INFLUENCE OF THE ATOMIC WEIGHT OF THE TARGET ON THE MAGNITUDE OF THE ENERGY ACCOMMODATION COEFFICIENT OF IONS OF A PARTIALLY IONIZED GAS FLOW

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UDC 533.932:533.601.18:539.198

One of the most essential parameters in the investigation of singularities in molecule interaction with the surface of a solid is the energy accommodation coefficient. Data on the positive ion accommodation coefficients in the energy range ~1-100 eV are scarce [1], hence the value of α_i is often taken close to one, although this condition is not satisfied in practice for the majority of working gases. In this paper we discuss the resultant measurements of the value of α_i in a high-speed flow of rarified plasma.

Experimental investigations were performed on a plasma gasdynamic apparatus in a rarefied plasma flow generated by an accelerator with electronic impact ionization of the working body. The diagram of such a source is presented in [2]. Nitrogen, argon, krypton, xenon, and helium of elevated purity were used as working gases.

The work of the source was characterized by the following parameters: ~ 0.1-8.0-A discharge current, −120-V discharge voltage relative to the working chamber housing, and ~ 650-Oe maximum intensity of the magnetic field at the center on the source axis.

An accelerated ion stream of intensity $j_\infty \simeq 10^{15}$-10^{17} ions/cm^2 · sec went into the working chamber in which the residual gas pressure was ~$7 \cdot 10^{-7}$-$1 \cdot 10^{-6}$ mm Hg. The measurements were performed for ~ $8.7 \cdot 10^{-6}$-$1.6 \cdot 10^{-5}$ mm Hg working chamber pressure. The magnetic field intensity at the measurement point did not exceed ~5 Oe.

A flat thermoanemometer probe in the form of a δ=0.12-mm disk with a 3.5-mm-diameter working surface to whose rear were connected the current leads and the thermocouple was used to measure the ion energy accomodation coefficients. The side surface of the transducer, thermocouple, and current supply elements were insulated from contact with the plasma by a ceramic tube. Before performing the experiment, the transducer was first calibrated in a thermostat and the dependence $T_W = T_W(E)$ was determined, where E is the thermocouple emf.

The energy balance equation for the working surface of such a transducer, oriented perpendicularly to the free-stream velocity vector, is written in the form [3, 4]

$$Q_n + Q_\alpha + J + A\varepsilon\sigma\left(T_0^4 - T_w^4\right) - Q_t = 0$$

or

$$A\alpha p u_\infty\left(S^2 + \frac{\gamma}{\gamma-1} - \frac{1}{2}\frac{\gamma+1}{\gamma-1}\frac{T_w}{T_n}\right) + Q_\alpha + J + A\varepsilon\sigma\left(T_0^4 - T_w^4\right) - \frac{\partial}{\partial x}\left(-AK_w\frac{\partial T_w}{\partial x}\right) = 0, \tag{1}$$

where

$$Q_\alpha \equiv Q_e = \frac{\dot{I}_e}{e}\left(\varkappa + W_e + e|V|\right) \quad \text{for} \quad V > 0;$$

$$Q_e = \frac{\dot{I}_e}{e}\left(\varkappa + W_e\right) \quad \text{for} \quad V \leqslant 0;$$

$$Q_\alpha \equiv Q_i = \frac{\dot{I}_i}{e}\left\{\xi + \alpha_i\left(W_i + e|V|\right) - \gamma_i\varkappa\right\} \quad \text{for} \quad V < 0.$$

Evidently $Q_\alpha = Q_i + Q_e$ for intermediate potentials on the probe surface.

Here Q_n is the total quantity of heat transferred to the probe by neutral particles in unit time; Q_α, quantity of heat transferred to the probe by the charged particles; J, electrical heating energy; A, surface area;

Dnepropetrovsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 3, pp. 83-87, May-June, 1979. Original article submitted March 28, 1978.

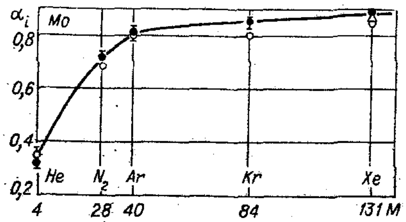

Fig. 1

ε, emission coefficient; σ, Stefan–Boltzmann constant; γ, ratio between the specific heats; $\xi = h_i - \varkappa$, difference between the ionization energy and the work function; γ_i, secondary emission coefficient; T_0, working chamber wall temperature; $S = u_\infty/v_n$, velocity ratio; K_w, heat conductivity coefficient; p, gas pressure; T_n, temperature of the neutrals; V, potential difference run through by the particles in the near-electrode layer; and α, accommodation coefficient of the neutrals.

