ENERGY ACCOMODATION COEFFICIENTS OF POSITIVE IONS IN A LOW-DENSITY PLASMA FLOW ON THE SURFACES OF CERTAIN MATERIALS

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In studying features of the interaction of solids with gas streams, one of the most important parameters is the energy accomodation coefficient of the stream particles on the surface of the solid. Laboratory measurements of accomodation coefficients are made difficult by the need to obtain flows with velocities close to the velocity of the solid(s) in the atmosphere. This article presents results of measurements of values of α_i for a wide range of flow velocities $u_\infty \cong 6.5$–25 km/sec.

The selection of the solid to be investigated is dictated by both the requirement of the presence of a nonthrushing mode of flow and the availability of suitable means for making measurements within the flow. The most convenient with regard to the latter is evidently a headpiece with a flat working surface. The energy balance equation for the working surface of such a headpiece, oriented perpendicular to the velocity vector of the incoming flow, is written in the form [1]

$$Q_t + Q_\alpha + J + A\varepsilon\sigma(T_0^4 - T_w^4) - \frac{\partial}{\partial x}\left(-AK_w\frac{\partial T_w}{\partial x}\right) = 0,$$

where $Q_\alpha = Q_i = (\dot{I}_i/e)\{\xi + \alpha_i(W_i + e|V|) - \gamma_i\varkappa\}$ at $V < 0$; $Q_\alpha = Q_e = (\dot{I}_e/e)(2kT_e + e|V| + \varkappa)$ at $V > 0$; $Q_\alpha = Q_i + Q_e$ at $V \leq 0$. Here Q_t is the total amount of heat transferred to the probe by neutrals per unit of time; Q_α is the amount of heat transferred to the probe by charged particles; J is the energy of electrical heating; A is the area of the surface; ε is the radiation factor; σ is the Stefan–Boltzmann constant; $\xi = h_i - \varkappa$ is the difference between the ionization energy and the work function; γ_i is the secondary emission factor; T_0 is the temperature of the walls of the working part of the unit; K_w is the coefficient of thermal conductivity; $\dot{I}_{e,i}$ is the probe current; W_i is the energy of the ions carried to the layer-plasma interface; V is the potential difference crossed by the particles in the electrode layer.

In the course of the experiment, during work with the hot-wire anemometer-probe, we simultaneously recorded two characteristics: $T_w = T_w(V)$, the temperature, and $\dot{I}_\Sigma = \dot{I}_\Sigma(V) = \dot{I}_e + \dot{I}_i$, the volt–ampere characteristic. On the temperature curve, there are always points with the same temperature at different probe potentials $T_w^A(V^A < 0) = T_w^B(V^B > 0)$ [1]. From the energy-balance equation for such points we obtain $Q_i^A = Q_e^B$ or

$$\frac{\dot{I}_i^A}{e}\{\xi + \alpha_i(W_i + e|V^A|) - \gamma_i\varkappa\} = \frac{\dot{I}_e^B}{e}(2kT_e + e|V^B| + \varkappa).$$

These relations allow us to determine the accomodation coefficient of the ions α_i on the material of the working surface of the hot-wire anemometers (probes).

The experimental studies were conducted on a plasma gasdynamic unit in a flow of partially ionized low-density gas generated by a plasma accelerator with ionization of the working solid by electron impact. A diagram of such a source is shown in [2]. The operation of the source is characterized by the following parameters: discharge current ~0.1–8.0 A, discharge voltage relative to the body of the working chamber ~–120 V, maximum strength of the magnetic field in the center on the source axis ~650 Oe.

The accelerated plasma stream, of intensity $j_\infty \cong 10^{15}$–10^{17} ions/cm^2·sec, entered the working chamber. The pressure of the residual gases in the working chamber was ~$7\cdot10^{-7}$–$1\cdot10^{-6}$ mm Hg. Measurements were made for a wide range of energies of stream ions at pressures in the working chamber of $(0.87\text{–}1.6)\cdot10^{-5}$ mm Hg. Magnetic field strength at the measurement point did not exceed ~5 Oe.

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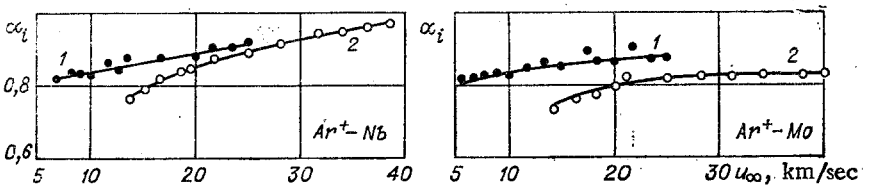

Fig. 1

To measure the accomodation coefficient of the ions, we used a flat hot-wire anemometer-probe made in the form of a disk $\delta = 0.12$ mm with a working surface 3.5 mm in diameter. A conducting wire 0.1 mm in diameter and a thermocouple 0.15 mm in diameter were attached to the back side of the disk. The lateral surface of the transducer, and thermocouple and elements of the wire were insulated from contact with the plasma by a ceramic tube.

