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AIR FORCE SYSTEMS COMMAND

BURNING OF GRAPHITE IN AN AIR FLOW AT HIGH TEMPERATURES

by

N. A. Anfimov

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А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yë or ë.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	sian	English	Russian	English
sin	sin	sh	sinh	arc sh	$\sinh^{-1}$
cos	cos	ch	cosh	arc ch	$\cosh^{-1}$
tg	tan	th	tanh	arc th	$\tanh^{-1}$
ctg	cot	cth	coth	arc cth	$\coth^{-1}$
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

BURNING OF GRAPHITE IN AN AIR FLOW AT HIGH TEMPERATURES

N. A. Anfimov

In the overwhelming majority of theoretical investigations the examination of various problems of the boundary layer is conducted with the use of a presentation of component mixtures of gases as binary. In work [1] it was shown that this presentation gives good results and is fully warranted with the calculation of heat exchange and friction on an impermeable surface in dissociated air.

However, the presentation of a multi-component mixture of gases as a binary proves to be unsuitable in the presence in the mixture of three or more components with different properties, and also for a pseudo-binary mixture of gases in the presence of interdiffusion within each group of components.

The importance of the condition of constancy of direction of diffusion for the latter case can be demonstrated in the example of a boundary layer on the surface of graphite streamlined by high-temperature dissociated air.

The problem on the breakdown of graphite in a flow of high-temperature air is also of independent interest since graphite is a promising material for use at high temperatures [2].

1. Scheme of breakdown of graphite in a flow of dissociated air. With the streamlining of a graphite body by dissociated air two processes occur simultaneously which are connected with carry-off of the mass of material - sublimation and chemical interaction between carbon and and drag. Let us examine some features of these processes.

Sublimation. With normal pressure, graphite changes to a gas-like state, by-passing the liquid phase. Graphite vapors consist of various gas-like carbon compounds: C, C_2, C_3, C_4, C_5, C_6 and C_7 [3]. In the case of a substance whose vapors consist of a single product, the rate of evaporation is determined by the Knudsen-Langmuir ratio

$$G_i = \frac{\alpha (p_{i\text{н}} - p_i)}{\sqrt{2\pi T_w R / M_i}} \tag{1.1}$$

Here $p_{i\text{н}}$ - pressure of saturated vapors (equilibrium pressure), p_i - pressure of the vapors of the material at the surface, α - evaporation coefficient, R - gas constant, M_i - vapors' molecular weight, T_W - surface temperature.

Here, it turns out that in the absence of chemical reactions in the process of carry-off of mass, the pressure of vapor at the surface is close to equilibrium [4].

In the case of a substance whose vapors consist of several gas-like products, just as in the case of graphite, the full evaporation rate is determined as the sum of evaporation rates in the form of individual products. For graphite, according to the data in work [3], $\alpha_C=0.3$; $\alpha_{C_2}=0.5-1.0$; $\alpha_{C_3}=0.1$, and for the remaining compounds of carbon the evaporation coefficient is close to null. According to the data of other authors, we obtain other values of evaporation coefficient [5].

Chemical interaction of graphite with dissociated air. At high temperatures there can occur the following chemical reactions between carbon and the components of air (we have written only independent reactions):

$$C + O \rightleftarrows CO, \quad C + N \rightleftarrows CN$$
$$C + 2O \rightleftarrows CO_2, \quad 2C + 2N \rightleftarrows C_2N_2$$

There are data in literature [6] which attest to the fact that reactions between graphite and oxygen are heterogeneous. This means that carbon is combined with oxygen of air directly in the solid phase, by-passing the sublimation stage. Chemical reactions between graphite and oxygen occure in several stages [7]. First, atoms and molecules of oxygen diffuse through the boundary layer to the graphite surface. After this, they are adsorbed by the surface. Then there occurs a strictly chemical reaction between carbon and oxygen. The following stage - desorption of products of the reaction from the surface and, finally - diffusion of these products through the boundary layer.

