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EFFECT OF ANGLE OF ATTACK OF A METAL SURFACE ELEMENT ON THE ENERGY ACCOMODATION COEFFICIENT OF NITROGEN IONS

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In computing aerodynamic characteristics and heat transfer for vehicles in free-molecular flow it is important to know the energy accommodation coefficient for incident stream particles and its dependence on the orientation of a surface element relative to the flow velocity vector. The literature does not have the required volume of information on the accomodation coefficient as a function of surface orientation for the particle energy range of practical interest, ~1-100 eV. The present paper reports the dependence of the accommodation coefficient α_i for nitrogen ions on the angle of attack of metal targets with atomic weight in the range 27 to 197, measured in a high-speed rarefied plasma flow ($u_\infty \simeq 10$ km/sec).

The experimental investigations were conducted in a gasdynamic plasma facility in a flow of partially ionized gas, generated by an accelerator in which the working substance was ionized by an electron beam. The accelerated ion flux, of intensity $j_\infty \simeq 10^{17}$ ion/cm^2•sec was directed into the working chamber, where the residual gas pressure was $\sim 7\cdot10^{-7}-1\cdot10^{-6}$ torr. The measurements were done at a working chamber pressure of $\sim(0.87\text{-}1.6)\cdot10^{-5}$ torr.

To measure the accommodation coefficient of the nitrogen ions we used a planar hot wire anemometer probe, in the form of a disk of thickness $\delta \simeq 0.12$ mm with a working surface diameter of 3.5 mm, and with current leads and a thermocouple attached to its back face. The lateral surface of the sensor, the thermocouple, and the current leads were insulated from contact with the ceramic plasma tube.

A rake of sensors with working surfaces made of different materials was set up in the high-speed stream of rarefied plasma. The volt–ampere characteristics $\lg I_e = f(V)$ had a clearly pronounced straight-line section. Thus, we could determine the electron temperature $T_e \simeq 3.5\text{-}4.7$ eV ($W_e = 2kT_e$) by the usual method [1]. The plasma potential φ_0 was determined by the second derivative method, and also from the electron part of the probe characteristic. This gave high accuracy in measuring the stream ion energy W_i. The values of W_i obtained agree satisfactorily with values found by use of a multielectrode analyzer probe, and also with values calculated on the assumption that the accelerating potential is the difference between the source anode and the local plasma potential φ_0. The scatter in the values of W_i obtained does not exceed ± 4.5%. To check the local values of the flow operating parameters and the orientation of the sensors relative to the flow vector u_∞ we used a slender cylindrical probe made of molybdenum wire of diameter 0.09 and length 4.0 mm. The peak ion current measured by this probe, when rotated about horizontal and vertical axes, corresponds to the probe orientation in the flow [2], and allows an estimate to be made of the degree of nonisothermality of the flow $T_i/T_e \simeq 0.13$.

The ion energy accommodation coefficient α_i was determined, using the technique of [3], from the relation

$$\frac{j_i^A}{e}\{\xi + \alpha_i(W_i + e|V^A|) - \gamma_i\varkappa\} + \frac{j_e^A}{e}(W_e + \varkappa) = \frac{j_e^B}{e}(W_e + \varkappa + e|V^B|), \quad (1)$$

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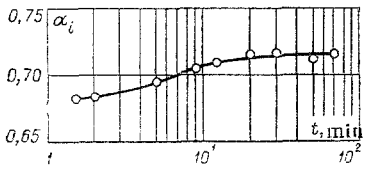

Fig. 1

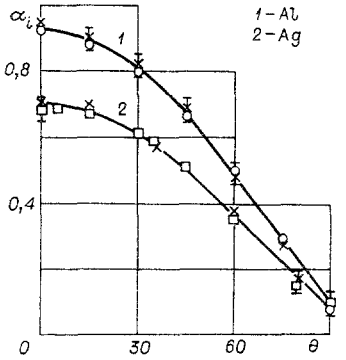

Fig. 2

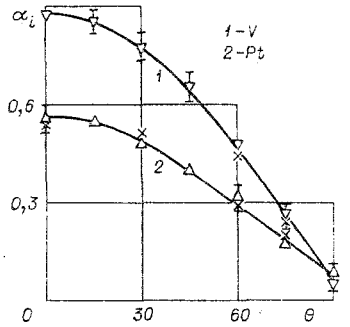

Fig. 3

obtained from the energy balance equation for points on the temperature characteristic $T_w = T_w(V)$ with equal temperatures at different probe potentials $T_w^A(V^A < 0) = T_w^B(V^B > 0)$. Here $\xi = h_i - \varkappa$ is the difference between the ionization energy and the work function; γ_i is the secondary emission coefficient; V is the potential difference traversed by the particle in the near-electrode layer; $\dot{I}_{i,e}$ is the probe current; and $W_{i,e}$ is the energy of particles transported to the plasma-electrode layer interface. In determining the electron current $\dot{I}_e^A$, as is usual in electric probe theory [1], we used a linear extrapolation of the ion branch of the probe characteristic. Points on the curve $T_w = T_w(V)$ were chosen in such a way that $e|V^A| \ll W_i$. The ion current in Eq. (1) was determined in accordance with the theory of current to a planar probe in a moving plasma [4, 5].

