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RESISTANCE OF A BODY WITH AN INTRINSIC MAGNETIC FIELD IN A SUPERSONIC FLOW OF A PARTIALLY IONIZED GAS

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The presence of an intrinsic magnetic field substantially alters the nature of the flow, the structure of the perturbed zone, and the charged particle distribution of a body surface in supersonic rarefied plasma flow [1]. A system of currents or permanent magnets can be the source of the magnetic field of the body. The decisive influence of the self-consistent field on the charged particle distribution in the neighborhood of bodies with an intrinsic magnetic field is clarified in [1, 2] for $\rho_e \ll R \ll \rho_i$ (R is the characteristic body dimension, and ρ_α is the Larmor radius of particles of the species α). The perturbations induced by the intrinsic magnetic field result in a change in the functional characteristics of different systems and singularities of dynamic body interaction with the flow. Results of an approximate numerical solution of the problem of MHD-interaction of a body with a supersonic rarefied plasma flow [3, 4] indicate the possibility of controlling the forces acting on the body, the change in heat elimination to the surface. Experimental data are scarce, limited to a narrow band of interaction parameters, and do not take account of the influence of the body surface geometry [5, 6]. Results of an experimental investigation of the influence of the intrinsic magnetic field on resistance of bodies of simple geometric shape (disc, sphere, cylinder, cone) are presented in this paper. Dependences of the body frontal drag coefficient on the magnetic field intensity are determined for $\mathbf{U}_\infty \| \mathbf{H}$ and $\mathbf{U}_\infty \perp \mathbf{H}$ ($\mathbf{U}_\infty$, and $\mathbf{H}$ are the flow velocity and magnetic field intensity vectors). The possibility of an effective MHD deceleration of bodies in a supersonic rarefied plasma flow is given a foundation.

1. Experiments were performed in a plasma gasdynamic installation in a partially ionized nitrogen flow generated by a gas-discharge accelerator with ionization of the working body by electron impact and plasma "self-acceleration." The diagram of the installation is presented, in principle, in [7]. An accelerated plasma flow entered the working chamber, in which the residual gas pressure was ~10^{-5} Pa. Evacuation was realized by a vacuum electrodischarge unit of AVED-40/800M type and a turbomolecular pump of TMH-500 type. The rarefied plasma flow parameters at the ~10^{-1}-10^{-3} Pa working pressures in the chamber were measured by using mobile electrical probes and a multielectrode probe analyzer. Measurement of the current–voltage characteristics and the derivatives of the probe current was performed in the automatic mode. The scheme of probe measurements with current–voltage characteristics

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recorded on a dc milliammeter recorder operating in conjuction with a photoamplifier using a resistance box as measuring resistance permits fixing the probe currents in the $\sim 1 \cdot 10^{7}$-$1.5 \cdot 10^{-1}$ A range with smooth regulation of the probe potential between 0 and 250 V. The error in measuring the individual current—voltage characteristic does not exceed ±2%.

The method of harmonics [8] was used to measure the derivatives of the probe current with respect to the voltage. Since the derivatives of the probe current were used just to determine the plasma potential, the amplitudes of the probe current harmonics were not calibrated. The plasma potential was found by the method of the second derivative as well as by the electron branch of the probe characteristic constructed in a semilogarithmic scale. The scheme of measuring the probe current derivatives permits recording the plasma noise in the probe loop as well, which affords the possibility of controlling the accuracy of measuring the plasma potential. The maximum of the plasma noise corresponds to the potential of space. It here turns out that the plasma potential found at the point $d^2I_e/dV^2 = 0$ and the noise maximum corresponds better to the beginning of the deviation of the semilogarithmic characteristic from rectilinearity than the point of intersection of the asymptotes. An analogous phenomenon was observed in the determination of the space potential by using a cylindrical probe executed in the form of a thermoanemometer and operating in the thermal probe mode. The plasma potential was measured at the point of divergence of the cold and hot probe characteristics. The scatter in the plasma potential values was not more than ±4%. This determined the sufficiently high accuracy of the flow ion energy measurement W_i. The values of W_i computed under the assumption that the acceleration potential equals the difference between the source anode potential and the local plasma potential, are in satisfactory agreement with the data of measurements by using a multielectrode probe analyzer. The spread in these values did not exceed ±4.5%.

Special attention was spent on the cleanness of the probe surfaces in the current—voltage charactersitics measurements. Directly before the measurements the working surfaces were subjected to compulsory conditioning, were cleansed because of intensive bombardment in the rarefied plasma flow for high values of the accelerating potentials. This permitted elimination of the influence of surface contaminations on the results of the probe measurements and utilization of traditional methods of processing the current—voltage characteritics [8].

