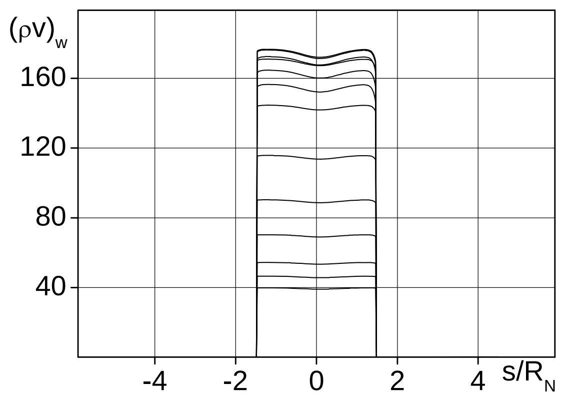

Fig. 7, *a* Blowing rates $(\rho v)_{1w}$ in symmetry plane (kg/(m^2·s)) against dimensionless s/R_N for Cu

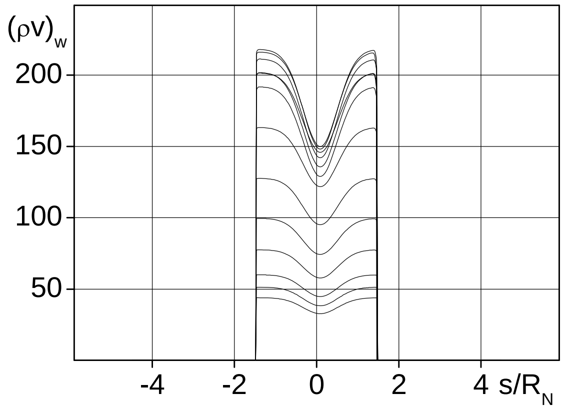

Fig. 7, *b* Blowing rates $(\rho v)_{1w}$ in symmetry plane (kg/(m^2·s)) against dimensionless s/R_N for Fe

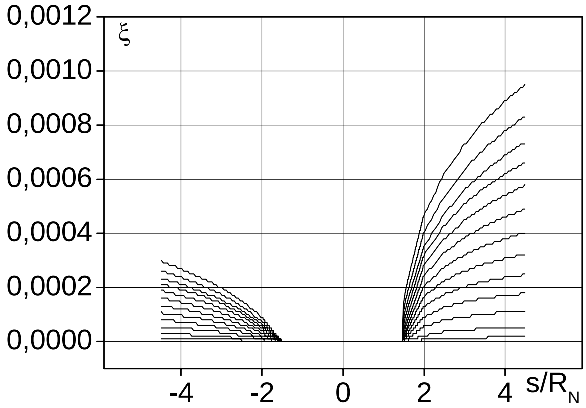

Fig. 8, *a* Burnout depth for graphite in symmetry plane (m) against dimensionless s/R_N for Cu

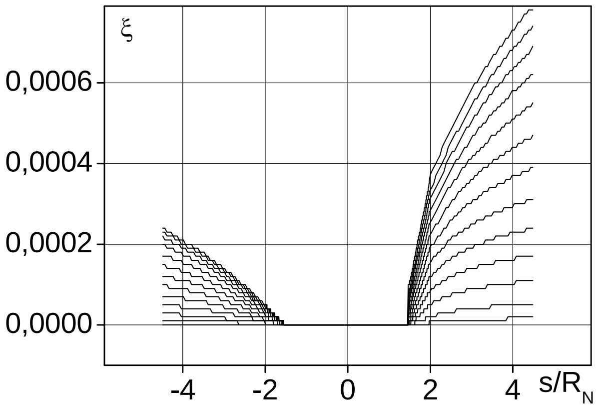

Fig. 8, *b* Burnout depth for graphite in symmetry plane (m) against dimensionless s/R_N for Fe

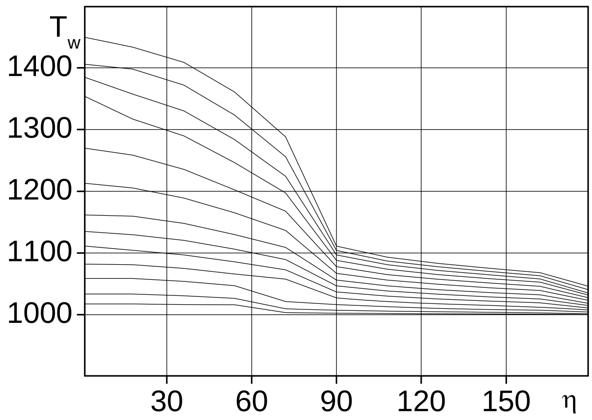

Fig. 9, *a* Outer surface temperature on circumferential coordinate T_w (K) on cone near sphere-cone conjugation for Cu

