On the influence of surface roughness of polymer Kapton-H on momentum transfer in supersonic flow of atomic oxygen plasma

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Abstract

The environment in ultra-low Earth orbits (at altitudes ranging from 150 to 350 km) is extremely aggressive for polymer materials. The materials are susceptible to erosion, which results in mass loss and a reduction in the thickness of polymer coatings. During prolonged spacecraft operation in orbit, the roughness of polymers increases significantly due to the effect of chemically active atomic oxygen. As a result, the momentum and energy transfer coefficients, as well as the aerodynamic drag coefficients of spacecraft structural elements, change.

This paper presents the results of experimental and theoretical studies of the effect of surface roughness in spacecraft polymeric materials, in particular Kapton-H polyimide, caused by surface degradation in a supersonic flow of atomic oxygen plasma (with ion velocities ranging from 8 to 10 km/s), on the aerodynamic drag of bodies (models) with simple geometric shape (sphere, cylinder, cone).

The experimental studies were conducted using a plasmoelectrodynamic test bench. The drag and tangential forces acting on the surface elements of the polymer-coated model with a given roughness were measured as a function of the angle of attack and the flow rate of the atomic oxygen plasma.

It is shown that for primary smooth surfaces ('mirror scattering'), the drag coefficient of a sphere and a cone increases by up to 40% as the roughness coefficient increases. For the Kapton-H polymer, such an increase corresponds to approximately one year of operation at ~250 km altitude during solar minimum or ~340 km during solar maximum. For a transverse cylinder, the drag coefficient increases by about 8.6%. For predominantly rough surfaces ('diffuse reflection'), the drag coefficient also increases for bodies with simple geometries: by ~11% for a sphere, by ~9% for a transverse cylinder, and between 2% and 11% for a cone, with the increase being greater for cones with smaller apex angles.

Introduction

The motion of objects in hypersonic flows of rarefied gas is an important aspect of research in such fields as aviation and astronautics. The near-satellite environment at altitudes of about 300 km is extremely aggressive for polymeric materials used in spacecraft. Studies conducted on orbital stations have shown that materials undergo erosion, which is manifested in mass loss and a decrease in the thickness of coatings. At altitudes of 300 km, aerodynamic drag is one of the main problems, as it directly determines the efficiency of movement of objects at ultra-high speeds, and also affects the stability and safety of aerospace vehicles operating in such conditions.

At hypersonic speeds, various factors play an important role in the formation of aerodynamic drag, among which the surface roughness of an object is one of the key ones. At high speeds and high temperatures, complex, nonlinear gas flows are formed around an object, where surface roughness can significantly affect the structure of the boundary layer, the development of shock waves, and, as a result, the value of aerodynamic drag. It is known that under conditions of low pressure and high temperatures even minor changes in the surface structure can have a significant impact on the overall aerodynamic behavior of an object. Surface roughness can lead to the formation of additional turbulent flows, change the structure of shock waves, and affect the temperature distribution on the object surface, which can significantly change the aerodynamic drag. The study of aerodynamic coefficients for bodies of simple geometric shapes is the basis for understanding the general principles of aerodynamics in hypersonic regimes and the main aerodynamic effects for bodies of complex shapes.

Research objectives and methods

The aim of this paper is to study the effect of surface roughness on aerodynamic drag coefficients for bodies of simple geometric shapes (sphere, cylinder, and cone) in hypersonic flow of a rarefied gas. The object of study is Kapton-H polyimide, which belongs to the class of initially smooth and slightly rough surfaces. This material is widely used in aerospace applications, especially for exterior coatings. The most probable mechanism is the "mirror scattering" of gas atoms during hypersonic flow. However, conditions in low Earth orbits make the "diffuse scattering" mechanism more likely. It is important to consider both of these mechanisms.

The experimental studies were conducted on the plasma-electrodynamic facility, which allows reproducing the processes and phenomena that occur when spacecraft materials interact with gas and plasma flows in low Earth orbits. A high-speed flow of rarefied plasma of atomic and molecular oxygen is created by an atomic oxygen generator; particle energies from 5 eV to 10 eV, i.e., at the velocity of ions from 8 km/s to 10 km/s. To determine the degree of degradation of polymer samples in the atomic oxygen plasma flow, surface profilograms were taken, from which the roughness coefficient was determined as a function of the ion flux fluence at a fixed ion energy. The dynamic interaction of a solid body with a flow of a rarefied partially ionized gas is characterized by the lifting force and drag force, for the measurement of which aerodynamic microbalances of the compensation type were used; the coefficients of momentum and energy transfer and lift fnd drag coefficients were calculated.