The speed of the reaction is wholly determined by the speed of the slowest of the elementary processes. At low temperatures of the surface, this determining process is the strictly chemical reaction. There is, presently, a sufficient amount of data on the kinetics of burning of carbon at temperatures up to 1300-1800° K [6]. These data can also be used for conducting quantitative calculations, as was done in work [8]. Here, we must not forget that the constants of the rate of oxidation of graphite strongly depend on the porosity and on technological factors.

At temperatures of the surface on the order of 3000° K, the determinant becomes the rate of diffusion in the boundary layer. In this case the chemical composition of gas in the surface can be considered equilibrium since the gas-like products of carry-off continuously are led away from the surface by means of convection and diffusion through the boundary layer. Here, the rate of this lead-off depends on the interaction of various mechanisms of the carry-off of mass-chemical reactions and sublimation. It also turned out above that reactions between carbon and oxygen occur on the surface of the body; therefore, it is incorrect to propose that graphite first sublimates then enters into the chemical reaction with oxygen as was done in work [9]. In this case, the rate of the process is limited by the rate of sublimation of carbon, which leads to a decrease in the rate of carry-off of mass and an increase in temperature of the decomposing surface. For example, according to the data in work [9], for the breakdown of spherical body made of graphite with a diameter of 2 m, with streamlining by an oxygen flow with temperature T_e=6661° K and pressure p=0.93 atm, the rate of carry-off of mass is acquired as equal to $G \approx 0.013$ kg/m^2sec, and the temperature of the surface $T_w \approx 3600°$ K, while according to the method of the present work it turns out that G=0.050 kg/m^2sec and T_w=2515°K.

However, even if we consider the reaction of carbon with oxygen to be heterogeneous, the question on the path of formation of gas-like carbon remains unclear - C, C_2, C_3, C_4, C_5, C_6 and C_7. Carbon vapors can be formed as a result of sublimation of graphite or as a result of dissociation of gas-like products of the chemical interaction of graphite with carbon and nitrogen.

We propose that the rate of dissociation of these products is low in comparison with the rate of sublimation and that, consequently, the entire gas-like carbon is formed as a result of sublimation of graphite.

The system of boundary conditions on the surface of graphite has the form:

equation of continuity for carbon

$$\rho \sum_i \nu_i^{(C)} c_i V_i + G_V \sum_i \nu_i^{(C)} c_i = G_V \qquad (1.2)$$

equation of continuity for nitrogen

$$\rho \sum_i \nu_i^{(N)} c_i V_i + G_V \sum_i \nu_i^{(N)} c_i = 0 \qquad (1.3)$$

equation of nonequilibrium sublimation

$$\sum_{k=1}^{7} \frac{\alpha_{C_k} (p_{C_{kn}} - p_{C_k})}{\sqrt{2\pi T_w R / M_{C_k}}} = \rho \sum_{k=1}^{7} c_{C_k} V_{C_k} + G_V \sum_{k=1}^{7} c_{C_k} \qquad (1.4)$$

equation of equilibrium for independent chemical reactions

$$\frac{p_O}{\sqrt{p_{O_2}}} = K_{p_1}, \quad \frac{p_N}{\sqrt{p_{N_2}}} = K_{p_2}, \quad \frac{p_{NO}}{\sqrt{p_{O_2} p_{N_2}}} = K_{p_3} \quad \frac{p_{CO}}{p_C p_O} = K_{p_4}$$

$$\frac{p_{CO_2}}{p_C p_{O_2}} = K_{p_5}, \quad \frac{p_{CN}}{p_C p_N} = K_{p_6}, \quad \frac{p_{C_2N_2}}{p_C^2 p_N^2} = K_{p_7}, \quad \frac{p_{C_k}}{p_C^k} = K_{p_{6+k}} \quad (k = 2 + 7) \qquad (1.5)$$

curves of elasticity of saturated carbon vapors

$$p_{C_{kn}} = f_k(T_w) \qquad (k = 1 + 7) \qquad (1.6).$$

balance of energy on the surface of graphite

$$\lambda \frac{\partial T}{\partial y} - \Sigma \rho c_i V_i h_i - G_V h_w + G_V h_{1w} - \lambda_1 \frac{\partial T_1}{\partial y} - \varepsilon \sigma T_w^4 = 0 \qquad (1.7)$$

