

Forces Acting on a Spherical Particle in a Rarefied Plasma

A.G. Gnedovets, A.V. Gusarov, A.A. Uglov

A.A. Baikov Institute of Metallurgy, Russian Academy of Sciences
Leninsky Prospect 49, Moscow 117911, Russia

Abstract. The methods of molecular gas dynamics are applied to the description of plasma-particle charge and momentum transfer under subsonic and hypersonic flow conditions. The analysis is based on the combined solution of the Poisson and Boltzmann equations. The influence of the speed ratio and Debye screening parameter on the drag force is investigated by numerical and analytical methods.

Introduction. It is well known that the drag force acting upon the particle in a plasma flow is conditioned by the momentum transfer by heavy plasma species - molecules and ions. The contribution of electrons to the drag force is negligible. The drag force expressions under plasma conditions have been established for the free-molecular (collisionless) [1-3] and transition [4] flow regimes based on the thick and thin plasma sheath assumptions. Thermophoresis caused by temperature gradient in plasma have been described in [5-7]. In contrast with particle drag, the contributions of electrons and ions to thermophoretic force are of the same order of magnitude due to high thermal conductivity of electron gas.

This paper is concerned with the drag force on a spherical metallic (conducting) particle in two different situations: (a) subsonic, and (b) hypersonic flow of rarefied (collisionless) plasma.

The total drag force acting on a particle $F = F_a + F_i$ is the sum of the terms due to direct collisions (F_h^s) and reflection (F_h^r) from the surface of molecules and neutralized ions, and Coulombic interaction (F_i^C) of noncolliding deflected ions with the charged particle:

$$F_a = F_a^s + F_a^r, \quad F_i = F_i^s + F_i^r + F_i^C$$

The processes of plasma-particle charge and momentum transfer are studied by simulating the plasma flow around the particle. The potential and number densities distributions are obtained by numerical solution of the Poisson and Boltzmann equations for an arbitrary Debye screening parameter $x_D = r_D / R$. The value of the particle floating potential φ_f is determined proceeding from the condition of equality of the total fluxes of plasma electrons and ions absorbed by the particle surface.

Subsonic plasma flow. In the case of relatively low speed of plasma flow, the velocity distribution functions of j th kind of plasma species in nondisturbed flow region far from the particle can be represented as

$$f_{j\infty} = [1 + 2cs_j]f_{j\infty}^0 = f_{j\infty}^0 + f_{j\infty}^1$$

where $f_{j\infty}^0 = N_{j\infty} (m_j / 2\pi kT_{j\infty})^{3/2} \exp(-c^2)$, $c = v / (2kT_{j\infty} / m_j)^{1/2}$, $s_j = V / (2kT_{j\infty} / m_j)^{1/2}$. The charge fluxes and the potential distribution around the particle with an accuracy up to $\sim s_j$ are determined by the symmetrical part $f_{j\infty}^0$ of the velocity distribution function, while the intensity of plasma-particle momentum transfer is conditioned by the anisotropic component $f_{h\infty}^1$.

The dimensionless drag force components

$$\Psi_h^t = F_h^t / (\frac{16}{3} \pi^{1/2} R^2 N_{h\infty} kT_{h\infty} s_h)$$

are calculated as

$$\psi_h^r = 2 \int_0^{\infty} \int_0^{\xi_m} \xi d\xi c^5 \exp(-c^2) dc$$

$$\psi_h^s = (\pi \tau_s)^{1/2} \int_0^{\infty} \int_0^{\xi_m} \cos \Phi_1 \xi d\xi c^4 \exp(-c^2) dc$$

$$\psi_h^c = 2 \int_0^{\infty} \int_0^{\xi_m} (1 - \cos \Psi) \xi d\xi c^5 \exp(-c^2) dc$$

where $\xi = \rho / R$, $\xi_m = \rho_m / R$, $\tau_s = T_s / T_{h\infty}$. The maximum impact parameter ρ_m , the angle of orientation $\Phi_1 = \Phi(\nu, \rho, R)$ and the scattering angle $\Psi(\nu, \rho)$ are determined from the solution of the equations of motion of heavy plasma species in the electrostatic field of the charged particle.

Hypersonic plasma flow. Another flow regime corresponds to the case when the thermal velocities of ions \bar{v}_i and electrons \bar{v}_e and the speed of plasma relative to the particle V maintain the following relationship between them: $\bar{v}_i \ll V \ll \bar{v}_e$. This means that electrons arrive at the particle surface from all directions, whereas ions due to their relatively low thermal velocities are streaming toward the particle in one direction with the speed of plasma flow. The ion trajectories are affected by electrostatic field near the charged particle. Since the thermal velocity of j th kind of plasma species is $\bar{v}_j \sim (kT_{j\infty} / m_j)^{1/2}$, the ion-electron temperature ratio $\tau = T_{i\infty} / T_{e\infty}$ and speed ratio $s = V / (2kT_{e\infty} / m_i)^{1/2}$ are ordered as $\tau^{1/2} \ll s$. Therefore, the hypersonic ($M = [2 / (1 + \gamma\tau)]^{1/2} s \gg 1$) plasma flows or two-temperature plasma flows with cold ions ($\tau \rightarrow 0$) are considered.

