Experimental Research of Reflected Flux at Interaction of High-Velocity Free Molecular Beam with Solid Surfaces.

Erofeev A.I., Nikiforov A.P., Friedlander O.G.

Central Aerohydrodynanic Institute (TsAGI) 140180 Zhukovsky, Russia

Abstract. The report presents the results of the experimental investigation of the interaction of high-velocity free molecular beams of Nitrogen molecules - N_2, He, Ne and Ar - atoms with the surface of flat plate. The plate is made of aluminum-magnesium alloy (AMA). The experiments were carried out in the vacuum molecular beam facility VAT-103 TsAGI. The intensity of the flows is $j \leq 10^{21}$ particles/m^2s. The velocity of the flow of N_2 is up to 4, He – up to 6, Ne and Ar – up to 2.5 km/s. Main attention is given to the analysis of the fluxes of atoms and molecules reflected from the surface. The fluxes of the atoms of inert gases reflected from the surface are measured. The parameters of the velocity distribution function of the reflected atoms (Nocilla model) were obtained on basis of experimental data.

INTRODUCTION

The effects of the space on spacecraft orbiting the Earth are various and numerous [1, 2]. These problems were actively studied at recent decades. Some of them, such as the investigation of the force and heat effects of the Earth atmosphere, the persistence of the structural elements and equipment especially in the aggressive media of monatomic oxygen at the altitudes higher than 200 km, and the existence of the outer atmosphere of the spacecraft are still of vital importance.

The interaction of the gas flows with solid surfaces can be studied in more or less detailed way depending on the technological problem under consideration. For example, to determine the ballistic coefficient of the vehicle one should know the drag coefficient. If you want to study the problems of the spacecraft orientation in free-molecular flow, in some cases you may need in the dependence of the accommodation coefficients upon the angle of incidence of the gas flow on the surface element. Other cases studying the interference of the surface elements require the knowledge of the distribution function of reflected molecules (Boltzmann level). This is also true for the problems of the outer atmosphere of the spacecraft. We also need in the Boltzmann level to define the boundary conditions for the problems of the flow past the vehicle in the transition regime.

This work concentrates on the analysis of the atom and molecule fluxes reflected from the surface. This approach was used in [3, 4] for the analysis of the results of the interaction of the nitrogen molecular beam with flat samples of various materials. Here the accommodation dependences upon beam component, energy and angle of attack are researched. Additionally angle distributions of reflected molecules number flux are researched. The parameters of Nochilla model reflected distribution function are determined on basis of these measurements.

1. THE TEST FACILITY. FLOW PARAMETERS.

The experimental research of the interaction of the high-velocity free-molecular gas beams with the surface of plane models was carried out on the vacuum facility VAT-103 [3, 4]. The sketch of facility is given in Fig.1. The mixture of gases is supplied into pre-chamber 2 where it is heated by a high-frequency discharge. From the pre-chamber the gas exhausts to pre-skimmer chamber 3 through sonic nozzle. Gas pressure in the pre-skimmer chamber is $5 \cdot 10^{-4}$-$2 \cdot 10^{-3}$ torr. Skimmer 4 forms the molecular beam from the gas flow exhausting

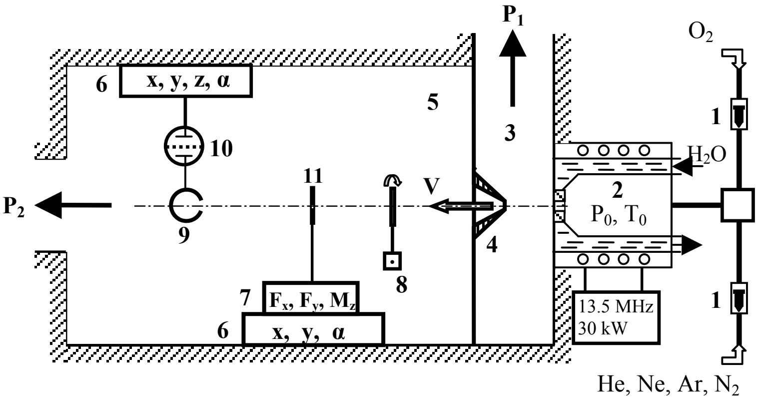

FIGURE 1. A schematic test facility configuration.