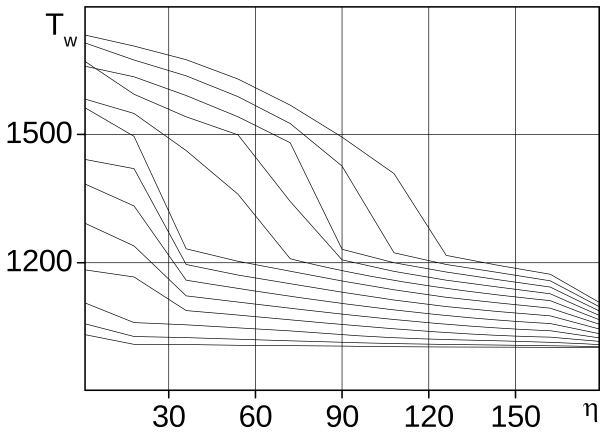

Fig. 9, *b* Outer surface temperature on circumferential coordinate T_w (K) on cone near sphere-cone conjugation for Fe

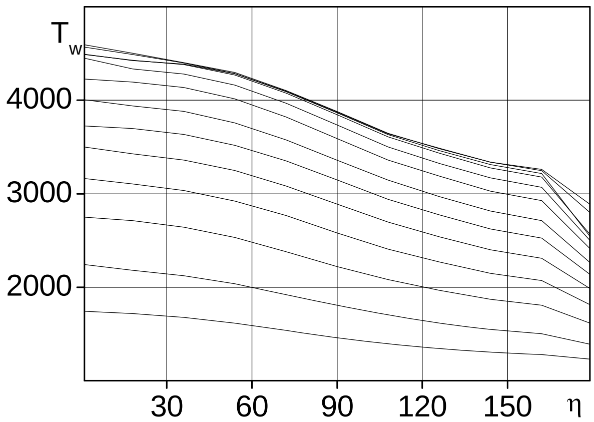

Fig. 10, *a* Outer surface temperature on circumferential coordinate T_w (K) on cone near sphere-cone conjugation for Cu

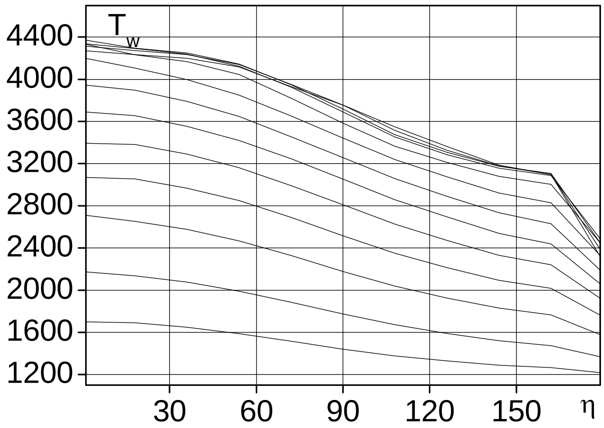

Fig. 10, *b* Outer surface temperature on circumferential coordinate T_w (K) on cone near sphere-cone conjugation for Fe

A monotonic growth of conical part's temperature is responsible for growth of burnout depth for graphite material of conical part (Fig. 8). An analysis of temperature distributions (Fig. 9, 10) leads to a withdrawal about possibility by using intensive freezing gas blowing to provide thermal protection for spherical blunting from metals. For conical graphite part a growth of temperature leads to thermal chemical destruction of graphite material. On windward side with less intensive gas curtain may takes place a sublimation (Fig. 10).

Conclusions

It takes larger level of cavity's pressure of refrigerating air for Cu material in comparison with Fe material as a result of larger resistance of Cu pores in comparison with Fe pores.

Describing conjugate model gives a possibility to estimate requirements for ATHPS and PTHPS to protect from thermal destruction spherical porous metallic blunting.

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