TRANSFERRING THE ENERGY OF ATOMIC IONS FROM A SUPERSONIC FLOW OF A PARTIALLY DISSOCIATED GAS TO THE SURFACE OF A SOLID

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The energy exchange that takes place among the ions of a supersonic flow in a partially dissociated gas streamlining a surface is characterized by a multiplicity of physical processes and phenomena, such as neutralization, secondary ion-electron emission, heterogeneous recombination, accommodation of the energy of the particles at the surface of a solid, etc. The presence of atomic ions within the stream of gas considerably complicates the problem, since for purposes of determining the convective heat flows, in addition to the energy accommodation coefficients and the secondary ion-electron emission, we must also know the coefficients of the heterogeneous recombination of the atomic components at the surface of the body. This is particularly important for the exchange of heat that occurs between bodies in the upper layers of the atmosphere, where the quantity of atomic particles is predominant. The literature lacks adequate information regarding the values of the recombination coefficients for the atomic particles at the surfaces of monocrystals and polycrystals in the range of particle energies (~1-15 eV) that is of such practical importance from the standpoint of aerodynamics. It is therefore essential that we study the unique features involved in the transmission of energy for various systems involving an atomic ion and a solid within the indicated range of particle energies.

In the present paper we present results from experimental research into the exchange of energy between the atomic ions of supersonic gas flows with streamlined surfaces. We propose a method and determine the coefficients of recombination for the atomic ions of nitrogen, hydrogen, and oxygen, at the surfaces of polycrystals of electrically conductive materials and alloys. We have measured the values and relationships for the coefficients of transparency in the case of permeable surfaces.

1. The exchange of energy from a streamlined surface in the flow of a rarefied plasma in a steady-state regime is characterized by the energy balance equation

$$Q_n + Q_\alpha + J + Q_\nu - Q_r - Q_t = 0. \tag{1.1}$$

Here Q_n is the quantity of heat transferred to the surface of the body by neutral particles per unit time; Q_α is the quantity of heat transferred to a surface bombarded with charged particles; J is the Joule heat; Q_ν denotes plasma radiation; Q_t denotes losses due to heat conduction; $Q_r = A\varepsilon\sigma(T_w^4 - T_0^4)$ represents the radiation losses; ε, the integral emittance of the surface material; T_w, the surface temperature; σ, the Stefan–Boltzmann constant; T_0, the temperature of the walls in the operating chamber of the installation; A, the area of the bombarded surface.

In the case of a sensor made in the form of a plane thermoanemometric probe with a working section fashioned out of a thin isothermal plate or disk of thickness $\Delta \approx 0.05$-0.15 mm and diameter $d \gg \Delta$, to whose rear section power-supply and thermocouple elements are connected, we can neglect the Joule heating. The side surface of the sensor as well as the current-supply and thermocouple elements have been insulated against contact with the plasma.

During the course of the experiment we synchronously recorded two characteristics: the temperature $T_w = T_w(V)$ and the volt-ampere characteristic $I_\Sigma = I_\Sigma(V)$ (I_Σ is the current to the probe, V is the potential of the probe relative to the potential of the plasma). The temperature characteristic always has points of equal temperature for various potentials $T_w^A(V^A > 0) = T_w^B(V^B < 0)$. An advantage of choosing two points with equal temperature is the possibility of isolating the contribution from the ion component of the stream.

From the energy balance equation (1.1) for two points with equal temperature at various surface potentials, the power received from the flow is written in the form

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$$(1-\xi)I_i^A[h_i^m-\varkappa(1+\gamma_i^m)+\alpha_i^m(e|V^A|+W_i+\chi^m)+ \\ +\xi\gamma_w I^A{}_i[h_i{}^m-\varkappa(1+\gamma_i^m)+E_d^m+\alpha_i^m(e|V^A|+W_i+\chi^m)]+ \\ +(1-\gamma_w)\xi I_i^A[h_i^a-\varkappa(1+\gamma_i^a)+\alpha_i^a(e|V^A|+W_i+\chi^a)]= \\ =I_e^B(W_e+\varkappa+e|V^B|), \tag{1.2}$$

where h_i is the potential of ionization; W_α is the energy transferred by an α kind of particle to the surface separating the plasma from the layer; I_α is the probe current; ξ is the dissociation ratio for the flow; α_i is the energy accommodation coefficient for the ions; $\varkappa$ is the work done at the output; γ_i is the coefficient of secondary ion-electron emission; γ_w is the coefficient of heterogeneous atomic ion recombination; $E_d{}^m$ is the dissociation energy of the gas molecule; $\chi = 3.6/s$ is the polarization energy; s is the distance from the surface of the body at which the positive ions are neutralized. For the majority of surfaces and gas ions within the range of particle energies under consideration here we have $s \approx (2\text{-}4)\cdot 10^{-7}$ mm [1].