TABLE 1.

Gas	P_0, torr	T_0, K	G, mg/s	V_∞, km/s	Re_*	S_∞
N_2	50÷100	1500÷3000	10÷25	1.5÷2	400÷300	6.5÷5.5
	150÷200	5000÷6000		4÷5	80÷40	
$Ar+O_2$	50÷100	2000÷5000	8+(1÷1.5)	1.8÷3	80÷50	7÷5.5
$Ne+O_2$	100	3000	7+1	2.5	50	6
He	100÷200	1500÷4000	4÷5	3÷7	200÷50	10÷6
$He+O_2$	100÷200	2000÷4000	5+0.5	5.5÷6.5	80÷40	7÷6

from the nozzle. The background gas pressure in the work chamber 5 is (2-5)·10^{-6} torr. The facility is equipped by coordinate systems 6, three component balance 7, flow chopper 8, Pitot pressure probe 9, pressure gauges 10. The tested sample (model) 11 is a disc (diameter 50 mm, thickness 0.5 mm) fixed onto the three-component balance. The operating regimes of the VAT-103 for various gases are given in the table 1. In the table: G is flow rate, V_∞- the average velocity, $Re_*=d_* a_0\rho_0/\mu_0$ - Reynolds number, a_0, ρ_0, $\mu_0=\mu(T_0)$ are the sound velocity, density and the viscosity coefficient, respectively, S_∞- the longitudinal velocity ratio.

The molecular beam parameters (velocity V_∞ and number density n_∞) are determined by measuring the forces acting on the probe sample and the molecule beam intensity with the Pitot pressure probe (Fig.2). There can be defined from the following relationship:

$$n_\infty V_\infty = \frac{c_w}{2\sqrt{\pi k T_w}}(p_2 - p_1),\ c_w = \sqrt{2kT_w/m},\ F = C_x \frac{\rho_\infty V_\infty^2}{2} A_m \quad (1)$$

Here, T_w is the temperature of gas in the gauge, c_w is the thermal velocity of the molecules of mass m, p_1 is the static pressure in the work chamber with the cut-off flow, p_2 is the Pitot pressure, C_x is the drag coefficient, A_m is the frontal area. In our experiments a hollow cylinder with a cone bottom as a probe sample was used (Fig.2). The drag coefficient of this body with the ratio of the cylinder length to the base radius L/R>5 can be defined as:

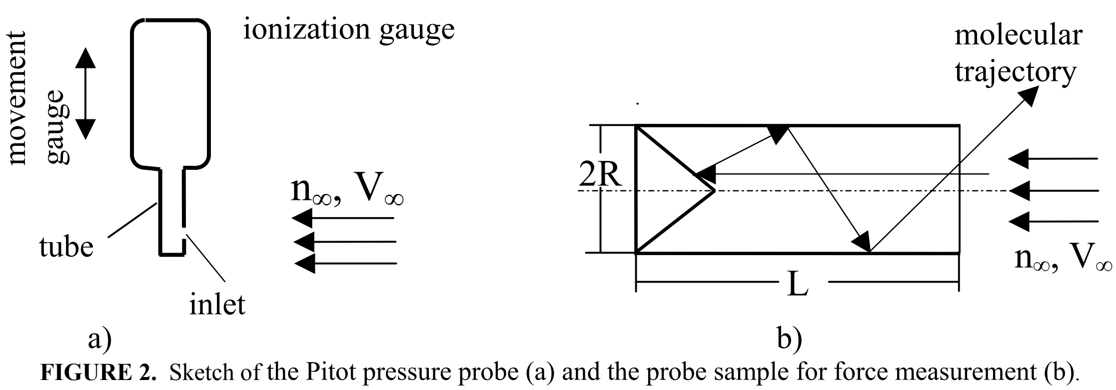

FIGURE 2. Sketch of the Pitot pressure probe (a) and the probe sample for force measurement (b).