Results

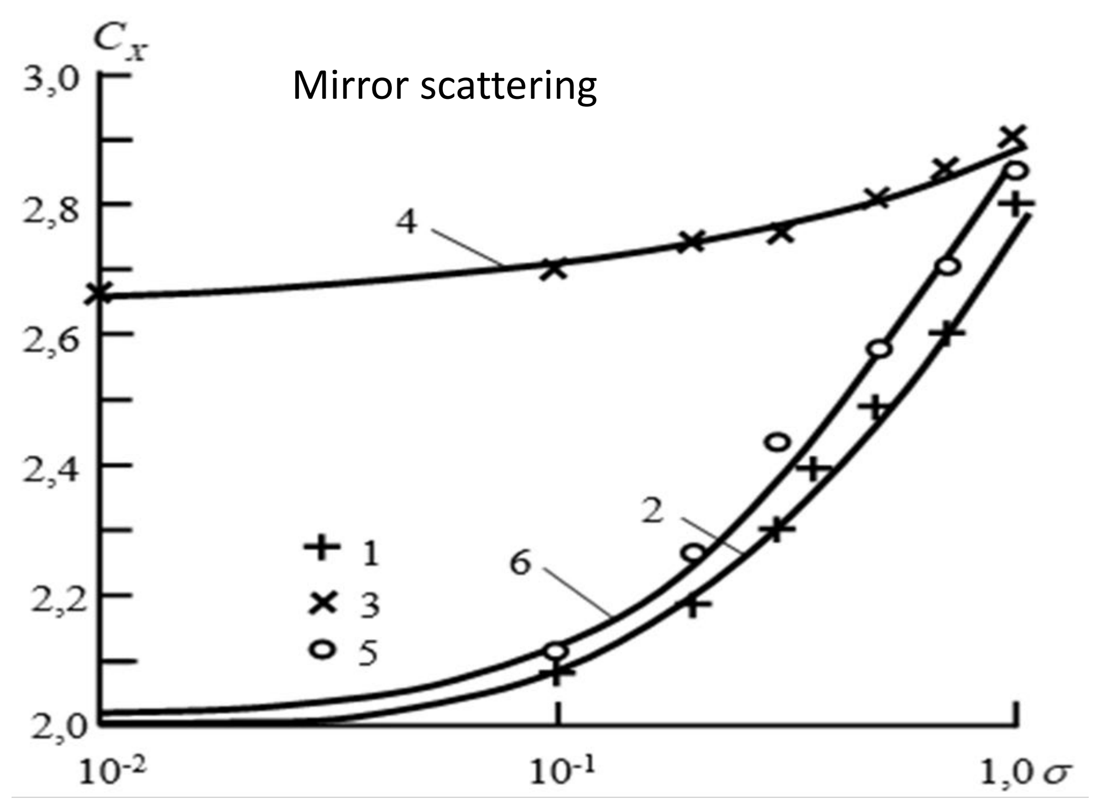
At the "mirror scattering" of particles from initially smooth surfaces, the dependence of the drag coefficient of a sphere on the roughness coefficient of the body surface σ is shown in the figure. With an increase in the roughness coefficient, the drag coefficient C_X of a sphere in a hypersonic flow increases from $C_X = 2.0$ (at σ = 0.01) to $C_X = 2.80$ (at σ = 1.0), i.e. by ~40 %. The drag coefficient of a sphere during the "diffuse scattering" of particles on the surface in a hypersonic flow increases from a value of $C_X = 2.24$ (at σ = 0.01) to $C_X = 2.48$ (at σ = 1.0), i.e. by ≥11 %.