In addition, the accommodation coefficient $\varkappa_i$ was also determined as the ratio of the power received by the probe to the nominal ion flux power

$$\alpha_i = \frac{P_B}{P_0} = \frac{\dot{I}_e^B\left(W_e + \varkappa + e|V^B|\right)/e}{P_0}, \qquad (2)$$

where $P_0 = \dot{I}_{0i} W_i / e$; and $\dot{I}_{0i}$ is the saturation current for $\theta = 0$. The received power was determined, as before, from the energy balance equation for two points with equal surface temperatures on the temperature characteristic. The values of α_i measured in this way agree with values found from Eq. (1). For example, for tin, with $\theta = 0$ (normal incidence) use of the two relations gave $\alpha_{Sn}^{N_2^+} \simeq 0.68 \pm 0.025$. This value is evidence in favor of a mechanism for neutralizing ions which come close to the metal surface, and which is the basis of the method of measurement of the energy accommodation coefficient of ions α_i using hot wire anemometer probes.

The sensor operating surfaces corresponded to Class 7 in cleanliness. Immediately prior to taking the measurements the sensor surfaces were exposed to the plasma stream, and were also subjected to electron bombardment for 15-20 min at high positive probe potential, and heated to temperatures at which there was no breakdown of the probe surface material. Figure 1 shows the results of measuring α_i on Mo for 65 min after heating the probe to temperature ~1500°K. The data of Fig. 1 indicate a comparatively weak variation of α_i during the measurement time. It should be noted that in the measurement of $\alpha_{Mo}^{N_2^+}$ the target surface was subjected to intense bombardment by particles of the incident plasma stream.

Figures 2-6 show the results of measuring the accommodation coefficient α_i as a function of the angle of attack for metal targets with atomic weight in the range 27 to 197. The work function $\varkappa$ for the clean metals was determined from tables [6], and the data of [7, 8] were used to estimate the secondary emission coefficient γ_i. The probe surface temperature in the measurement of α_i was $T_w \simeq$ 304-318°K. To monitor the probe surface temperature in the measurement of α_i, the sensors were calibrated in a thermostat before conducting the experiments; the relation $T_w = T_w(E)$ was determined, where E is the thermocouple emf.

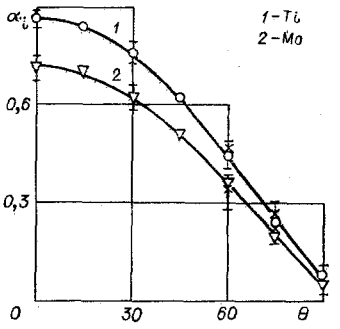

Fig. 4

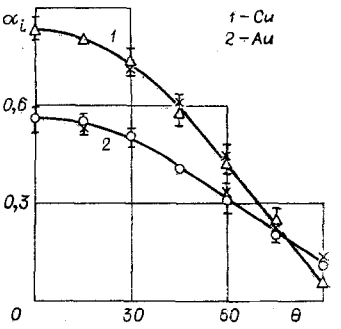

Fig. 5

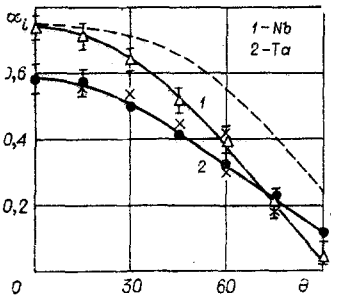

Fig. 6

For practically all the materials examined, within the measurement error limits, we find that the approximation $\mu \gtrsim 0.26$ (μ corresponds to normal incidence), determined from the data of several series of experiments, and shown by the bars in Figs. 2-6, for $\mu \gtrsim 0.26$ (μ is the ratio of the gas particle mass to the target atomic weight) and for $\theta \lesssim 75°$ we find that the approximation $\alpha_i \simeq \alpha_0 \cos\theta$ is valid (α_0 corresponds to normal incidence), and for $\mu \lesssim 0.17$ the value of α_i begins to deviate from the values characterized by the relation $\alpha_0 \cos\theta$, for angles $\theta \gtrsim 60°$. This evidently stems from capture of particles by the target surface [9, 10]. The crosses in Figs. 2-6 show values of α_i found from Eq. (2).