In approximate terms, with an error of no more than ±10%, d can be found as the half-sum of the gas molecule diameter, calculated on the basis of the viscosity coefficient and from the distance between the nearest atoms of the lattice of the material making up the surface being studied here.

The superscript m corresponds to the molecular ions while the superscript a denotes the atomic ions. The first term in the left-hand side of Eq. (1.2) characterizes the contribution of the molecular ions whereas the second term reflects the flow of heat generated by the atomic ions undergoing recombination at the surface of the body, with the third term representing the flow of heat transferred to the unrecombined atomic ions.

The coefficient of ion accommodation in this case can be defined as the ratio of the power received by the probe to the nominal power of the ion stream [2], which in the case of a partially dissociated gas can be represented as follows:

$$(1-\xi)\alpha_i{}^m+\xi\alpha_i{}^a \approx I_e^B(W_e+\varkappa+e|V^B|)/I_{0i}W_i, \tag{1.3}$$

where I_{0i} is the ion saturation current to the probe, oriented perpendicularly to the velocity vector of the approaching flow. After substitution of $\alpha_i{}^a$ into (1.2) and with consideration of the fact that for the given energy the molecular ions, as a rule, remove a quantity of electrons larger by a factor of 2 than the atomic ions $\gamma_i{}^a \approx 0.5\gamma_i{}^m$, from the energy balance equation we will obtain an expression to determine the coefficient of heterogeneous recombination for the atomic ions at the surface of materials capable of conducting electricity [3]:

$$\gamma_w \approx [I_e^B(W_e+\varkappa+e|V^B|+(\xi-1)Z-\xi K]/\xi(Z-K+ \\ +I_i^A E_d^a). \tag{1.4}$$

Here

$$Z=I_i^A[h_i{}^m-\varkappa(1+\gamma_i^m)+\alpha_i^m(W_i+e|V^A|+\chi^m)]; \\ K=I_i^A\{h_i{}^a-\varkappa(1+0.5\gamma_i^m)+(W_i+e|V^A|+\chi^a)[(1 \\ -\xi^{-1})\alpha_i{}^m+I_e^B(W_i+\varkappa+e|V^B|)/\xi I_{0i}W_i]\}.$$

The values of the parameters characterizing the interaction of the rarefied plasma flow with the solid surface, such as $\alpha_i{}^m$, $\gamma_i{}^m$, and $\varkappa$, can be found in [2-6]. Relationships (1.3) and (1.4) make it possible to determine the energy accommodation coefficients as well as those of the heterogeneous recombination of the atomic ions of a flow of a partially dissociated gas at the surfaces of electrically conducting materials.

2. The experimental studies were performed on a plasma gasdynamic installation with a high-speed flow of a partially dissociated ionized gas. Highly purified nitrogen, oxygen, and hydrogen were used as the working gases. The accelerated flow with an intensity of $j_\infty \approx 10^{16}\text{-}10^{18}$ cm$^{-2}\cdot$sec^{-1} at an ion energy of $W_i \approx 10$ eV entered the working chamber, with the pressure of the residual gases in that chamber amounting to $\sim 10^{-5}$ Pa. The measurements were carried out at pressures within the working chamber of $\sim 10^{-1} \lesssim p \lesssim 10^{-3}$ Pa. An AVED-40/800M type vacuum electrodischarge unit and a TMN-500 turbomolecular pump were employed to produce a vacuum. The operational portion of the chamber was shielded by means of liquid-nitrogen cooled panels. To generate the flow of the partially dissociated ionized gas we used a gas discharge accelerator in which the working fluid was ionized by means of an electron shock with "self-acceleration of the plasma." To raise the efficiency of the ionization and dis-

sociation of the gas supplied to the ionization chamber of the accelerator, the said gas was directed at the surface of the heated cathode. It has been established [7] that with an electron-beam energy higher than 28 eV the appearance of doubly charged ions in the flow becomes possible. Although at pressures of ~$1.5 \cdot 10^{-2}$ Pa the number of doubly charged ions is no greater than ±0.5% of the total number, the studies were carried out in gas flows of nitrogen, oxygen, and hydrogen, with electron beam energies of up to 28 eV. This made it possible to eliminate the presence of doubly charged ions in the partially dissociated streams.