In the equations given above, ρ - density, T - temperature, h - enthalpy, λ - coefficient of heat conductivity, p_i - partial pressure of the i-components, c_i - mass concentration of the i-component, V_i - rate of diffusion, $\upsilon_i^{(j)}$ - mass content of the j-element in the i-component, G_V - rate of carry-off of mass of the material in the gas-like form, K_p - constants of reactions' rates, ε - integral radiating ability of graphite, σ - Stephan-Boltzmann constant; with index w we indicate the values of parameters on the surface, with index 1 - the properties of solid graphite.

If we propose that graphite breaks down exclusively by means of sublimation and chemical interaction, then from the equation of balance of energy we can determine the temperature of the surface of graphite in the process of breakdown. However, with large heat flows it turns out that the thusly-determining temperature of graphite surface can reach too-high values (4000°K and more). There arise doubts relative to the ability of graphite to maintain dynamic forces present at such a temperature. For this, in order to acquire the higher evaluation of the rate of breakdown of graphite in similar conditions, we propose the following approach.

We propose that graphite loses mechanical strength with some "threshold temperature" T^*. Then, if from equation (1.7) with $G=G_V$ it follows that $T_W>T^*$, then we consider that the temperature of the surface is equal to its maximum value T^*, and the excess energy occurs for the mechanical breakdown of graphite, in which regard we propose that the break-off of solid particles of graphite occurs without additional consumption of energy; the separated particles do not test the physical-chemical conversions within the boundary layer and, moreover, these particles do [illegible]nder an influence on the heat and diffusion flows which approach the surface of the body. In this case, from equation of balance of energy (1.7) we can determine the full speed of carry-off of mass of graphite with consideration of its mechanical breakdown.

The lead-off of heat with heat conductivity within the body, generally speaking, must be calculated with consideration of the specifics of the problem since the coefficient of heat conductivity of graphite is extremely great. We will propose that the heat flow within graphite corresponds to the stationary linear breakdown of the semi-infinite body. In this case (h_{10} - enthalpy of unheated graphite)

$$\lambda_1 \frac{\partial T_1}{\partial y} = G\left(h_{1w} - h_{10}\right)$$

and equation (1.7) takes the form

$$\lambda\frac{\partial T}{\partial y}-\Sigma\rho c_i V_i h_i-G_V h_w-(G-G_V)h_{1w}+Gh_{1e}-\varepsilon\sigma T_w^4=0 \qquad (1.8)$$

After the system of boundary conditions on the surface of graphite is recorded, for a full solution to the problem we must have a method for calculating the heat- and mass-exchange on the surface of the breaking-down body. With this purpose, we can use either approximation engineering methods or methods of numerical integration of equations of boundary layer.

The approximation method of calculating heat- and mass-exchange on the breaking-down surface leads to the following: a) we calculate the coefficients of heat exchange on an equivalent impermeable surface; b) we conduct a correction for the injection of products of breakdown of graphite into the boundary layer; c) we calculate the coefficients of mass exchange according to the coefficients of heat exchange with the use of an analogy between the processes of heat- and mass exchange.

For conducting similar calculations, there are different approximation formulas. Some of them are done in works [10,11] and many others.

A numerical solution to the equations of multi-component boundary layer is very difficult and laborious, although it permits considering all the features connected with the complex character of the processes of transfer in the multi-component boundary layer which cannot be fully clarified with the aid of approximation solutions.

In the present work, a theoretical investigation of the carry-off of mass of graphite is done on the basis of a numerical solution to the equations of a multi-component boundary layer.