In [11] an empirical dependence of α_i on the angle of attack of a metal target relative to the flow vector was found

$$\alpha_i(\theta) = \begin{cases} \alpha_0(\theta = 0), & 0 \leqslant \theta \leqslant \beta, \\ \alpha_0 \cos(\theta - \beta), & \beta \leqslant \theta \leqslant \pi/2. \end{cases} \tag{3}$$

from the results of experimental investigation of scattering of cesium, potassium and rubidium ions with $u_\infty \simeq 8.5$ km/sec by clean surfaces of tungsten and molybdenum [12], and of potassium ions with $u_\infty \simeq 10$ km/sec by contaminated surfaces of tungsten, nickel, aluminum and stainless steel [13]. Here β was assumed to be $\beta \cong 25°$.

In the present series of experiments α_i was measured in conditions where the target surfaces were not subjected to any type of process to achieve cleanliness, apart from natural irradiation by the incident plasma stream. The values of $\alpha_i^{N_2^+}$ obtained on a Nb surface are shown as the broken line in Fig. 6. Similar measurements were also obtained for the other materials used in the series. From the results of the measured α_i in a nitrogen plasma flow, we find the value of β in Eq. (3) to be $\beta \cong 18°$.

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COMPUTATION OF GASDYNAMIC AND KINETIC PROCESSES IN HYPERSONIC WAKES BEHIND AEROSOL PARTICLES

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In many technical problems one is interested in achieving fast mixing of the reacting components in times comparable with the characteristic chemical reaction time. One possible method of achieving fast mixing of reacting substances is that described in [1], where one of the components is sprayed as an aerosol into a hypersonic stream of the other reacting component.

The chemical and gaskinetic processes occurring in the wakes behind aerosol particles are difficult to describe theoretically.

The difficulties stem from the fact that the flow of a gas mixture behind the particles, because of the small particle size, comparable with the molecular mean free path, varies over wide limits, from continuum flow described by the Navier-Stokes equations, to free-molecular flow described by the Boltzmann equation. The flow region near the particle and behind it is conventionally divided into two zones (Fig. 1, 1) a particle; 2) shock wave; 3) wake). In Zone I the flow is described by the Boltzmann equation, and in Zone II by the continuum equations. At a sufficient distance from the particle ($x \gg d$) the transverse velocity components will be much less than the longitudinal, and in that case in Zone II the flow is described by equations of boundary layer type.

If we neglect the variation in particle velocity due to stagnation, on a scale in which the perturbations behind the particles in the gas are damped, then, in the coordinate system moving with the particle, the equations have the form [2]

$$\frac{\partial p}{\partial r} = 0, \quad \frac{1}{r}\frac{\partial}{\partial r}(\rho v r) + \frac{\partial}{\partial x}(\rho u) = 0,$$

$$\rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial r} = \frac{1}{r}\frac{\partial}{\partial r}\left(\mu r \frac{\partial u}{\partial r}\right), \tag{1}$$

$$\rho u \frac{\partial H}{\partial x} + \rho v \frac{\partial H}{\partial r} = \frac{1}{r}\frac{\partial}{\partial r}\left\{\frac{\mu}{\mathrm{Pr}} r\left[\frac{\partial H}{\partial r} + (\mathrm{Pr}-1)\frac{\partial}{\partial r}(u^2/2) + \sum_i \left(\frac{\rho D_i}{\mu}\mathrm{Pr} - 1\right) T c_{p_i} M_i \frac{\partial F_i}{\partial r}\right]\right\} + \sum_j Q_j.$$

Equations (1) must be supplemented by the transfer equations for the various components of the mixture

$$\rho u \frac{\partial F_i}{\partial x} + \rho v \frac{\partial F_i}{\partial r} = \frac{1}{r}\frac{\partial}{\partial r}\left(\rho D_i r \frac{\partial F_i}{\partial r}\right) + \rho W_i \tag{2}$$

and the equations of state

$$p = \rho R T \sum_i F_i, \quad \sum_i M_i F_i = 1. \tag{3}$$

The enthalpy H is determined by the relation

$$H = \sum_i M_i F_i c_{p_i} T + u^2/2. \tag{4}$$

In addition, the terms appearing in Eqs.(1) and (2) $-Q_j$, corresponding to the heat release per unit volume due to the reaction of type j, and W_i, corresponding to the variation in the component F_i due to all the chemical reactions – must be determined from the chemical kinetic equations.

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