The volt–ampere characteristics $\log \dot{I}_e = f(V)$ had a clearly expressed straight section. This made it possible to determine the temperature of the electrons $T_e \approx 2.5$–4.1 eV by a standard method [3].

The potential of the plasma φ_0 was determined by the method of second derivatives, as well as from the electron part of the probe curve plotted in semilog coordinates. This provided for sufficiently accurate measurement of the energy of the ions in the flow W_i carried as particles to the plasma–layer interface. The resulting values agreed satisfactorily with the values of W_i computed under the assumption that the accelerating potential is equal to the difference between the potential of the source anode and the local potential of the plasma. Scatter of the values of W_i obtained did not exceed ±4.5%.

The comb of the transducers, with working surfaces made of different materials, was inserted in the high-speed flowof partially ionized low-density gas. To monitor local values of the working parameters of the flow and orient the transducers relative to the flow velocity vector u_∞, we used a thin cylindrical probe made of a molybdenum filament 0.09 mm in diameter and 4.0 mm long. The peak ion current measured by this probe upon rotation about its horizontal and vertical axes corresponded to the orientation of the probe along the flow [4].

The probes weremade of molybdenum, niobium, aluminum, aluminum alloys AMg6-M and D16T, conventional steels 2Kh13, 12Kh18N10T, and St.25, and the silicon element of solar battery panels. The working surfaces of the Mo the Nb probes corresponded to a class seven purity, while the surfaces of the remaining probes corresponded to the working condition of the surfaces of these materials [5]. Just before the measurements were made, the working surfaces of the probe were exposed to the plasma flow, as well as having been subjected for 15-20 min to forced bombardment by electrons at positive potentials of ~250 V and heating to temperatures at which the probe material did not fail. The work function $\varkappa$ of the pure materials was determined from the tables in [6], and we used the data in [7] to evaluate the secondary emission factor γ_i.

The results of measurement of the accomodation coefficients of Ar^+ ions on molybdenum and niobium are shown in Fig. 1. The points on curve 2 are the results of measurement of α_i by the calorimetric method in [8]. It should be noted that in determining α_i the points on curve $T_w = T_w(V)$ were selected so that $e|V^A| \ll W_i$. At ion energies $W_i \ll 20$ eV, to determine α_i we used the relation $(Q_i + Q_e)^A = Q_e^B$, where $Q_e = (\dot{I}_e/e)(2kT_e + \varkappa)$. In this case the electron current $\dot{I}_e^A$ was determined by means of a linear extrapolation of the ion branch of the probe curve. The resulting data agrees satisfactorily with the results of measurement of α_i for Ar^+ on Mo and Nb made by independent methods. Moreover, the results of measurements on Mo (curve 1) agree satisfactorily with the values of $\alpha_i = 0.75 \pm 0.05$ and $\alpha_i = 0.81$; 0.84 for Ar^+ ions with energies $W_i \approx 21$–141 eV obtained in [9, 10]. The results of measurement of accomodation coefficients of N_2^+ ions on the surfaces of other materials are shown in Fig. 2. It is typical for this series of measurements that α_i increases with an increase in the velocity of the flow. The latter agrees qualitatively with the results of measurement of the accomodation coefficient of air neutrals within the Mach number range 1.5-3.0 on a tungsten–rhenium alloy filament coated with gold and palladium [11].

Figure 3 shows the character of change in α_i for N_2^+, Ar^+, Kr^+, and Xe^+ ions at $u_\infty \approx 10$ km/sec. For Ar^+ on Al, the clear point denotes a result obtained in [10], while the triangle denotes a result from [9]. The temperature of the probe surface in the measurements was