The degree of dissociation ξ for the stream of ions was determined by means of an MKh-7303 mass spectrometer in conjunction with an energy analyzer. It turned out that $\xi_{N_2} \approx 0.3$, $\xi_{O_2} \approx 0.4$, and $\xi_{H_2} \approx 0.4$. For purposes of measuring and monitoring the parameters of the rarefied plasma flow we used a system of movable electrostatic probes, a multielectrode probe analyzer and a superhigh frequency interferometer for the 3 cm range. In our study of the features involved in the energy exchange within the system formed by the plasma and the solid we used thermoanemometric probes fabricated in the form of a disk $\Delta \approx 0.12$-0.15 mm and a working section with a diameter of ~3.5 mm. The probes were fabricated from chemically pure materials with an atomic mass from 27 to 207 and a polished working surface, as well as of such industrial materials as aluminum AMg5-BM alloys, D16AT (sheet), stainless steels 12Kh18N10T, 2Kh13, St.25, and a solar-battery panel element. Two sensors were fabricated out of the solar-battery panel element: a silicon element (a polished silicon polycrystal with an admixture of phosphorus or arsenic, the front side of the panel) and a solder (a lead–tin alloy, the shaded side of the panel). The surfaces of the sensors fabricated from industrial materials corresponded to the operational state of these materials [8]. The ensemble of sensors was positioned within the high-speed stream of the rarefied plasma. The temperature and the volt-ampere characteristics as well as the derivatives of the probe current were measured automatically.

The probe-measurement circuit includes recording of the volt-ampere characteristics on a direct-current self-recording milliammeter working in conjunction with a photomultiplier and with the use of a resistance box to measure the resistance we can establish the probe currents in the range $1 \cdot 10^{-7}$-$1.5 \cdot 10^{-1}$ A with smooth control of the probe potential from 0 to 250 V. The error in the measurement of an individual volt-ampere characteristic does not exceed ±2%. The derivatives of the probe current with respect to the voltage were measured by a harmonic method [9]. Since the derivatives of the probe current are used only to find the potential of the plasma, no calibration of the harmonic amplitudes of the probe current were undertaken.

The plasma potential was determined by the second-derivative method, as well as on the basis of the electron portion of the probe characteristic, constructed in a semilogarithmic scale. Moreover, during the course of the experiments we measured the plasma noise recorded by the probe, thus making it possible to monitor the measurement accuracy of the plasma potential. The plasma noise maximum corresponds to the space potential. Here it turned out that the plasma potential found from the point $d^2I_e/dV^2 = 0$ and from the noise maximum better corresponds to the origin of deviation of the semilogarithmic characteristic from rectilinearity than does the point of asymptote intersection. An analogous phenomenon was observed in the determination of the space potential through the use of a solitary cylindrical probe fashioned in the form of a thermoanemometer operating as a thermal probe. The plasma potential was determined from the point of divergence between the characteristics of the cold and heated probes. The scattering of the plasma potential values does not exceed ±3%.

The energy W_i of the ion stream was found from the magnitude of the local plasma potential relative to the anode of the source. The derived values for the ion energies are in satisfactory agreement with the values of W_i found with utilization of the multielectrode probe analyzer and from the characteristic of the plane probe [10]. The scattering in the values of W_i does not exceed ±4.5%. In order to control the local values of the stream parameters and the orientation of the sensors relative to the velocity vector of the flow, we used a thin cylindrical probe made out of molybdenum filaments 0.04 mm in diameter and 2.3 mm in length. The peak of the ion current measured with this probe, on rotation about the vertical and horizontal axes, corresponds to the orientation of the probe in the direction of the flow [11]. The error in the angular orientation of the probes in the flow did not exceed ±20'.