Comparison of the values of the charged particle concentrations N_∞ found for different sections of the electron branch of the current—voltage characteristic of a cylindrical probe yields the spread of the local values of N_∞ within the limits of the band characterized by the factor 3 [9]. Underlying such a spread is the uncertainty in the selection of the magnitude of the electronic probe current corresponding to the plasma potential as well as the difference in the real from the ideal current—voltage characteristic because of secondary emission effects, electron reflection, etc. Hence, to raise the accuracy in finding N_∞ a microwave diagnostics method using a 3 cm range interferometer [10] in parallel with the probe was used. Local values of the charged particle concentration, calculated for the electronic probe current measured by plane and cylindrical probes at a point corresponding to the plasma potential are in satisfactory agreement with the microwave measurement data [10].

A single cylindrical probe from a molybdenum filament of 0.04 mm diameter and 2.3 mm length was used also to control the orientation of the model relative to the flow velocity vector. The peak of the ionic current measured by this probe during rotation around the vertical and horizontal axes corresponds to probe orientation along the flow and permits estimation of the degree of nonisothermy of the flow [11].

2. Experimental investigations were performed in a section of the jet with a uniform parameter distribution: the external magnetic field intensity of $H \lesssim 2$ Oe, the flow ion energy $W_i \approx 10$-60 eV and the charged particle concentration of $N_\infty \approx 10^8$-10^{11} cm^{-3}. A solenoid with 50 mm external, 20 mm internal diameters and 34 mm height was the source of the intrinsic magnetic field of the body. The distribution of the axial and radial-azimuthal components of the solenoid magnetic field intensity is illustrated in Fig. 6 of [2]. The intrinsic magnetic field intensity is such that a domain of locally magnetized plasma occurs in the neighborhood of the body. The structure of the perturbed zone during plane and axisymmetric flow around a large ($R/\lambda_d \gtrsim 10^2$, λ_d is the Debye radius of the unperturbed plasma) body is shown for $\mathbf{U}_\infty \| \mathbf{H}$ and $\mathbf{U}_\infty \perp \mathbf{H}$ in Fig. 6a in [1] and Fig. 7 in [2]. The singularities of the flow and the distribution of the charged particles around a body with an intrinsic magnetic field for $R/\lambda_d \gtrsim 10^2$ and $\mathbf{U}_\infty \| \mathbf{H}$ indicate that the dynamic interaction of the

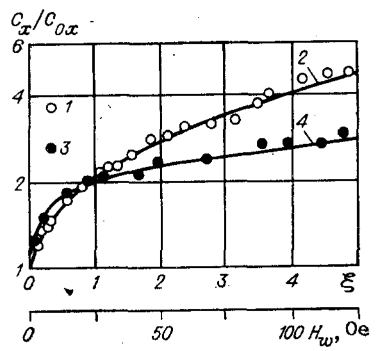

Fig. 1

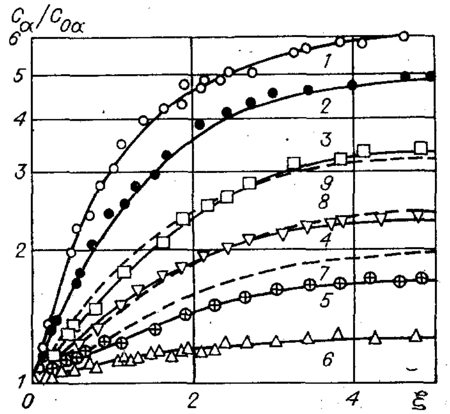

Fig. 2

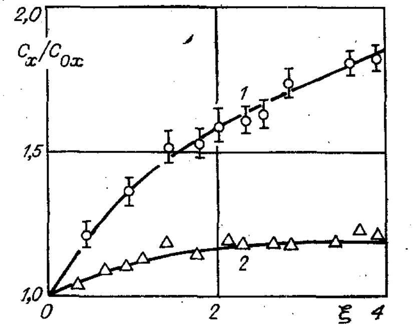

Fig. 3

rarefied plasma flow occurs with the facial surface. This circumstance was utilized in studying the influence of the intrinsic magnetic field ($\mathbf{U}_\infty||\mathbf{H}$) on the resistance of a large ($R/\lambda_d \gtrsim 10^2$) disc. The solenoid fastened to a stationary support is located in the near wake behind the disc. A disc, sphere, cylinder, and cone fabricated from dense paper were used as models.