2. Numerical solution to the equations of a multi-component boundary layer on the surface of graphite. We will confine ourselves to an examination of the laminar boundary layer in the area of the critical point of an axisymmetrical blunt body. In this case the introduction of variables

$$\xi = \int_0^x \rho_w \mu_w u_e r^2 dx, \qquad \eta = \frac{r u_e}{\sqrt{2\xi}} \int_0^y \rho dy$$

permits switching tc normal differential equations. In these variables the system of equations of a multi-component boundary layer has form

$$(lf'')' + ff'' + \frac{1}{2}\left(\frac{\rho_e}{\rho} - f'^2\right) = 0, \qquad l = \frac{\rho\mu}{\rho_w \mu_w} \qquad (2.1)$$

$$\left(\frac{c_p l}{P}\theta'\right)' + \left(c_p f - \sum c_{pi} v_i\right)\theta' - \frac{1}{B}\sum \frac{w_i h_i}{\rho T_e} = 0, \quad \theta = \frac{T}{T_e}, \quad B = 2\left(\frac{du_e}{dx}\right) \qquad (2.2)$$

$$v_i' - f c_i' - \frac{w_i}{\rho B} = 0, \qquad v_i = \frac{l \rho c_i V_i}{\mu \partial\eta / \partial y} \qquad (2.3)$$

Here x and y - axes of coordinates directed along the surface and along the normals to it, u_e - speed at the outer boundary of the boundary layer, 3 - dimensionless temperature, v_i - dimensionless diffusion flow of the i-component, c_p - specific heat capacity with constant pressure, μ - viscosity, f - dimensionless function of flow, P - Prandtl number, w_i - speed of formation of the i-component as a result of chemical reactions. With index e we indicate the values of parameters at the external border of the boundary layer, the dash indicates the differentiating with respect to η.

In the previous work of the author [12], devoted to the carry-off of mass of textolite and graphite, the diffusion flows were calculated according to the Wilke approximation formula [13, which proposes that the diffusion flow of each component is determined only by the derived strict concentration

$$c_i V_i = -D_i \frac{\partial c_i}{\partial y}, \qquad D_i = (1 - x_i)\left(\sum_{j \neq i} \frac{x_j}{D_{ij}}\right)^{-1} \qquad (2.4)$$

Here D_{ij} - coefficients of binary diffusion, and x_i - mole concentration. For a strict formulation, we must consider the dependence of diffusion flow of each component on the derived concentrations of all components which are present in the mixture. The relationships between derived concentrations and diffusion flows are presented in work [14]; after transition to mass concentrations and the dimensionless variables accepted in the present work, these relationships are written in the form

$$\frac{1}{l}\sum_{j=1}^{N}\frac{M}{M_j}(c_i v_j - c_j v_i)S_{ij} = c_i' + \frac{c_i}{M}M' - (\ln\theta)'\sum_{j=1}^{N}\frac{M}{M_j}(c_i D_j^T - c_j D_i^T)S_{ij} \qquad (2.5)$$

$$(S_{ij} = \mu/\rho D_{ij})$$

Here, S_{ij} - Schmidt number for binary diffusion, and D_i^T - dimensionless coefficients of thermodiffusion. The system of equations (2.5) is closed by relationship

$$v_1 + \ldots + v_N = 0, \qquad (2.6)$$

which shows that the sum of diffusion flows is identically equal to null within the boundary layer.

A direct substitution into the equations of continuity of the individual components (2.3) of diffusion flows, acquired from the solution of the linear system of algebraic equations (2.5) and (2.6) leads to a system of differential equations of the second order, impermissable relative to the higher derivatives. A direct solution to this system with iteration methods causes objections from the point of view of stability. Therefore, it is desirable to preliminarily solve this solution of equations (examined as algebraic) relative to the second derived concentrations. On the whole, this method proves to be ineffective.