Particular attention was devoted in these measurements to the cleanliness of the working surfaces for the materials being studied. Prior to the measurements the working surfaces of

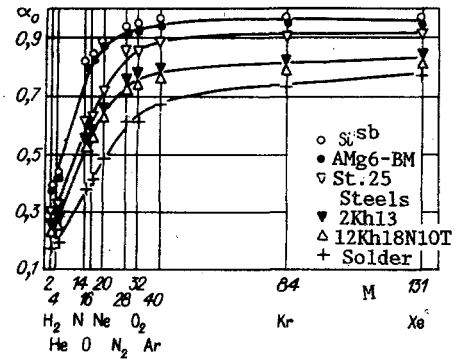

Fig. 1

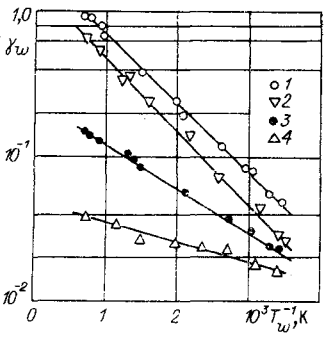

Fig. 2

TABLE 1

Surface material	$\gamma_w^{O^+}$			$\alpha_i^{O^+}$
		Source		
		[15]	[16]	
Mo	$3{,}6\cdot10^{-2}$	—	—	0,53
Pt	$2{,}29\cdot10^{-1}$	$1{,}08\cdot10^{-1}$	—	0,38
Cu	$1{,}88\cdot10^{-1}$	$1{,}83\cdot10^{-1}$	$1{,}7\cdot10^{-1}$	0,63
Al	$5{,}93\cdot10^{-2}$	—	—	0,76
Ag	$2{,}06\cdot10^{-1}$	$2{,}58\cdot10^{-1}$	$2{,}4\cdot10^{-1}$	0,55
Si sb	$9{,}2\cdot10^{-2}$	—	—	0,84
St.25	$3{,}2\cdot10^{-2}$	—	$3{,}6\cdot10^{-2}$	0,63
Steel 12Kh18N10T	$7{,}7\cdot10^{-2}$	—	—	0,54

the probes with potentials of V ≃ −250 V over a duration of 10-15 min were subjected to forced bombardment by the ions of a flow of a rarefied plasma, subsequent to which, for 15-20 min, because of the forced electron bombardment, were heated to temperatures at which the material of the probe and the thermocouple are not subjected to destruction. A high negative potential V ≈ −250 V was then applied again to the probe and for ~10 min directly prior to the measurement the working surfaces of the probes were subjected to conditioning by bombardment with a plasma stream. The working surfaces were cleaned by intensive bombardment with an ion flow and the volt-ampere and temperature characteristics were taken here, beginning with V ≃ −250 V.

Information with regard to the state of the working surfaces directly during the measurement process can be obtained from the results of the determination of the integral hemispherical emittance of the material in independent fashion from the volt-ampere and temperature characteristics of the probe. The derived values of ε_{th} make it possible to eliminate the effect of surface contamination on the measurement results [12].

The presence of negative ions in the flow was monitored on the basis of the volt-ampere characteristic of a single probe and from the readings of the SHF interferometer [13, 14]. For this purpose we employed the condition of quasineutrality. This is a perfectly valid approach, since the SHF-diagnostic methods are based on the scattering of the electromagnetic radiation on the free electrons of the medium. Comparison of the concentration values for the charged particles, found from the electron and ion branches of the volt-ampere characteristic of the electric probe, against the N_e measurement data obtained through use of an SHF interferometer [14] enables us to estimate the fraction of negative ions in the flow: $N_e + N_i^- = N_i^+$. No negative ions were observed in plasma flows of nitrogen, hydrogen, and oxygen, generated with a gas-discharge accelerator in which the working fluid was ionized by an electron shock.

