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THEORETICAL AND EXPERIMENTAL INVESTIGATION OF THE DESTRUCTION OF GRAPHITES IN A FLOW OF DISSOCIATED AIR

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16. Abstract

A method is presented for claculating the heating and erosion of blunt bodies made of graphite in a high-enthalpy flow of dissociate air, assuming thermal effects of combustion and sublimation of graphite. The analysis involves the use of a finite difference scheme to solve an equation of unsteady heat conduction. Attention is given to the equilibrium vaporization of C, C_2, and C_3 molecules. The calculations agree well with experimental data for a wide range of temperatures and stagnation pressures.

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THEORETICAL AND EXPERIMENTAL INVESTIGATION OF THE DESTRUCTION OF GRAPHITES IN A FLOW OF DISSOCIATED AIR

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Authors in this country and abroad have devoted a whole /85* series of experimental and theoretical studies to combustion of carbon materials in high-enthalpy air flows. However, the results of different researchers' calculations correlate quite poorly because of the difference in approaches to identifying definitive physico-chemical processes on the carbon's surface at high temperatures. Existing experimental relationships between carbon material gasification rate and surface temperature are also extremely contradictory.

Ablation of carbon material in a low-temperature air flow results basically from two processes: chemical interaction with the components of the air (accompanied by heat release) and sublimation of carbon (with heat absorption). While it is not difficult to follow the first process at rather high temperatures (2,500 K +), there is no consensus on the description of the second regarding either the kinetics of carbon sublimation or the composition of the sublimating gas. Disagreements in interpretation of the carbon sublimation mechanism result in considerable discrepancies in results in terms of carbon material gasification rate and temperatures of the surface being destroyed.

When the analytical procedure presented below was being developed, the authors' goal was to account as much as possible for all basic features of the process by which carbon material interacts with an air flow at high temperatures. In contrast to most existing studies, the problem of unstable heating and

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erosion of a blunted graphite body immersed in a dissociated air flow was also solved.

The proposed analytical procedure is used to solve the equation for unstable heat conductivity

$$\rho c \frac{\partial T}{\partial \tau} = -\frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right),$$ (1)

which is considered in finite-difference form with regard for dependency of the material's thermophysical properties on temperature for the given temperature profile and with the following boundary conditions:

● Heat insulation on the cold surface

$$\lambda \frac{\partial T}{\partial x} = 0 .$$ (2)

The energy balance on the surface where the carbon material interacts with the air flow is preserved in the form

$$\alpha c_p \left(J_e - J_w\right) - \varepsilon \sigma T_w^4 = -\lambda \left(\frac{\partial T}{\partial x}\right)_w + G\left(J_w - h_w\right),$$ (3)

where $$J_e = \sum_i h_i C_{ie} , \qquad J_w = \sum_i h_i C_{iw}.$$

For h_i, the study used approximations of tabular data from [2] in the form $$h = a_1 + a_2 T exp\left(\frac{a_3}{a_4 + T}\right).$$

The solution to the thermal conductivity equation requires that the "mobility" of the surface where the material interacts with the flow be taken into account.

To close system of equations (1)-(3) given known relationships between the enthalpies of the subject components and temperature, one must know the relationships between the gas mixture's composition and carbon ablation velocity, as well as pressure, temperature, and the coefficient of heat and

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mass exchange on the material's surface.

The carbon composition and ablation velocity at the material's surface can be determined only by defining the physico-mechanical interaction between the carbon material and the high-temperature flow of dissociated air.

The following physical model was used for the process by which carbon material interacts with a high-enthalpy air flow.

Just as in [3], the compositions of the gas in the flow and at the material's surface were regarded as equiponderant. On the "catalytic" surface of the carbon material, all chemical reactions proceed at an infinitely high speed.

Profiles for complete enthalpy and for the concentrations of all subject components are similar in the boundary layer.

Five components are considered on the outer edge of the boundary layer: O, N, O_2, N_2, NO; eleven on the carbon's surface: C_1, C_2, C_3, CO, N_2, CN, CO_2, N, NO, O_2, O.

Carbon vaporizes in the form of C, C_2, and C_3 molecules. Saturating vapor pressures for these components also satisfy conditions for chemical equilibrium at surface temperature.

It is not difficult to calculate the equilibrium composition of air at the outer edge of the boundary layer for the assigned temperature and pressure.

The following relationships are considered in determining composition at the surface.

● Equations for the law of mass action for molecular component (CO, CO_2, NO, O_2, C_2, C_3) atomization

reactions in the form

$$K_{AB} = (C_A \cdot C_B)/C_{AB} \qquad (4)$$

(of the seven equations, one can be replaced by Dalton's law
$\sum_i C_i = 1$).

● Equations for mass balance at the material's surface for atoms of

- nitrogen

$$\sum_i v_i^N \left[\alpha/c_p (C_{iw} - C_{ie}) + G C_{iw}\right] = 0, \qquad (5)$$

- oxygen

$$\sum_i v_i^o \left[\alpha/c_p (C_{iw} - C_{ie}) + G C_{iw}\right] = 0, \qquad (6)$$

- and carbon

$$\sum_i v_i^c \left[\alpha/c_p (C_{iw} - C_{ie}) + G C_{iw}\right] = G. \qquad (7)$$

● Mass balance for carbon vaporization

$$(\alpha/c_p + G)(C_{1w} + C_{2w} + C_{3w}) = \sum_{n=1}^{3} \dot{m}_{Cn}, \qquad (8)$$

where $\dot{m}_{Cn} = \alpha \sqrt{M_{Cn}} (P_{Cn}^{HOC} - P_{Cnw})/\sqrt{2\pi R T_w}$ is the speed of vaporization for carbon in the form of C_n molecules, where

$$P_{Cn}^{HAC} = (P_{C1}^{HAC})^n / K_{Cn}$$

To solve system of equations (4)-(8) relative to G and C_{in} (which are functions of T_w), static pressure and the factor for heat-mass exchange (α/c_p) must be set.