More effective is another method which is used below. In order to obtain a system of differential equations for concentrations, we must differentiate the system for diffusion flows [15,16]. Here, the derived diffusion flows are expressed with the aid of equations of continuity of individual components, and the second derivative of temperature - with the aid of energy equation. Here, we immediately acquire a system of differential equations, permissable relative to the higher derivatives (with an accuracy to the small member of the set $(M\Sigma c_i'/M_i)']$. In the final form, the equations for concentrations in a multi-component boundary layer looks like this:

$$c_i'' + a_i c_i' + b_i = 0, \qquad a_i = -M\sum_{j=1}^{N}\frac{c_j'}{M_j} - fk_{ii}$$

$$b_i = -c_i\left(M\sum_{j=1}^{N}\frac{c_j'}{M_j}\right)' - \sum_{j=1}^{N-1}k_{ij}'v_j - f\sum_{j\neq i}^{N-1}k_{ij}c_j' + \sum_{j=1}^{N-1}k_{ij}\frac{w_j}{\rho B} + \tag{2.7}$$

$$+\frac{K_i}{\Theta}\left\{\frac{P}{c_p l}\left[\left(\frac{c_p l}{P}\right)' + c_p f - \sum_{j=1}^{N}c_{p_j}v_j\right]\Theta' - \frac{P}{\rho l B}\sum_{j=1}^{N}\frac{w_j h_j}{\rho T_e}\right\} + \left(\frac{\Theta'}{\Theta}\right)^2 K_i - \frac{\Theta'}{\Theta}K_i'$$

and coefficients K_{ij} and K_i are determined from system of equations

$$c_i' - c_i M\sum_{j=1}^{N}\frac{c_j'}{M_j} = \sum_{j=1}^{N-1}k_{ij}v_j - K_i(\ln\Theta)'$$

With a practical solution to the system of equations of the boundary layer in the present work, we used the following additional propositions: a) the rates of chemical reactions within the boundary layer are equal to null, b) the contribution of thermodiffusion to the processes of transfer of mass and energy can be disregarded.

With a numerical integration of the full system of equations of a multi-component boundary layer, the time of calculation quickly grows with an increase in the number of components (approximately proportionally to the square number of components). Therefore, we decided to stay with a relatively small number of components, with which it would be possible to conduct a rather wide series of calculations and clarify the basic features of carry-off of mass of graphite. Thus, the number of components in the boundary layer was shortened to eight: O, O_2, N, N_2, NO, C, CO and CN.

The sequence of solution to the system of equations (2.1), (2.2), (2.5) - (2.7) with consideration of the boundary conditions (1.2)-(1.7) was as follows.

1. As the null approximation, we assign random values of the flow function on the wall, temperatures of the surface and concentrations of all components at the wall; in the present work, the null approximation for the conditions on the surface was selected in the following manner:

$$f_w^\circ = 0, \qquad T_w^\circ = 1000 + 0.25T_e$$
$$\dot{c}_{\mathrm{CO}_w} = \dot{c}_{\mathrm{N}_{2w}} = 0.5, \qquad \dot{c}_{\mathrm{O}_w} = \dot{c}_{\mathrm{O}_{2w}} = \dot{c}_{\mathrm{NO}_w} = \dot{c}_{\mathrm{N}_w} = \dot{c}_{\mathrm{C}_w} = \dot{c}_{\mathrm{CN}_w} = 0 \qquad (2.8)$$

2. After this, we assign initial profiles of speed, temperature and concentrations within the boundary layer. For this purpose, we used profiles similar to the profile of speed in uncompressed liquid (Blazius profile).

3. Profiles of concentrations were differentiated, and, according to values c_i' from system (2.5), (2.6) diffusion flows were found.

4. Then system (2.1), (2.2) and (2.7) was solved with normal boundary conditions (2.8) on the wall. For solving this system, we used a method of trials, the use of which in equations of boundary layer is described in work [17].