The results from our study of the energy exchange between the atomic ions of nitrogen, oxygen, and hydrogen and the bombarded surfaces (the energy accommodation coefficients and those of heterogeneous recombination) with W_i ≈ 10 eV and T_w ≈ 320 K can be found in Fig. 1

TABLE 2

Surface material	$\gamma_w^{N^+}$	Source [15]	Source [17]	Source [18]	$\alpha_i^{N^+}$	Surface material	$\gamma_w^{N^+}$	$\alpha_i^{N^+}$
Ti	$3{,}66\cdot10^{-2}$	—	—	—	—	Cd	$8{,}61\cdot10^{-2}$	—
V	$2{,}21\cdot10^{-2}$	—	—	—	0,69	Pb	$8{,}9\cdot10^{-2}$	—
Nb	$3{,}2\cdot10^{-2}$	—	—	—	0,50	AMg6-BM	$7{,}8\cdot10^{-2}$	0,76
Ta	$4{,}04\cdot10^{-2}$	—	—	—	—	D16AT	$9{,}1\cdot10^{-2}$	0,73
Mo	$2{,}45\cdot10^{-2}$	—	$6\cdot10^{-4}$	$8\cdot10^{-3}$	0,51	Si sb	$8{,}5\cdot10^{-2}$	0,81
Pt	$1{,}89\cdot10^{-1}$	$1{,}02\cdot10^{-1}$	$1{,}8\cdot10^{-1}$	$8\cdot10^{-1}$	0,33	Solder	$1{,}92\cdot10^{-1}$	0,35
Al	$5{,}86\cdot10^{-2}$	—	—	$6{,}5\cdot10^{-2}$	0,74	St.25	$2{,}8\cdot10^{-2}$	0,62
Cu	$1{,}51\cdot10^{-1}$	$7{,}81\cdot10^{-2}$	—	$1{,}7\cdot10^{-1}$	0,59	Steels		
Au	$1{,}64\cdot10^{-1}$	—	$1{,}5\cdot10^{-1}$	$8\cdot10^{-1}$	—	2Kh13	$5{,}27\cdot10^{-2}$	0,5'
Ag	$1{,}78\cdot10^{-1}$	$1{,}88\cdot10^{-1}$	—	$6\cdot10^{-1}$	0,49	12Kh18N10T	$7{,}3\cdot10^{-2}$	0,49
						Si (III)	$4{,}7\cdot10^{-3}$	—

TABLE 3

Surface material	$\gamma_w^{H^+}$	Source [19]	Source [20]
Ti	$7{,}64\cdot10^{-2}$	$1\cdot10^{-1}$	$3{,}5\cdot10^{-1}$
Mo	$1{,}68\cdot10^{-2}$	—	—
Cu	$1{,}31\cdot10^{-1}$	$1{,}9\cdot10^{-1}$	$1{,}4\cdot10^{-1}$
Al	$2{,}7\cdot10^{-2}$	$\sim10^{-3}$	$2{,}9\cdot10^{-1}$
Au	$8{,}89\cdot10^{-2}$	$1\cdot10^{-1}$	$9\cdot10^{-2}$
Ag	$1{,}21\cdot10^{-1}$	$1{,}3\cdot10^{-1}$	—

and in Tables 1-3. However, here for purposes of comparison we give the values of γ_W from [15-20]. In this case the accommodation coefficients of the atomic ions for various "gas-surface" systems within the limits $10^{-2} \lesssim \mu \lesssim 10^1$ (μ represents the ratio of the atomic masses of the gas and of the surface) with an error not exceeding ±6% are in agreement with the data of Fig. 5 from [2], illustrating the relationship $\alpha_i = \alpha_i(\mu)$. The maximum error in the determination of γ_W from (1.4) is no lower than ±20%. The observed scattering in the values of γ_W relative to the data from other studies, apparently, is a consequence of the nonuniformity of the conditions prevailing at the surface and the different methodologies employed in the measurements. A variety of factors affect the recombination coefficients which primarily characterize the state of the surface: the existence of adsorption layers, roughness, oxide films, etc.