$$C_{x,ps} = 2 + \frac{1}{S_\infty^2} + \frac{\kappa}{V_\infty}\sqrt{2\pi \frac{k}{m} T_{w2}} \qquad (2)$$

Here T_{w2} is the temperature of the probe sample surface, $\kappa > 1$ is the parameter defined by the molecular flow exhausting from the cylinder (at diffuse reflection from plane plate $\kappa = 1$). The Monte-Carlo calculations for different cases of local reflection of the molecules from the surface elements proved that this parameter may be κ = 1.1 [5]. Equations (1), (2) define the required beam parameters. By the same way the beam parameters for the gas mixture may be defined.

2. THE EXPERIMENTAL RESULTS.

Define the ratio of the reflected particles momentum to incident particles momentum as β_i for the force analysis of the molecular beam acting on the plate (see also [4]):

$$\beta_n = P_{nr} / P_i, \quad \beta_\tau = P_{\tau r} / P_{\tau i}$$
$$P_i = P_{i0} \cos\theta, \; P_{\tau i} = P_{i0} \sin\theta \cos\theta, \; P_{i0} = 0.5 \rho_\infty V_\infty^2 (2 + S_\infty^{-2}) \qquad (3)$$

The value of the relative normal momentum $\beta_n > 0$; as for the value of the tangential momentum β_τ, its sign depends on the direction of the reflected flow: $\beta_\tau = 0$ in case of the diffusion reflection, $\beta_\tau < 0$ for the molecules reflected in the direction of the incident flow ($\beta_\tau = -1$ in case of the specular reflection), and $\beta_\tau > 0$ for molecules reflected in the backward direction. The values of β_n and β_τ are determined by the measured forces

$$\beta_n = \frac{C_{x,ps} A_{st}}{2A_m} \frac{F_n}{F_{ps}} \frac{1}{\cos\theta} - \cos\theta, \quad \beta_\tau = \frac{C_{x,ps} A_{st}}{2A_m} \frac{F_\tau}{F_{ps}} \frac{1}{\sin\theta \cos\theta} - 1 \qquad (4)$$

where A_m, A_{st} are the area of the model and the inlet section of the probe sample, F_n and F_τ – normal and tangential forces, acting on model, F_{ps} is the force, acting on the probe sample.

Figure 3 shows the dependence of β_n vs. the beam energy, mass of the gas molecules and the incidence angle θ. One can see that at $\theta = 0$ the normal momentum of the reflected particles for the given mass decreases with the increase of the energy of the molecules, and at a given value of energy the less is the mass of the molecules the larger is the momentum. As for other special features of the results of the ratio β_n upon the angle of incidence given in Fig. 3 we should point out that the normal momentum of the reflected flow β_n of *He* grows considerably with the increase of the angle of incidence, though for *Ne* and *Ar* the value of β_n slightly depends on the angle θ. The experimental data on the tangential momentum of the reflected flows β_τ vs. the angle θ are presented in Fig. 3 also. It is obvious that the dependency $\beta_\tau(\theta)$ for *He* differs greatly from the relations for other gases. In case of helium we see the reverse reflection of the beam, and the value β_τ increases with the increasing the angle θ. Pay attention that in paper [6] the isotropic reflection take place: $\beta_\tau \approx 0$. For heavier gases $\beta_\tau < 0$. It means that the