The "floating" negative potential of the body surface diminished towards positive values with the appearance of a weak magnetic field. Later as the magnetic field intensity grew, the body surface potential remained practically unchanged. The maximal change in the negative "floating" potential does not exceed ~12% and the minimal ~4%, for a charged particle concentration range in the free stream of $N_\infty \approx 10^8$-10^{11} cm^{-3} for magnetic field intensities of $H_w \approx$ 0-150 Oe on the surface of a 60 mm diameter metal sphere surface. The plasma interacts with negatively charged magnetized body. The structure of the perturbed zone for axisymmetric and plane flow around a large ($R/\lambda_d \gtrsim 10^2$) dielectric body is identical to the structure of the perturbed zone near the negatively charged body. The influence of a change in surface potential within the limits ~4-12% on the resistance of a large negatively charged body is negligibly small [12, 13].

The body being investigated with the solenoid fastened on a stationary support located in an internal cavity is the sensor of microbalances of compensation type. Measurements of the force action of the rarefied plasma flow on a body with an intrinsic magnetic field were performed in the automatic mode with the dependence of the resistance force on the solenoid magnetic field intensity recorded on an X−Y plotter.

The dependence of C_x/C_{0x} on the parameter $\xi = \beta e U_\infty P_m/W_i$ is presented in Fig. 1 (C_{0x} is the frontal drag coefficients for $H_w = 0$, $\beta \approx 2.17$ cm^{-2}, P_m is the magnetic moment of the solenoid, e is the charge, U_∞ is the flow ion velocity) for a sphere and disc of radius $R \approx 32.5$ mm with an intrinsic magnetic field for $\mathbf{U}_\infty||\mathbf{H}$. The parameter ξ is the ratio between the deceleration force of the body with the intrinsic magnetic field in a supersonic rarefied plasma flow is proportional to $\sim eN_\infty U_\infty P_m$ [14] and the velocity head $N_\infty W_i$. The magnetic field source is located at the center of the sphere. The points 1 and 3 are experiments for the sphere and disc, respectively, the curve 2 (sphere) corresponds to the empirical approximation $C_x/C_{0x} \approx 1 + (2.17eU_\infty P_m/W_i)^{0.8}$, and curve 4 (disc) to $C_x/C_{0x} \approx 1 + (2.17eU_\infty P_m/W_i)^{1/3}$.

The influence of the intrinsic magnetic field on the frontal drag and lift coefficients of a cone with angle ~20.5°, base radius $r \approx 58.5$ mm, height $h \approx 99$ mm and bluntness in the form of a secant of a sphere of radius $r \approx 25$ mm at angles of attack $\theta \approx$ 0-90° is illustrated in Fig. 2. The magnetic field source is in the cone base. The angle of attack θ characterizes the cone orientation relative to the free stream velocity vector $\mathbf{U}_\infty$. The vectors $\mathbf{U}_\infty$ and $\mathbf{H}$ are collinear. Curves 1-6 show the change in the frontal drag coefficient C_x/C_{0x} of the cone as a function of the magnetic field intensity for θ = 0, 15, 45, 60, 67.5, 90° and 7-9 display the change in the lift coefficient C_x/C_{0y} for θ = 10, 20.5, 30°. As the angle of attack of the model increases the influence of the intrinsic magnetic field on the frontal drag coefficient attenuates: the nature of the flow, the charged particle distribution in the neighborhood of the body and the currents on the surface, the field structure and the nature of body screening by the magnetic field change. The experimental data of Fig. 3 for a transverse cylinder of radius $R \approx 36$ mm and length $L \approx 139$ mm with an intrinsic magnetic field also confirm this for $\mathbf{U}_\infty||\mathbf{H}$ and $\mathbf{U}_\infty \perp \mathbf{H}$ (curves 1 and 2). The spread in the measured values of the body frontal drag force is shown by dashes.

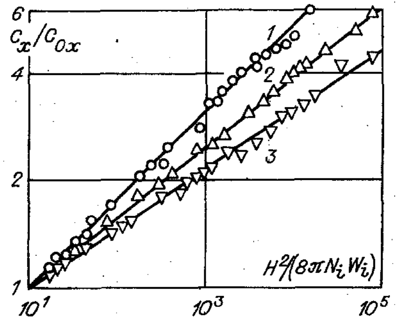

Fig. 4

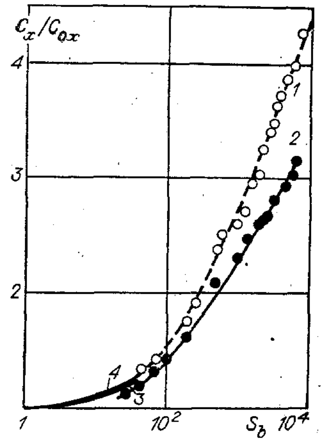

Fig. 5

The frontal drag coefficients of bodies of simple geometric shape in a rarefied plasma flow are proportional to the magnetic field pressure. Figure 4 illustrates the dependence of the frontal drag coefficient of a dielectric cone, a metallic and dielectric sphere (curve 1-3) on the parameter $\eta = H_w^2(8\pi N_\infty W_i)$, the ratio between the magnetic and gasdynamic pressures. The data of Fig. 4 for a sphere, as indeed the data of Fig. 5, confirm that the MHD interaction is stronger and the Hall effect weaker for conducting bodies than for nonconductive bodies [4]. A collisionless almost free-molecule flow mode was realized here for all models during experiments at working chamber pressures of $\sim 10^{-1}$-10^{-3} Pa. The measurements were executed in rarefied plasma flows with concentrations $N_\infty \approx 10^8$-10^{11} cm^{-3}, electron temperature $T_e \approx 1.5$-4 eV, degree of nonisothermy $T_e/T_i \approx 4$-7, and velocities $U_\infty \approx 7$-15 km/sec.