5. According to the acquired solution to equations of boundary layer, we found the coefficients of mass exchange β_i and coefficients of heat exchange due to the molecular heat conductivity α_λ

$$\beta_i = \frac{(\rho c_i V_i)_w}{c_{i_w} - c_{i_e}}, \qquad \alpha_\lambda = \frac{1}{T_e - T_w}\left(\lambda \frac{\partial T}{\partial y}\right)_w,$$

6. On the basis of the thusly-determined coefficients β_i and α_λ with the aid of boundary conditions on the breaking-down surface (1.2) -(1.7) we made more accurate values f_W, T_W and c_{i_W}. Here, the tie

between value of flow function on the wall and the speed of carry-off of mass of the material in gas phase is given by expression

$$f_w = -\frac{G_V}{\sqrt{B\rho_w\mu_w}}$$

If it turns out that $T_W > T^*$, then this is an indication of the presence of mechanical carry-off. In this case, as was shown above, we propose $T_W = T^*$, and from relationship (1.7) we find the full speed of carry-off of graphite mass with consideration of its mechanical breakdown.

Table. Parameters of potential function of the interaction between particles (asterisks * indicate interpolation according to molecular weights).

Компо-ненты ①	σ_i [Å]	Источник ②	$\frac{\varepsilon_i}{K}$ [°K]	Источник ②
O	2.96	[20]	44	*
O_2	3.433	[14]	113.2	[14]
N	2.88	[20]	38	*
N_2	3.681	[14]	91.46	[14]
NO	3.47	[14]	119	[14]
C	2.80	*	33	*
CO	3.59	[14]	110.3	[14]
CN	3.50	*	100	*

Key: 1 - component; 2 - source.

The sequence given above of actions was repeated, beginning from point 3 up to the time when the relative divergence between the two sequential approximations did not become less than some value δ. The approximations were compared according to values of speed of carry-off of mass, temperature and concentrations, also their derivatives on the surface of the body. For acquiring convergence with an accuracy of $\delta = 10^{-4}$ about 40 approximations were required.

The method of calculating the properties of individual components was the same as in works [1, 12, 15]. Here, for calculating enthalpies of individual components and constants of equilibrium, we used the tables from work [18]. It was proposed that the interaction of all particles present in the mixture is described by the Lennard-Johns potential (6-12). The values of force constants used are given in the table.

3. Simplified methods of numerical solution to the system of equations of a multi-component boundary layer. For diffusion flows, as usual, we accepted the following presentation

$$c_i V_i = -D_i \frac{\partial c_i}{\partial y} \tag{3.1}$$

In this case, the equations of continuity of individual components are simplified and have the form

$$\left(\frac{l}{S_i} c_i'\right)' + f c_i' = 0 \quad \left(S_i = \frac{\mu}{\rho D_i}\right) \tag{3.2}$$

where S_i - Schmidt number.

The diffusion coefficients in (3.1) are determined by two methods: by the Wilke formula (2.4) and by the formula for binary mixture of gases where the coefficient D_i is one and the same for all components.

The presentation of diffusion coefficient of each component according to the Wilke formula was used in the author's preceding work [12]. In this case, the sum of diffusion flows does not change identically to zero; therefore, with the solution to equations, we introduced into the diffusion flows a proportional correction.

In the case of the presentation of a multi-component mixture of gases as the binary, the coefficient of diffusion in exrression (3.1) is identical for all components. In the given case, the mixture of gases can be divided into two groups with approximately identical properties: 1st group - O, N, C; 2nd group - O_2, N_2, NO, CO, CN.

We normally recommend as the single coefficient of diffusion taking the coefficient of binary diffusion one of of the components of the

1st group with one of the components of the 2nd group. However, we can only do this in the case when all the components of each group are differentiated in one direction. In the problem of carry-off of graphite mass, the latter condition is not accomplished. So, in the 1st group the atoms of oxygen and nitrogen diffuse to the surface, and the atoms of carbon - from it; in the 2nd group the molecular oxygen and some other components diffuse to the surface, and the carbon oxide and cyane - to the opposite direction. Therefore, we decided to conduct calculations for two coefficients of binary diffusion: (a) $D_i = D_{O-CO}$, (b) $D_i = D_{O_2-CO}$

The system of boundary conditions on the surface of graphite and the sequence of computations with the presentation of diffusion flows in the form (3.1) remain unchanged.

Figure 1.