Thus the correspondence between the measured values of $\gamma_W^{H^+}$ and the results of [19] is apparently due to the coincidence of the conditions under which the experiments were carried out: preliminary conditioning to a rarefied plasma of the surfaces being studied. At the same time, the difference in the values of $\gamma_W^{N^+}$ relative to the data of [18], measured in the flow of a neutral gas with a nitrogen atom energy of ~1.1 eV and $T_W \approx 300$-350 K is due to the presence of a stable coating produced by oil vapors from diffusion pumps and the absence of any measures to protect the bombarded surfaces from contamination during the measurement process described in [18]. Figure 2 shows the relationships $\gamma_W = \gamma_W(T_W)$ of the recombination coefficients for atomic nitrogen at the surface of 2Kh13 stainless steel and polycrystalline molybdenum (curves 1 and 3), of atomic oxygen and hydrogen on Mo (curves 2 and 4). For these relationships the following is valid: $\gamma_W = \gamma_0 \exp(-E_a/RT_W)$, where $\gamma_0 = \text{const}/T_W$; E_a denotes the activation energy; R is the universal gas constant. The following values have been obtained from the data of Fig. 2 for the activation energy:

$$E_a^{Mo-H^+} = 2.69 \text{ kJ/mole}, \quad E_a^{Mo-N^+} \approx 5.81 \text{ kJ/mole},$$

$$E_a^{Mo-O^+} \approx 9.53 \text{ kJ/mole}, \quad E_a^{2X13-N^+} \approx 8.76 \text{ kJ/mole}.$$

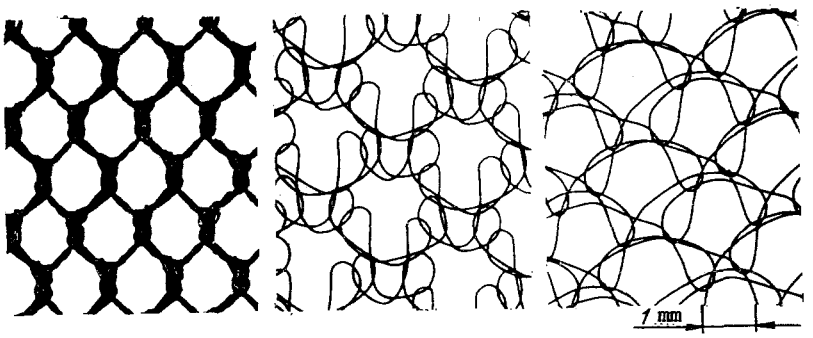

Fig. 3

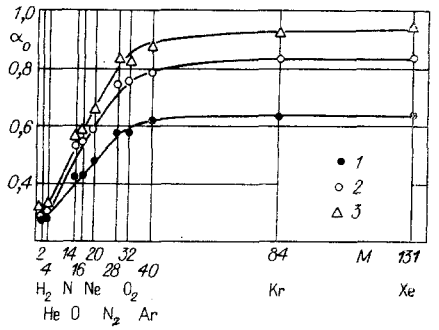

Fig. 4

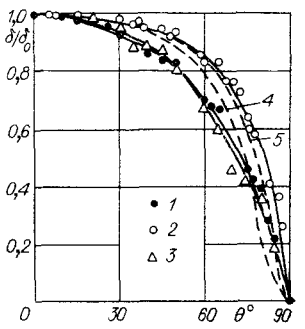

Fig. 5

The relatively low values for the activation energy give evidence of the predominance of the Éli–Raidil mechanism for the reactions of heterogeneous catalysis, characteristic for the recombination of the gas atoms with weak adsorption of the bombarding particles at the surface. This is further confirmed by the measurement data of the integral emittance of the materials being studied here within the flow of the rarefied plasma [12], and the results of [21, 22], which point up the fact that with clean metallic surfaces the activation energy E_a for heterogeneous recombination is close to zero and the activation energy increases with an increase in the density of the coating.

The derived values for the coefficients of heterogeneous recombination may be used to refine the flows of heat to the surface of a solid, determined from the contribution of the heat produced by chemical reactions. Comparison of the flows of heat carried to the surface gives evidence to the effect that the relationship between the heat flows from the transfer of kinetic energy and the chemical reactions is equivalent to the ratio of the coefficients of energy accommodation and heterogeneous recombination [16] $Q_{chemical}/Q_{kinetic} \sim \gamma_w/\alpha_i$. With a normal drop in the flow of particles (nitrogen, oxygen) to the surface, if in the majority of electrically conducting materials the contribution of the reaction of heterogeneous catalysis can be neglected, then in the case of large angles of attack for the element of the streamlined surface and the hydrogen flows the fraction of the heat transferred by heterogeneous catalysis is comparable to the quantity of heat attributable to the transfer of kinetic energy.