Under hypersonic flow conditions, the fluxes of charge, momentum and energy transferred to the particle by heavy plasma species can be expressed in terms of the interaction cross sections S_h^t .

The drag coefficients, defined as

$$C_{Di}^t = F_h^t / \left(\frac{1}{2} m_h N_{h\infty} V^2 \pi R^2 \right)$$

are calculated in the following way

$$C_{Di}^s = 2\sigma_i^s, \quad C_{Di}^r = \frac{(\pi\tau_s)^{1/2}}{s} \sigma_i^r, \quad C_{Di}^C = 2\sigma_i^C$$

where $\sigma_h^t = S_h^t / R^2$ and the interaction cross sections are determined as

$$S_h^s = \pi \rho_m^2, \quad S_h^r = 2\pi \int_0^{\rho_m} \cos\Phi_1 \rho d\rho, \quad S_h^C = 2\pi \int_{\rho_m}^{\infty} (1 - \cos\Psi) \rho d\rho.$$

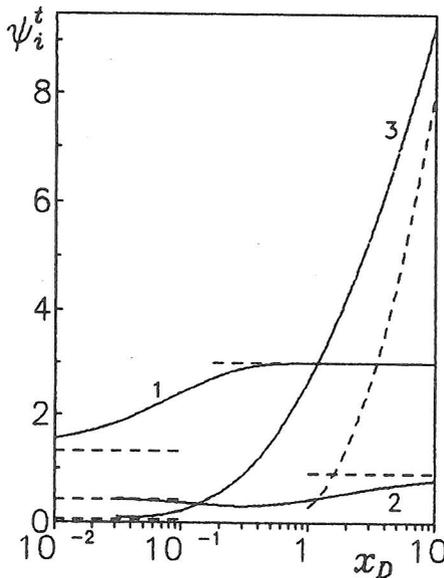


Figure 1. Variations of the dimensionless drag force components Ψ_i^s (curve 1), $\Psi_i^r / \tau_s^{1/2}$ (2) and Ψ_i^C (3) with Debye screening parameter x_D in subsonic argon plasma flow. Solid lines - numerical solution; dashed lines - approximations of weak and strong Debye screening.

Results and discussion. Variations of the dimensionless drag force components ψ_i^f with the Debye screening parameter x_D and the total drag force coefficient C_{Di} with the speed ratio s for spherical metallic particle in argon plasma are shown in Fig. 1 and Fig. 2, respectively. Both numerical and analytical results corresponding to weak ($x_D > 1$) and strong ($x_D \ll 1$) Debye screening conditions are presented.

The difference between the sphere drag at weak and strong screening regimes specifies the contribution of the particle charging effect to momentum transfer. For low speed ratios s , the particle drag in a weakly screening plasma is caused mainly by the interaction of ions with electrostatic field of the charged particle. Under hypersonic flow conditions, only direct collisions are important and with an increase of the speed ratio s , the drag coefficient C_{Di} decays toward the limit $C_D = 2$, which is the well-known result of rarefied gas dynamics for free-molecular flow.

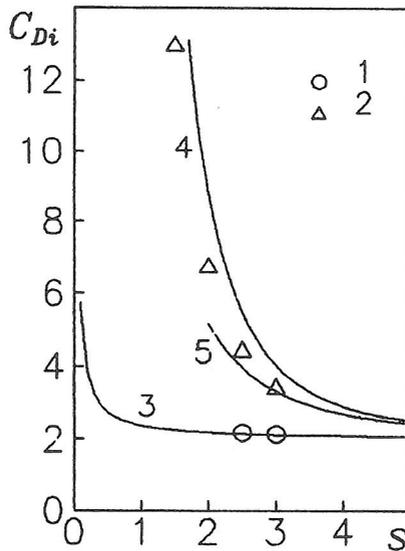


Figure 2. Drag force coefficient C_{Di} of the particle in argon plasma flow as a function of the speed ratio s for different Debye screening conditions: $x_D = 0$ (1), $x_D = 1$ (2), approximations of strong screening (3) and of weak screening for $x_D = 10$ (4) and $x_D = 1$ (5).

Nomenclature

C_D - drag coefficient; e - electron charge; f_j - velocity distribution function; F_h^t - drag force components; k - Boltzmann constant; m_j - mass; M - Mach number; N_j - number density; r_D - Debye length; R - particle radius; s - speed ratio; S_h^t - interaction cross section; T_j - temperature; \mathbf{v} - plasma specie velocity; \mathbf{V} - plasma flow velocity; x_D - Debye screening parameter; ρ - impact parameter; Φ - angle of orientation; Ψ - scattering angle.

Subscripts: a - molecules; e - electrons; i - ions; h - heavy plasma species (molecules and ions); ∞ - nondisturbed plasma region far from the particle.

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