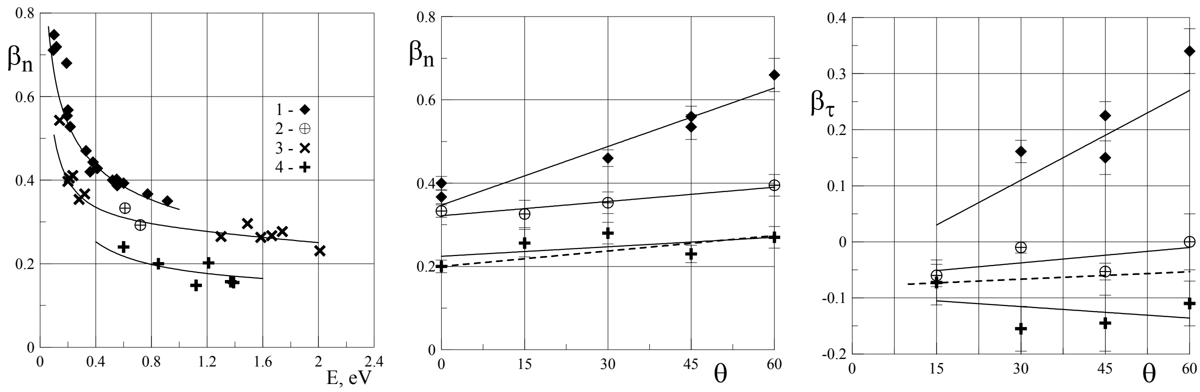

FIGURE 3. The dependence of β_n, β_τ vs. the beam energy, mass of the gas molecules and the incidence angle θ. Notation on all graphs: 1 – *He*, 2 – *Ne*, 3 and dashed line – N_2, 4 – *Ar*.

reflected flux has a specular component. The data for the angles of incidence $\theta \neq 0$ were obtained for the following average values of the energy of atoms in the beam (in eV): *He* – 0.8, *Ne* – 0.6, *Ar* – 0.85.

The comparison of the obtained results with the published data on the relation $\beta_n(E_\infty)$ for *Ne* and *Ar* at the values of energy $E_\infty \leq 20$ eV for the incidence angle θ=0 is shown in Fig. 4. The surface material of the samples was mainly aluminium, or *Al-Mg* alloy. In Fig. 4 the dependency of reflected molecules momentum at the diffuse reflection upon temperature T_w (solid line) is shown also:

$$\beta_{nw}(T_w, E_\infty) = \frac{P_{nw}}{P_i} = \frac{\sqrt{\pi}}{2}\sqrt{\frac{kT_w}{E_\infty}} \tag{5}$$

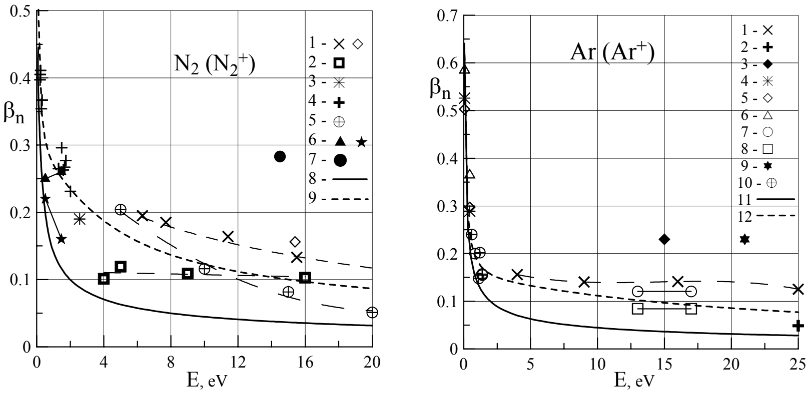

FIGURE 4. The dependence $\beta_n(E_\infty)$ for the interaction of N_2 and Ar with the surface of aluminium (and its alloys). Notation and references for left graph: 1 – [7], 2 – [8], 3 – [4], 4 – our results, 5 – [9] (ion), 6 – [10], 7 – [11] (ion), 8 – eq. (5), 9 – eq. (6). Right graph: 1, 2 – [8], 3 – [12] (ion), 4, 5, 6 – [13], 7, 8 – [14], 9 – [11] (ion), 10 – our results, 11 – eq. (5), 12 – eq. (6) *a*=1.75, *b*=0.2.