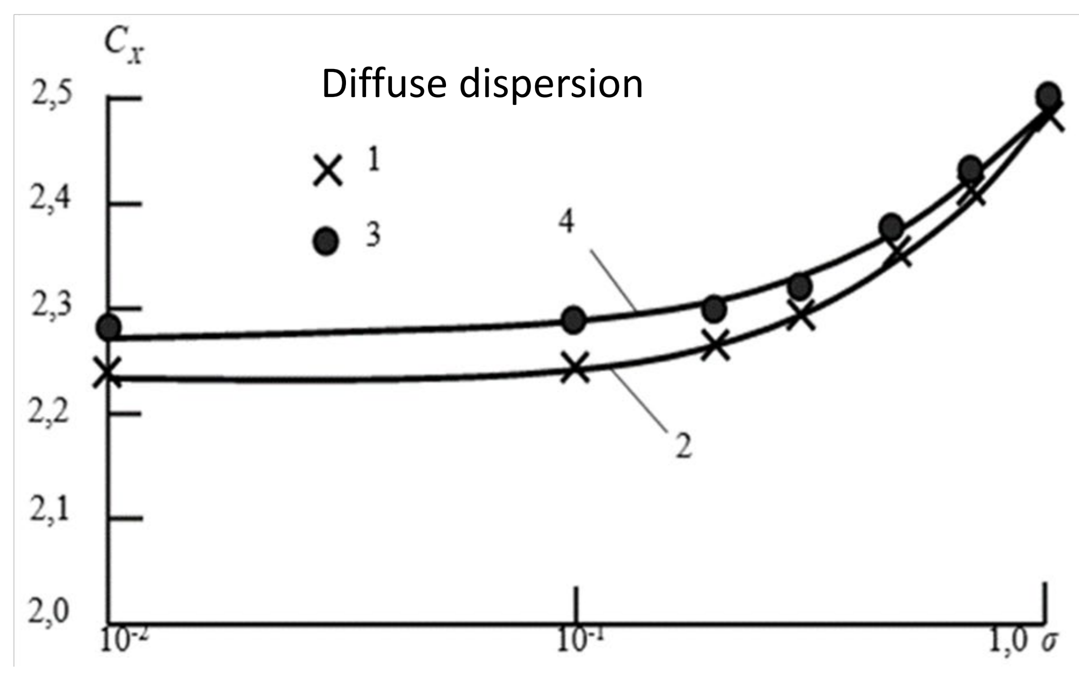
The value of the drag coefficient of the transverse cylinder at the "mirror scattering" of particles increases from $C_X = 2.67$ (at σ = 0.01) to $C_X = 2.90$ (at σ = 1.0), i.e. by ~ 8.6 %. The drag coefficient of the transverse cylinder at the "diffuse scattering" of particles from the surface changes from $C_X = 2.28$ (at σ = 0.01) to $C_X = 2.49$ (at σ = 1.0), i.e. by ≤ 9.2 %.

At "mirror scattering" of particles from the initially smooth surface of a cone with a half angle at apex β = 45°, the drag coefficient at hypersonic flow changes from $C_X = 2.05$ (at σ = 0.01) to $C_X = 2.85$ at (σ = 1.0), i.e. by ~39 %. At the "diffuse scattering" of particles from the surface of the cone, the drag force coefficient increases from $C_X = 2.25$ (at σ = 0.01) to $C_X = 2.51$ at (σ = 1.0), i.e. by ~11.6 %. With "diffuse" scattering of particles, the coefficient of drag force of the cone at β = 15° increases by 11 %; for β = 30° - by ~ 6.9 %; for β = 45° - by ~ 4.5 %, and for β = 60° - by ~ 2.2 %. For comparison, the coefficient changes by about 39 % at β = 45° for "mirror scattering" of particles from the initially smooth surface of the cone.