3. In studying the energy exchange between gas flows and permeable surfaces of electroconductive materials the procedure becomes more complicated: we encounter a need to determine the coefficients of transparency δ or population r. The utilization of two-electrode thermoanemometric or plane standard probes makes it possible, in addition to the coefficients of accommodation, recombination, and integral emittance, also to find the coefficient of transparency and population. The working elements of the two-electrode thermoanemometric probe are: the first outside electrode which is a plane thermoanemometric probe (grid); the second electrode which is a collector made in the form of a conducting cylindrical beaker whose diameter is equal to that of a reticulated and standard electrode. Equal potentials are applied to the electrodes. The ratio of the ion currents in the case of potentials close or equal to the space potential, applied to the reticulated electrode I_i^r and the standard probe I_i^s, determined the population coefficient $r \approx I_i^r/I_i^s$, while the current ratio for

the electrode-collector I_i^C and the standard probe determines the transparency of the grid $\delta \approx I_i^C/I_i^S$. Here $\delta + r = 1$ represents the condition for control of measurement accuracy. When working with ion saturation currents and when determining the relationships $r = r(\theta)$ or $\delta = \delta(\theta)$ from the angle of attack θ we must take into consideration the correction factors that are ascribed to the effects of the layer at the electrode [23].

In these measurements we used probes with a working section ~11.3 mm in diameter, made in one-, two-, and three-row grids with structures such as that shown in Fig. 3. The grid material: 1) a metallic coating (a lead-tin alloy); 2, 3) stainless steels. The measured values of the energy accommodation coefficient in the case of $W_i \approx 10$ eV, $T_w \approx 3 \cdot 10$ K and $\theta = 0$ are shown in Fig. 4. The results from the measurements of the relationships $\alpha_i(\theta)/\alpha_0$ for molecular ions characterize the approximation [24]

$$\alpha_i/\alpha_0 \approx \cos\theta + 0.887(1 + 1/\alpha_0)^{-2} \sin^2\theta(1 - \cos\theta)|\sin\theta - \cos\theta|,$$

for atomic ions (N^+, O^+)

$$\alpha_i/\alpha_0 \approx \cos\theta + 1.364(1 + 1/\alpha_0)^{-2}\sin^{2.5}\theta,$$

where α_0 is the energy accommodation coefficient when $\theta = 0$. The limit measurement error for α_0 does not exceed $\Delta\alpha_0 \approx \pm 0.04$. The values of α_0 and γ_w found at the surfaces of the conducting grids are in satisfactory agreement with data from analogous measurements carried out at surfaces of corresponding materials (stainless steels, solder).

Figure 5 shows the measurement results for the coefficients of transparency in the permeable surfaces. Just as in Figs. 3 and 4, here curves 1-3 represent the grid numbers while curves 4 and 5 represent the calculated values [25] for the fabric of the grid and of the knitted netting material. The values of δ correspond to the normal descent of the flow onto the bombarded surface ($\theta = 0$). The experimental data, with an error of no more than ±5%, approximate the following relationships: $\delta/\delta_0 \approx \cos^{0.5}\theta(1 - \cos^{1/6}\theta(1 - \cos\theta)^7)$ for grid 1 with $\delta_0 \approx 0.773$, $\delta/\delta_0 \approx \cos^{0.25}\theta(1 - \cos^{0.25}\theta(1 - \cos\theta)^7)$ for grid 2 with $\delta_0 \approx 0.838$, $\delta/\delta_0 \approx \cos^{2/3}\theta + 0.5(1 - \cos\theta)(1 - \sin\theta)$ for grid 3 for $\delta_0 \approx 0.764$. The theoretical curves 4 and 5 in [25] have been obtained for the case in which $\delta_0 \approx 0.775$.

The maximum error in the determination of the coefficients of transparency or population for the permeable surfaces made of electrically conducting materials, with utilization of two-electrode thermoanemometric probes, does not exceed ±4%.

The coefficients of transparency, energy accommodation, and heterogeneous recombination of the gas ions in electricity conducting materials are found, as a rule, with surface potentials close to or equal to the space potential, i.e., for conditions close to the streamlining of the bodies with a three-molecular supersonic flow of a neutral gas.

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