One can see a considerable qualitative data spread, but the tendency of the reduction of β_n at the increase of energy is obvious. The relation $\beta_n(E_\infty)$ for the interaction of nitrogen with the surface of aluminium (and its alloys) can be approximately defined as follows:

$$\beta_n = \beta_{nw}[1 + a\cdot(1 - e^{-bE_\infty})], \quad a = 1.75,\ b = 0.75 \tag{6}$$

This relation is presented in Fig. 4 also. An experimental data on the momentum of the reflected atoms and ions of argon (*Ar*) with the surface of aluminium, its alloys and some other materials show the same tendencies of variation of $\beta_n(E_\infty)$ as in the case of nitrogen. The only difference is a greater decrease of $\beta_n(E_\infty)$ dependency at the values of energy $E_\infty \leq 1$ eV. It is also possible to approximate of $\beta_n(E_\infty)$ by the relation of (6) type with constants *a* = 1.75, *b* = 0.2.

3. REFLECTED FLUX MEASUREMENT.

The fluxes of the molecules of the gas reflected from the surface of the model were studied in the plane of the beam incidence only. The results of measurements reflected flux dependency upon the angle of reflection (scattering indicatrix) for various gases are presented in Fig. 5. The data were obtained for the following average energy of atoms in the beam (in eV): *He* – 0.52, *Ne* – 0.55, *Ar* – 0.83. The surface temperature was *Tw*=293K. At $\theta = 0$ with the gas mass decreasing the indicatrix differs from the diffusion one. This tendency corresponds to the dependency of β_n vs the mass of atoms shown in Fig. 3. At the angle of incidence θ=45° all the indicatrixes show elongation in the direction opposite to the velocity of the incident beam, and the less the mass of the gas is the longer they are. This tendency corresponds qualitatively but not quantitatively to the variation of the tangential momentum of the reflected atoms (Fig.4).

As it was mentioned, some applications require the data on the reflected molecular distribution function. The presentation of the distribution function by approximate models of various complexity (depending on the problem of the flow past a body) has become quite usual. The some of these models is given in [15-18]. One of the most widely-spread models (if we do not take into account the model of a total diffusion reflection at the temperature equal to the

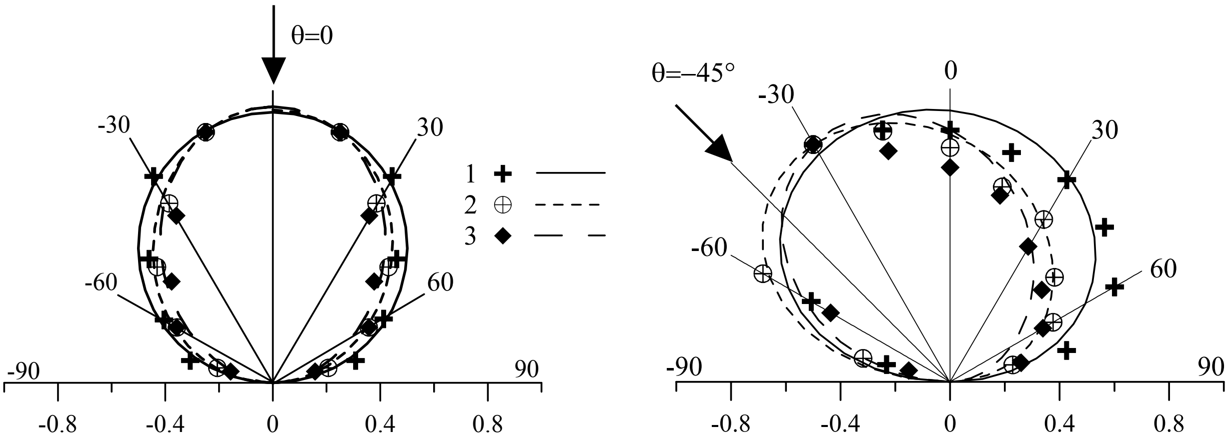

FIGURE 5. The scattering indicatrixes for Ar (1), Ne (2), He (3): symbols – experimental data, lines – Nochilla model.

TABLE 2. Parameters of the reflected distribution function.