Two characteristics, the temperature $T_w = T_w(V)$ and the current–voltage $\dot{I}_\Sigma = \dot{I}_\Sigma(V)$, are recorded in the experiment during operation with the thermoanemometric probes. There are always points with equal temperatures for different probe potentials $T_w^A(V^A < 0) = T_w^B(V^B > 0)$ [4] on the temperature characteristic. We obtain $Q_i^A = Q_e^B$ for such points from the energy balance equation, or

$$\frac{\dot{I}_i^A}{e}\{\xi + \alpha_i(W_i + e|V^A| - \gamma_i\varkappa\} = \frac{\dot{I}_e^B}{e}(\varkappa + W_e + e|V^B|).$$

This relationship permits the determination of the ion energy accommodation coefficient α_i in the material of the working surface of the thermoanemometric probe.

A rack of transducers with working surfaces fabricated from different materials was placed in a high-velocity stream of partially ionized, low-density gas. A thin cylindrical probe fabricated from a 0.09-mm diameter and 4.0-mm-long molybdenum whisker was used to check the local values of the stream working parameters and the transducer orientation relative to the stream velocity vector u_∞. The peak ion current measured by such a probe during rotation around the horizontal and vertical axes corresponds to probe orientation along the stream.

The transducer working surfaces corresponded to the seventh class of purity. Directly before performing the measurements, the transducer working surfaces were exposed to the plasma flux, and subjected to forced bombardment by electrons at 200-250 V for 15-20 min and heating to temperatures at which rupture of the probe material does not occur. The work function $\varkappa$ of the pure metals was determined by means of tabulated data [5], while data from [6, 7] were used to estimate the secondary emission coefficient γ_i.

The current–voltage characteristics log $\dot{I}_e = f(V)$ had quite definite rectilinear sections. This permitted determination of the electron temperature T_e by the usual method [8] ($W_e = 2kT_e$).

The plasma potential was determined by the second derivative method as well as from the electron portion of the probe characteristic constructed on a semilogarithmic scale. This governed a sufficiently high accuracy of the measurements of the stream ion energy W_i transferred to the plasma-layer interface surface by the particles. The values obtained are in satisfactory agreement with the values W_i found by using a multi-electrode probe-analyzer, as well as with values of W_i calculated under the assumption that the accelerating potential equals the difference between the anode potential of the source and the local potential of the plasma φ_0. The spread in the values obtained for W_i does not exceed ± 4.5%.

The results of measuring the accommodation coefficients of He^+, N_2^+, Ar^+, Kr^+, Xe^+ for $u_\infty \simeq 10$ km/sec on molybdenum are presented in Fig. 1. The dark points are the results of this series of measurements, the open circles for He^+ are results from [9], for N_2^+ are data from [10], for Ar^+, Kr^+, and Xe^+ are results from [9], for N_2^+ are data from [10], for Ar^+, Kr^+, and Xe^+ are results from [9, 11], and data from [11] taking account of a correction for atomization are denoted for Xe^+ by a triangle. The spread in the values of α_i for different series of measurements is shown in Fig. 1. The data presented indicate satisfactory agreement between results of measuring α_i in Mo performed by independent methods. It should be noted that the points on the curve $T_w = T_w(V)$ were selected in the determination of α_i such that $e|V^A| \ll W_i$.

Figure 2 illustrates the nature of the change in α_i of the Ar^+ ions in pure metals with the growth of the target atomic weight M for $u_\infty \simeq 10$ and 25 km/sec. For $u_\infty \simeq 10$ km/sec (curve 1) the triangle denotes data presented in [12], while for $u_\infty \simeq 25$ km/sec (curve 2), the open circles are results of measurements from [9, 11].