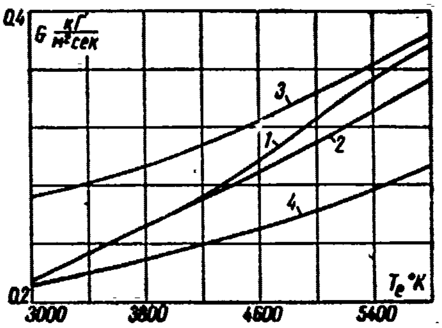
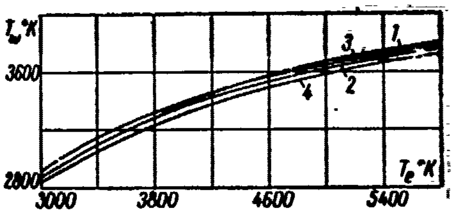


Figure 2.



4. Results of numerical solution. Calculations were conducted for drag with parameters T_e=3000-6000°K, p=5 atm.

It was accepted that graphite has the form of a cylinder with a flat end with a diameter of 14 mm. The integral radiating ability of graphite was considered equal to 0.8 [2], evaporation factor - α=1 [19].

Numerical integration of equations of the boundary layer was done in the region $0 \leq \eta \leq 10$ with a step of η equal to $h=0.1$. The control checks with step $h=0.05$ showed that the divergence of results has the same order as the assigned degree of convergence δ.

The results of calculation of speed of carry-off of mass G(kg/ /m^2·sec) and temperature of the surface of graphite T_W °K depending on temperature of braking T_e °K are presented in Fig. 1 and 2, where curve 1 - accurate solution; curve 2 - Wilke formula with a modification; curves 3 - binary solution for $D_i=D_{O-CO}$; curves 4 - binary solution for $D_i=D_{O_2-CO}$. Let us note that none of the limitations on value of temperature of the surface with those computed apply.

We can conclude that the rate of breakdown of graphite, which is directly connected with the rates of diffusion of various components within the boundary layer, is more sensitive to the method of calculation of diffusion in a multi-component boundary layer. The temperature of the surface is more stable a factor. As concerns a quantitative comparison of the approximation methods with an accurate solution," the best results are acquired for the modified Wilke method. With the aid of this method, a satisfactory comparison with the accurate colution is obtained for the entire studied range of change in parameters, in which regard the error of determining the speed of breakdown with T_e=3000-4000°K is less than 1%, and with T_e=5000-6000°K the error increases to 5%.

The fact that the Wilke approximation formula (with subsequent modification) qualitatively accurately describes the process of diffusion in a multi-component boundary layer on breaking-down graphite, we can see from a comparison of values of the coefficients of mass-exchange β_i, computed for various components with p=5 atm and T_e= =5000°K conforms to the accurate solution ($\beta_i=\beta_i'$) and according to the Wilke formula with modification ($\beta_i=\beta_i''$)

	C	CO	CN	O	O_2	N	N_2	NO
$\beta_i'=$	1.812	1.208	1.253	1.500	1.145	1.591	0.973	1.145
$\beta_i''=$	1.856	1.259	1.297	1.418	1.105	1.533	1.150	1.106

For all components, with the exception of molecular nitrogen, the divergence does not exceed 6%. In molecular nitrogen the divergence reaches 18%, in which regard this circumstance is connected with the anomolous behavior of the coefficient of mass exchange for N_2, which can be established only as a result of solving the full system of differential equations and is not transferred by approximation methods (binary mixture, Wilke formula). With a calculation of the boundary layer with the use of presentation of binary diffusion, the coefficients of mass exchange were identical for all the components and withe the indicated conditions composed, respectively, β=1500 and β=1479 for two values (which we used) of coefficient of binary diffusion D_{O_CO} and $D_{O_2\_CO}$.