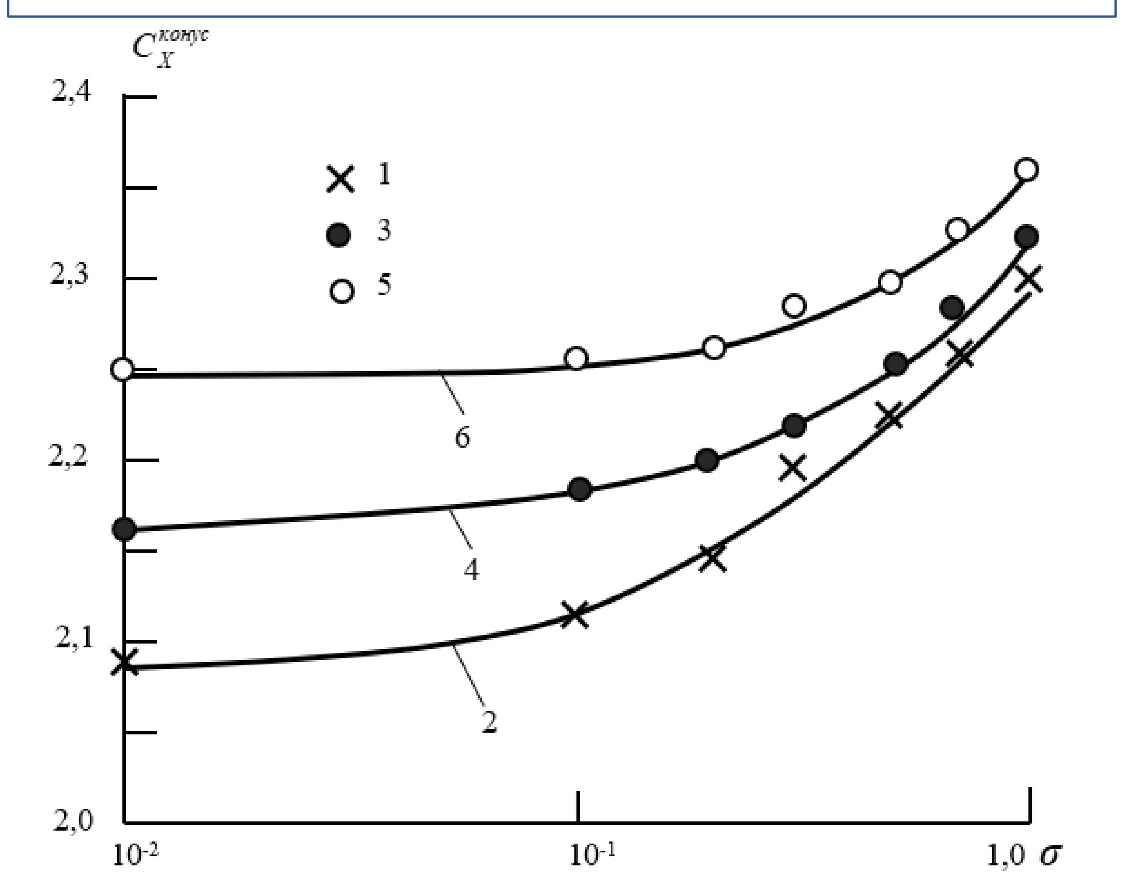
Kapton-H polyimide belongs to the class of initially smooth and slightly rough surfaces, for which the mechanism of "mirror scattering" of gas atoms during hypersonic flow around bodies of simple geometric shape is most likely. The coefficient of σ ≈ 1.0 occurs when irradiated by an atomic oxygen flux with an annual fluence of 10^{22} atomO/cm^2.

Dependence of the drag force coefficient C_X of a sphere (1,2), a transverse cylinder (3,4) and a cone (5,6) (with a half angle at apex β = 45°) on the roughness coefficient σ at "mirror scattering" and at "diffuse dispersion" of particles on the surface.





Dependence of the drag force coefficient C_X of a cone on the roughness coefficient σ at "diffuse dispersion" for different half angle at apex β:
(1,2 - β = 15°; 3,4 - β = 30°; 5,6 - β = 45°)



Conclusions

As a result of the study, we have estimated the effect of the surface roughness coefficient of the Kapton-H polymer on the aerodynamic drag coefficients of bodies of simple geometric shape (sphere and cylinder) from the hypersonic flow fluence of the atomic oxygen.

It is shown that for the initially smooth (slightly rough) surfaces, the aerodynamic drag coefficient of the sphere and cone increases by ~40 % with the increase of the roughness coefficient (up to a value near 1.0). For Kapton-H polymer, this occurs during annual operation at a minimum solar activity at an altitude of ~250 km, and at a maximum solar activity at an altitude of ~340 km. For the cylinder, the drag coefficient increases by ~8.6 %.

The research results are important for assessing the impact of Kapton-H polyimide surface degradation during long-term operation in very low orbits in the Earth's upper atmosphere on the aerodynamic characteristics and convective heat fluxes of rocket and space technology objects.