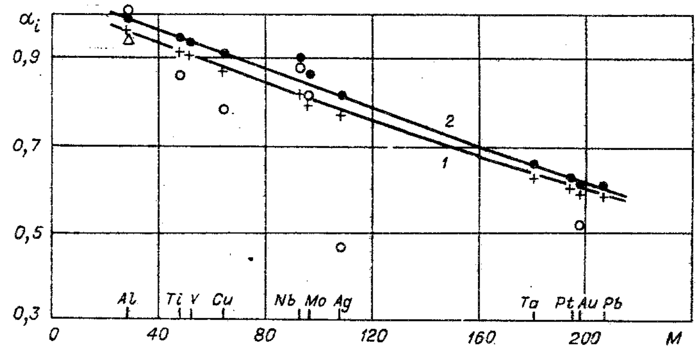

Fig. 2

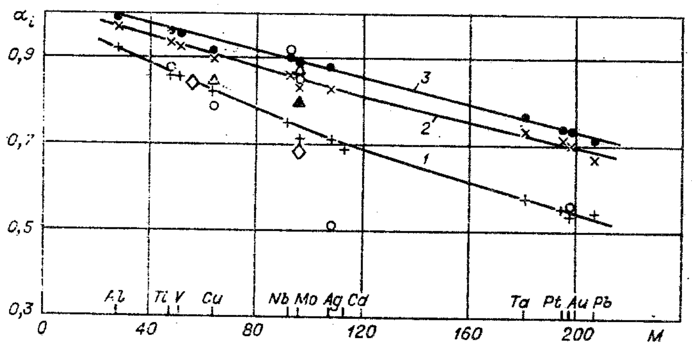

Fig. 3

The results of measuring α_i for N_2^+, Kr^+, and Xe^+ ions are shown in Fig. 3 for $u_\infty \simeq 10$ km/sec. For N_2^+ (curve 1) the rhombi denote the computed values of the accommodation coefficients of the N_2 molecule in Fe($\alpha_{Fe}^{N_2} \simeq 0.838$ for $u_\infty \simeq 7.0$ km/sec) and Mo ($\alpha_{Mo}^{N_2} \simeq 0.682$ for $u_\infty \simeq 10$ km/sec) [10]. The computed values of the accommodation coefficient of the nitrogen molecule on the surface of silver $\alpha_{Ag}^{N_2} \simeq 0.66$ and the results of measuring $\alpha_{Ag}^{N_2} \simeq 0.78$ on polished silver for $u_\infty \simeq 3.7$ [13] should be added here. The dark triangles for Kr^+ (curve 2) and the open circles for Xe^+ (curve 3) are the data from [11], the open triangles for Xe^+ are the results from [11] with the correction for atomization taken into account. The probe surface temperature in the measurement of α_i was $T_W \simeq 304$–318°K.

The results obtained are in satisfactory agreement with the data of other papers. The spread in the measured values of α_i does not exceed 7.5%. The diminution in α_i with the growth in the target atomic weight M is characteristic for the data presented.

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WAKE STRUCTURE IN HIGH-SPEED FLOW OF A RAREFIED PLASMA OVER A BODY

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UDC 533.9

In the study of qualitative features of flow of a rarefied plasma over bodies in ionospheric aerodynamics, the problem of flow behind a two-dimensional plate is often considered. The formulation of this problem and its relation to flow over real objects was considered in detail in [1]. This model problem has been analyzed in a number of papers using two main approaches: description of the flow with the help of the similarity solution found in [2, 3], and numerical solution of the equations of plasma motion [4-7]. A review of the main results obtained by the two methods can be found in [1, 6]. This paper gives a numerical solution of the problem of transverse supersonic flow over a flat plate. The plasma is assumed to be collisionless and is described by the kinetic equation with a self-consistent field. The particle-in-cell method is used to solve the kinetic equation. In contrast with most numerical calculations previously performed [4-6], the present paper considers the case, of greater practical interest, of flow over a body whose dimension R is much greater than the Debye radius D_i in the unperturbed plasma. Practically all the known results for this case have been obtained using the similarity solution [2, 3], which is not valid, however, in the entire region of unperturbed flow, and therefore does not give a complete solution to the problem. Individual numerical calculations (see [7]) do not add much to the similarity analysis, since they refer to a very narrow range of the flow parameters. The main emphasis in the present paper is the study of wake structure behind a flat plate and plasma instability in the wake. The computations were performed in a wide range of variation of the ratio $\beta = T_e/T_i$, and one can follow the processes of ion acceleration, interaction of the accelerated group of ions with the plasma, development of beam-type instability [1, 8], and formation and decay of the turbulent wake. The qualitative wake structure features discussed below are also found, of course, in plasma flow over actual three-dimensional bodies.

1. The formulation of the problem adopted here was discussed in detail in [1]. We consider steady-state plasma flow near a two-dimensional plate. The plasma velocity V far from the plate is directed normal to it and satisfies the inequalities

$$\sqrt{T_e/m_i} \ll V \ll \sqrt{T_e/m_e}. \tag{1.1}$$

The first inequality indicates that the flow is supersonic. Behind the plate a cylindrical region remains free from ions, with a cross section equal to the plate area. In this region, as in vacuum, the plasma expands. In a coordinate system in which the plasma is at rest far from the body, the filling up of the cylindrical cavity is an unsteady process which accurately corresponds to free expansion of a plasma into vacuum [2, 3, 9] until collision occurs between the two particle fluxes reaching the cavity from opposite directions. In the coordinate system fixed in the body, the flow is steady-state and is a superposition of a transverse expansion and a longitudinal drift with velocity V. Thus, the wake structure in successive cross sections at different distances z from the plate corresponds to successive stages of unsteady filling of the cavity by the plasma. One flow is obtained from the other by the substitution $z \to Vt$. This analogy, which is well known from hypersonic aerodynamics [10], and is discussed in detail in [1, 5], is used extensively in the calculations below.

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 3, pp. 87-94, May-June, 1979. Original article submitted May 23, 1978.

0021-8944/79/2003-0328$07.50