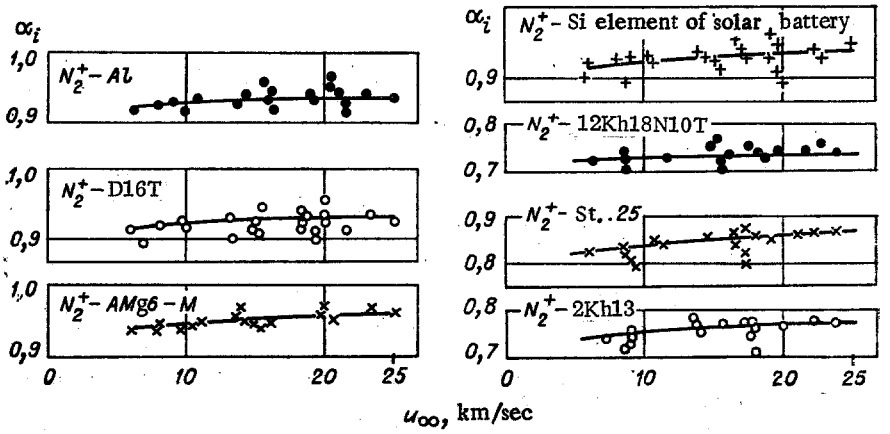

Fig. 2

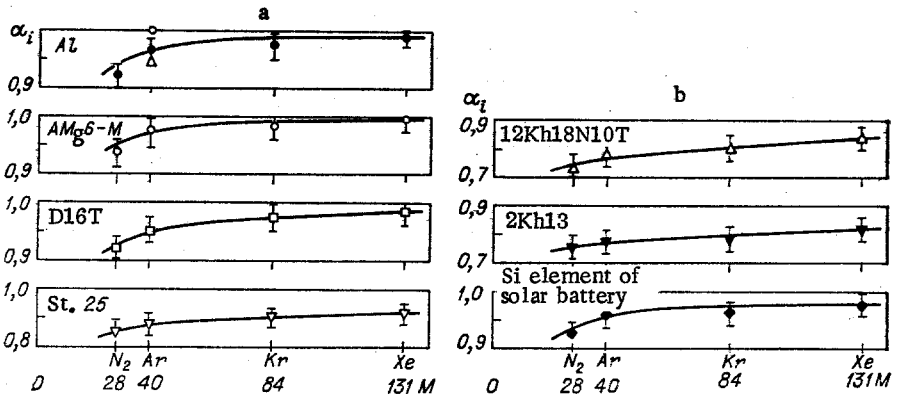

Fig. 3

equal to T_w = 304-318°K. To control the probe surface temperature in the measurement of α_i, before conducting the experiments we calibrated the transducers in a thermostat and determined the dependence $T_w = T_w(E)$, where E is the thermocouple emf. On practically all the materials there was an increase in the accomodation coefficient with an increase in the molecular weight M of the ion bombarding the surface. Figure 3 shows the scatter of α_i values for different series of measurements. The α_i measurement error did not exceed ~7.5% for the pure metals and ~10% for the alloys. A certain increase in the error for the alloys was due to the uncertainty of selecting values of the work function $\varkappa$ and secondary emission factor γ_i.

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TWO-WAVE MODEL OF THE PROPAGATION OF PERTURBATIONS IN A LIQUID WITH GAS BUBBLES

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The speed of sound is dispersed in the propagation of the sound in a liquid containing gas bubbles. The form of the dispersion curve is well known [1]: for bubbles of one size, there are two dispersion branches divided by a region of opacity. Propagation of acoustic waves was examined in the Burgers–Korteveg–de Vries (BKV) approximation in [2-4]. This approximation corresponds to only one (the left) branch of the dispersion curve.

A model of perturbation propagation is proposed in the present work which corresponds to both branches simultaneously. An equation is derived and its transient solutions are found. Ranges of application of the low-frequency and high-frequency approximations of the equation are established.

1. In studying long-wave perturbations, either the effect of the compressibility of the liquid is ignored or it is reduced to contributing to dispersion of the wave through acoustic radiation with pulsations of the bubbles in the wave [2-6]. A more complete account of the compressibility of the liquid leads to the appearance of a second branch in the dispersion curve $c_f = c_f(\omega)$, where $c_f = \omega/k$ is the phase velocity; ω is the frequency of the superimposed perturbation; k is the wave number. The equation for the dispersion curve has the form

$$c_f^{-1} = \left(\frac{1}{c_{01}^2 (1 - m^2)} - \frac{m_1^2}{c_2 (1 - m_1^2)} \right)^{1/2}, \tag{1.1}$$

$m_1 = \omega/\omega_0$; $\omega_0^2 = 3\gamma p_{02}/R_0^2 \rho_1$ is the square of the resonance frequency of the bubble; p_{02} is the pressure of the gas in the bubble; ρ_1 is the density of the liquid; R_0 is the initial radius of the bubble; γ is the adiabatic exponent; $c_{01}^2 = \gamma p_{02}/\rho_0 \varphi_0$ is the square of the low-frequency approximation of the speed of sound in a liquid with gas bubbles; φ_0 the initial gas content; c_2 is the speed of sound in the liquid. The curve of Eq. (1.1) is shown in Fig. 1a. The initial section of the left side of the dispersion curve corresponds to the Korteveg–de Vries (KV) equation [2-4]

$$\partial p/\partial t + c_{01} \partial p/\partial x - \beta c_{01} \partial^3 p/\partial x^3 = 0$$

(p is the pressure in the mixture). The right branch of the dispersion curve corresponds to the Klein–Gordon equation

$$\frac{\partial^2 p}{\partial t^2} - c_2^2 \frac{\partial^2 p}{\partial x^2} = -\frac{c_2^2}{2\beta} \delta p = -\frac{c_2^2 \omega_0^2}{c_{01}^2} \delta p.$$

Shown below is the derivation of an equation corresponding to both branches of the dispersion curve (Fig. 1a).

2. Let us turn to equations describing the gadynamics of a homogeneous bubble suspension

$$\frac{\partial u}{\partial t} = -\frac{1}{\rho} \frac{\partial p}{\partial x}; \quad (2.2) \quad \frac{\partial \rho}{\partial t} = -\rho \frac{\partial u}{\partial x} \tag{2.1}$$

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