Gas	S_r	θ_r	T_r, K
He	0.22	60	2650
Ne	0.2	129	1255
Ar	0.185	167.5	910

temperature of the surface) is the Nochilla model, suggested in 1960 (see [16]):

$$f_r(\vec{u},\vec{x})|_{u_n>0} = n_r\left(\frac{h_r}{\pi}\right)^{3/2} exp[-h_r(\vec{u}-\vec{V}_r)^2] \qquad (7)$$

This model was used to construct the reflected molecules distribution function based on the experimental momentum data and the measured scattering indicatrixes given above. For the given surface the parameters of function (7) – $n_r, h_r, \vec{V}_r$ – depend on the velocity vector and the type of the molecules of the gas beam. Instead of the velocity $\vec{V}_r$, we can introduce the dimensionless parameter $S_r = V_r\sqrt{h_r}$ (the velocity ratio in the reflected flow) and the angles determining the direction of the velocity vector. For the isotropic surface the velocity vector $\vec{V}_r$ is determined by only one angle θ_r and has the components $\vec{V}_r(V_r\cos\theta_r, V_r\sin\theta_r, 0)$. To determine the parameters $n_r, h_r, \vec{V}_r$ or n_r, h_r, S_r, θ_r we need in four equations connecting these parameters with the parameters of interaction. As we did not measure the energy flux onto the surface in the described experiments, only three constraint macroscopic equations are take place. Two additional relations may be derived by using the data on the scattering indicatrix. It allow determine two parameters of reflected distribution function. For modeling reflected molecules flux angle distribution two other parameters were determined by using the mass flow conservation law and relation (3) for β_n. The parameters S_r, θ_r of the distribution function of the reflected molecules were derived from the experimental data by the method of least squares. At θ_i=0, the analysis of the indicatrixes gives: S_r=0.282, T_r=930K *(He)*, 0.176 and 790K*(Ne)*, 0.008 and 485K *(Ar)*. For θ_i=45 the parameters of the distribution function are presented in the Table 2. The calculated indicatrixes are shown in Fig. 5 together with the experimental data.

4. CONCLUSIONS.

The analysis of the experimental data on the interaction of high-velocity molecules of nitrogen and the atoms of argon with energy up to 25 eV with aluminum and its alloys surfaces shows that at the incidence angle θ=0 the dependency of the normal momentum of the molecules reflected from the surface upon the energy of the beam E_∞ may be approximated by the following relation: $\beta_n = \beta_{nw}[1+a(1-exp(-bE_\infty)]$. The constants included in this formula are: a = 1.75, b = 0.75 – for nitrogen, and a = 1.75, b = 0.2 – for argon.

The general tendency of the reflected molecules normal momentum β_n dependency upon the incidence angle θ for all gases listed above can be approximated by the following linear relationship $\beta_n=c_n+d_n\,\theta$, where the constants

c_n, d_n depend on the type of the molecules. Within the whole range of the incidence angles θ, the value β_n increases with the decrease of the mass of the atoms.

The dependencies of the reflected molecules tangential momentum β_τ upon the incidence angle θ may be approximated by the linear relationship $\beta_\tau=c_\tau+d_\tau\ \theta$. Within the whole range of the incidence angles θ the following tendency of β_τ dependence upon the mass of the atoms in the flow is observed: with the reduction of the mass the value of β_τ increases. If for Ar we have $\beta_\tau<0$, then for Ne - $\beta_\tau \approx 0$, and for He - $\beta_\tau >0$.

The linear dependencies $\beta_n(\theta)$, $\beta_\tau(\theta)$ for the interaction of the N_2 molecules with the various materials surfaces were derived earlier in [4, 10]. The data obtained in these work prove that the dependencies are also true for the interaction of the inert gases with the surface of *Al – Mg* alloys. So, these relations can be used for estimation of the force action of the high-velocity molecules of various gases on the bodies in the flow if there are no experimental data or they are incomplete.

The investigation the reflected molecular fluxes along with momentum transfer data increase considerably the information about gas/surface interaction and allow to compose the model distribution function of reflected molecules more substantially.

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