The use of the presentation of a multi-component mixture of gases as a binary does not permit the satisfactorily-accurate consideration of all the laws of change in speed of breakdown of graphite with a change in temperature of impact. However, with the aid of a properly selected coefficient of binary diffusion, we can obtain a satisfactory coincidence at one or another temperature. For example, with T_e=3000°K, the difference from the exact solution is 1.3% for $D_i=D_{O_2\_CO}$, and with T_e=6000°K, the difference from the exact solution is 2% for $D_i=D_{O\_CO}$. If an identical coefficient of binary diffusion is used in the entire range of change in impact temperature, the error in calculating the rate of breakdown of graphite can reach 25%. We can conceive an approximation method of calculating a multi-component boundary layer based on the introduction of a "determining coefficient of diffusion" similar to the method of the determining temperature or determining enthalpy, with the aid of which the results for heat exchange or friction for uncompressed liquid with constant properties are transferred to the case of compressed gas.

As we noted above, the temperature of the surface of graphite depends on the method of calculation of the rates of diffusion less strongly. So, in the investigated range of parameter change, the maximum divergence in value of surface temperature does not exceed 100°K, i.e. 3%.

An increase in rate of carry-off of mass of graphite with an increase in impact temperature of the air flow is explained by two factors. First, we see here an increase in the degree of dissociation of oxygen, as a result of which the diffusion flow of oxygen to the surface grows, since the atoms of oxygen possess larger diffusion coefficients than molecules. Secondly, there occurs here a change in the mechanism of carry-off of mass of graphite. Since with an increase in impact temperature the surface temperature grows simultaneously, then besides the formation of a carbon oxide the role of sublimation of carbon (at low pressures) and formation of cyanogen (at high pressures) begins to increase. Figure _ shows the relative fraction of sublimation of graphite $\Psi_C=G_C/G$ and the formation of cyanogen $\Psi_{CN}=M_C G_{CN}/M_{CN} G$ in the process of carry-off of mass of graphite. We can see that with T_e=6000°K and p=5 atm, dur to the formation of cyanogen more than 30% of the mass of graphite is carried off.

Figure 4 shows the influence of limitation of surface temperature of graphite on its mechanical breakdown. Along the y-axis lies the fraction of carry-off of graphite mass in the gas-like form, and along the x-axis - maximum surface temperature. Calculations were conducted for the following parameters of drag: p=5 atm, T_e=6000°K. The results of calculations show that the slight decrease in surface temperature of graphite as a result of loss of mechanical strength leads to a sharp increase in mechanical carry-off of mass. We can also make an inverse conclusion: if the fraction of mechanical breakdown of graphite is not very great, its surface temperature here hardly decreases at all.

The degree of the nonequilibrium state of graphite sublimation for the mechanism of mass carry-off used proved to be very low. The pressure of carbon vapors can, with an accuracy sufficient for practice, be considered equal to the pressure of saturated vapors since it differs from this maximum value by only 1-2%.

Figure 3.

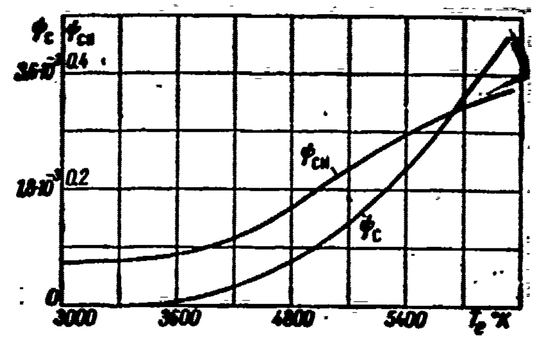
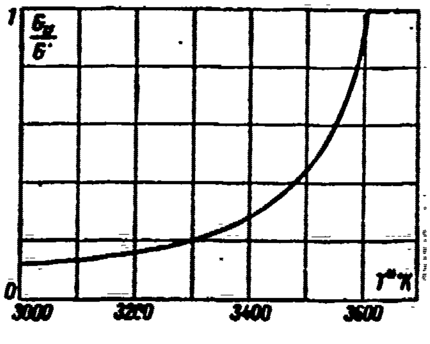


Figure 4.



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