The dependence of the frontal drag coefficient of a blunt axisymmetric body (the hemisphere R ≈ 43 mm with a cylindrical skirt of length L ≈ 50 mm) on the magnetic interaction parameter $S_b = \sigma_\infty H_w^2 E/(\rho_\infty U_\infty)$ is represented in Fig. 5 for $\mathbf{U}_\infty \| \mathbf{H}$ and $S_i = U_\infty/(2kT_e/M_i)^{0.5} \approx 4.6$. Here σ_∞ is the electrical conductivity, ρ_∞ is the density of the unperturbed flow, S_b is the product of the Reynolds magnetic number by parameter η. Curve 1 characterizes the conducting body, 2 are the nonconductive, 3 are experimental results [5, 6], and 4 are numerical data [6]. Taking account of the results of [6], the values of C_x/C_{0x} in Fig. 5 encompass a broad range of free stream parameters ($N_\infty \approx 10^8$-10^{12} cm^{-3}) and interactions from viscous to collisionless MHD flows.

The data presented indicate that particles reflected by an intrinsic magnetic field introduce a substantially greater contribution into the force action of the flow on the body than do particles colliding with the surface and verify the possibility of effective MHD deceleration of bodies in a supersonic rarefied plasma flow.

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RHEOLOGICAL BEHAVIOR OF A DILUTE SUSPENSION OF RELATIVELY COARSE DEFORMABLE PARTICLES IN A SIMPLE SHEAR FLOW

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The behavior of dilute suspensions of stiff and deformable ellipsoidal particles of such a size that it is necessary to take account of the influence of Brownian forces on the particle behavior is investigated in [1, 2]. The case is considered in this paper when the suspended deformable particles are relatively coarse, i.e., the influence of the Brownian and inertial forces on the microstructure behavior can be neglected. The rheological behavior of the suspension is here determined by the microstructure behavior under the action of just hydrodynamic forces.

It is shown in [3] that during simple shear the stiff ellipsoidal particle subjected to hydrodynamic forces performs periodic motion relative to its center of inertia along one of the closed orbits that form an infinite one-parameter family located on the surface of a sphere. The distribution of the suspended stiff particles over the orbits cannot possibly be determined uniquely without relying on some additional assumptions. Thus, it was considered in [3] that the particles are oriented in such a manner that the principle of minimum energy dissipation is satisfied. The hypothesis about equally probable suspended stiff particle distributions over orbits is examined in [4]. It is assumed in [5, 6] that the axis of rotation of a deformable ellipsoidal particle is in the shear plane. However, as is shown in [7], there are significant discrepancies between experimental data on the macroproperties of the suspension and the theoretical results obtained on the basis of given hypotheses. A method is presented in [8, 9] for finding the distribution of stiff particles over the orbits that is based on assumption of the presence of weak Brownian motion of the particles that does not influence the rheological properties of the suspension. Weak Brownian motion over the lapse of a long time interval results in a certain stationary distribution of the suspended particles over the orbits.

A hypothesis proposed in [8, 9] for stiff particles is used in this paper to find the distribution of deformable particles over the family of orbits. In contrast to the case of relatively coarse stiff particles, the one-parameter family of closed orbits of viscoelastic deformable particles is located on the surface of a triaxial ellipsoid whose geometry and orientation depend on the shear rate, the viscosity of the dispersion medium, and the properties of the suspended particle material.

1. RHEOLOGICAL EQUATIONS OF STATE

Let us consider a dilute suspension of suspended deformable particles. We simulate an element of the suspension microstructure by a deformable ellipsoid of revolution, whose stress state in the material is determined by the internal elasticity G and internal viscosity η. The rheological equations of state for such a suspension have the form [2]

$$T_{ij} = -\langle P\rangle\delta_{ij} + 2\langle\mu_0\rangle d_{ij} + \langle\mu_1 n_i n_j\rangle + \langle\mu_2 n_k n_m n_i n_j\rangle d_{km} + 2\langle\mu_3(d_{ik}n_k n_j + d_{jk}n_k n_i)\rangle. \quad (1.1)$$

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