Fey-Riddel's formula [4] was used to calculate α/C_p for

immersion of a blunted body.

If solid carbon gasification is intense, ... must be calculated with a correction for blowing (cf. e.g. [51]). Approximations of tabular data from [2] in the form

$$lg\ K = A + B/T + C\ lg\ T.$$

below were used for the temperature dependence of molecular component atomization constants and carbon vapor saturating pressure.

Thus, this system of basic equations (1)-(8) is closed, and its solution makes it possible, generally speaking, to determine flow parameters which are variable over time (P'_0, T'_0, $\mathcal{L}/C_p$), ablation velocity, gas composition at the surface, and temperature profiles deep in the material, at any time.

The algorithm for numerical solution of this system of equations has been compiled in ALGOL-60 for the BESM-4M computer.

A specially designed high-temperature setup (described in detail in [6]) was used to test cylindrical graphite samples 14 mm in diameter and 40 mm long in a supersonic flow of dissociated air. Flow parameters and test results are presented in the table below (tests 1-4).

Test No.	Graphite density g/cm^2	P'_0, ata	T'_0, K	W, mm/sec	T_w, K
1	1.94	5.5	5,600	0,17	3,100
2	1.65	6.0	4,500	0.20	3,100
3	1.65	5.75	5,900	0.36	3,000
4	1.80	17.0	4,800	0.4	3,200
5	2.2	1.2	6,310	0.078	3,100
6	2.2	1.0	8,100	0.31	4,000

Results of tests 5 and 6 are presented in [7] and pertain to pyrographite.

Results of calculation using the proposed procedure and the experimental data presented here are shown in the figure.

The arrangement of points on the figure close to the ray running at a 45° angle to the x-axis indicates a completely satisfactoy correlation between results of calculation and experimental data for the range of temperatures and pressures studied.
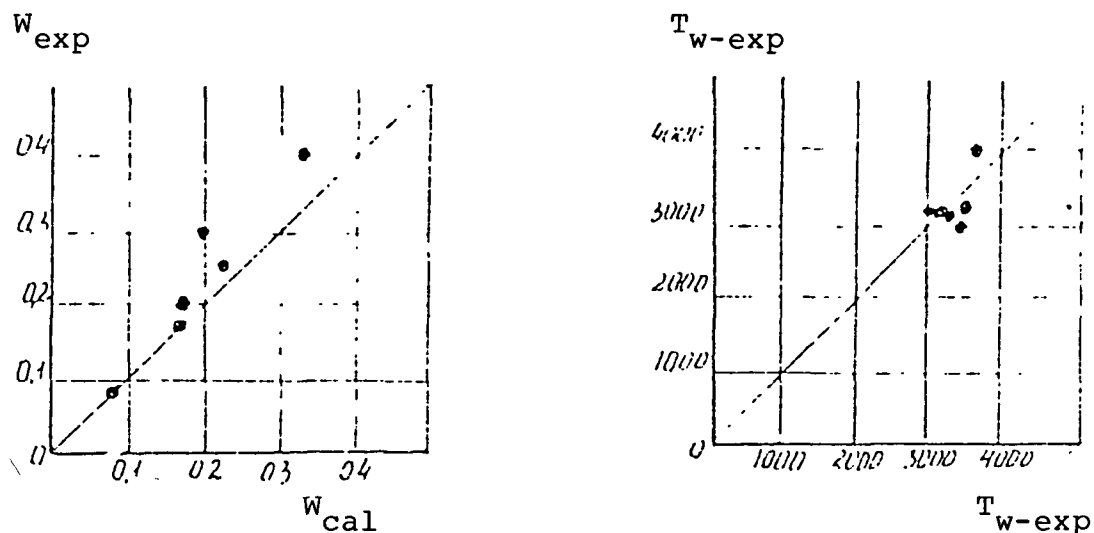

Fig. Comparison of calculated and experimental data on the linear velocity of ablation (W, mm/sec) and surface temperature (T_w, K).

A good correspondence of calculation results and experimental data for G and T_w indicates that elementary processes occurring during interaction of carbon materials and a high-temperature air flow have been correctly taken into account.

Symbols

λ/C_p - heat and mass exchange coefficient; α - vaporization factor; ε - emissivity factor; v_i^N - number of N atoms in a molecule of the i-th component; λ - thermal conductivity factor; ρ - graphite density; σ - Stephen-Boltzmann constant; C_i - weight concentration of the i-th component; G - carbon ablation velocity; h - specific chemical enthalpy; J - total chemical enthalpy of the gas mixture; K_{AB} - equilibrium constant for the reaction AB $\rightleftarrows$ A + B; M - molecular weight; P'_0 - pressure behind a straight shock wave; P_{Cn}^{HAC} - saturation pressure of C_n; R - universal gas constant; T'_0 - temperature behind a shock wave.

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