PARTICULATE INTERACTION WITH PLASMA IN A PULSED PLASMA THRUSTER

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Abstract

The presence of particulates (referred to as macroparticles, MP's) in the plume of a pulsed plasma thruster (PPT) may affect interaction with the spacecraft. The MP's emitted into the plasma during the discharge may be charged, accelerated and heated by the ion, electron and neutral fluxes depending on the MP residual time. In the present work we analyze different aspects of MP-plasma interaction in the experimentally observed range of MP radii (0.1-100 μm). A 1μm MP is found to have a charge of about 10^5 electrons in the case of an electron density of about 10^{23} m^{-3}. The calculation of the MP velocity shows that the maximum possible velocity of a 1μm MP is about 230 m/s, which is close to that estimated experimentally. Only small MP's (~0.1 μm) can be entrained by the plasma jet, while large MP's are generally slower and flow substantially behind the plasma jet. It is found that small MP's (<1 μm) may completely decompose during a 1 μ s pulse.

Introduction

The pulsed plasma thruster (PPT) has been reconsidered recently as an attractive spacecraft propulsion option[1,2]. This has happened mainly due to a greater accent being placed on the development of satellites with reduced size for many applications. PPT's are expected to provide exact impulse bits to be used for accurate attitude control. The principal advantage of PPT's is their simple design, which provides high reliability. In particular, the higher reliability of the PPT is achieved through using solid propellant, which eliminates design and operation complexity connected with using liquid and gas propellant.

Unfortunately, the PPT has a very poor performance characteristic. For instance, a flight qualified PPT design had an efficiency of about 8%[3]. One of the factors leading to low efficiency is the late neutral ablation[4]. Another factor, which may significantly reduce the efficiency, is the particulate emission. Estimates have shown that the particulate emission consumes about 40% of the total propellant mass, while contributing only 1% to the total thrust[5].

Particulates referred to sometimes as macroparticles (MP's) are emitted during the pulse and may interact with the surrounding plasma. Various experimental and theoretical aspects of macroparticle interaction with plasma have been studied in different systems such as plasma assisted chemical vapor deposition[6], plasma etching, rf and glow discharge[8,9], cathodic vacuum arc deposition[10,11] and in space plasma[12]. It may be concluded that in spite of many common features of MP-plasma interaction, the MP charge, velocity and temperature depend upon properties of the plasma and MP related to each specific system. Recently, results for the macroparticle size distribution in a PPT have been presented by Spanjers et al.[5] Particulates were observed to have characteristic diameters ranging from about 0.1 μm to over 100 μm. No analyses of MP interaction with the PPT plasma has been reported previously. The present work has the primary objective to remove this deficiency by analyses of different aspects of MP behavior of a PPT, such as charging, acceleration, heating and decomposition. This work will provide additional information about MP's to help mission planners in estimating the particulate contamination potential.

Model of macroparticle-plasma interaction

In the present section we will develop the model of MP interaction with plasma including MP charging, transport and heating in a pulsed discharge. As a working example, we will concentrate on a specific type of PPT, developed at the University of Illinois, the so-called PPT-4 (ref. 1). This PPT has a co-axial configuration in

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which Teflon is ablated from a cylindrical cavity sitting in front of the central electrode. The main physical process in this type of thruster occurs in the Teflon cavity. Rapid heating of a thin dielectric surface layer leads to decomposition of the material of the wall. As a result of heating, decomposition and partial ionization of the decomposition products, the total number of particles increases in the cavity.

At the same time, nonuniformities in the discharge distribution across the Teflon surface may cause overheating followed by phase change of propellant[1]. High plasma pressure in the PPT channel may lead to Teflon macroparticle generation. However, the mechanism of such macroparticle generation from the propellant is not understood sufficiently. Another possible source of macroparticle is the spot attachment at electrodes which is a typical phenomenon in the early stages of discharge[13].

In the experiment, basically two populations of macroparticles were found[5]. One population of macroparticles is characterized by diameter less than 1 μm and by spherical shape. It was concluded that these macroparticles come from the steel PPT electrodes[5]. The second population has a more random shape and size with maximal size up to 200 μm. The second population is concluded to be originated from the Teflon propellant[5]. It should be noted that the macroparticle generation from the electrodes is possible to eliminate by using an electrode material with high thermal conductivity. For instance in PPT-4, tracks of discharge attachment at the electrodes were not observed[14]. However Teflon macroparticles may still be generated that have a significant effect on propellant losses. Thus, as we consider the PPT-4 configuration in the present paper, we will concentrate on these macroparticles.

The MP's emitted into the plasma during the discharge may be charged, accelerated and heated by the ion, electron and neutral fluxes depending on the MP residual time. The present model is based on the assumption that during the MP flight the plasma parameters do not change significantly i.e. the following condition is fulfilled:

$V_p \Delta t << (\partial \ln X/\partial z)^{-1}$, where X is any of plasma parameters (velocity, density and temperature).

Macroparticle charging

An experimental investigation of the MP size distribution showed a variation from 0.1 μm up to 100 μm (ref. 5). It was found also that some MP's have spherical shape while generally MP's have a rather random shape distribution[5]. In order to make it possible to develop a model quantitatively, we will assume that all MP's have a spherical shape with radii in the experimentally observed range. In a typical PPT, the electron density in the cavity during the pulse is about 10^{21} - 10^{24} m^{-3}, which corresponds to a Debye length of about 10^{-6}-10^{-7} m. It is known that the thickness of the sheath around a MP is about the Debye length[15,16]. Therefore one can see that there are basically two cases: small MP's for which the Debye length is less than or about the MP radius, and large MP's for which the Debye length is much less than the MP radius. These two cases may be handled using different approaches for modeling the charging process. The second case is more straightforward and corresponds to that of a plane probe. The MP charging in the first case was developed in detail in Ref. 16. In both cases, the MP charging process is modeled with the aid of the following assumptions: (i) the plasma consists of two species of charged particles. For PPT conditions, thermal equilibrium between all species is achieved and therefore we assume $T=T_e=T_i$, (ii) the plasma jet flow is not substantially obstructed in the sheath around the MP, and thus spherical symmetry of the plasma density relative to the macroparticle is assumed, and (iii) self magnetic field effects are neglected.

The kinetics of the MP charging is controlled by the ion and electron fluxes to the MP which depend on the potential distribution in the sheath. Using Maxwell's equation and assumption (iii) the electric field E(r) changes with time according to the relation:

$$\varepsilon \, \partial E(r)/\partial t = -[J_i(r)+J_e(r)] \qquad (1)$$

The time derivative of the electric field is a function of the radius r. An estimation indicated[16] that the characteristic time for the electric field to reach steady state decreases with radius and has its maximum value at the macroparticle surface (i.e. where $r=R_p$). Thus, equation (1) will be solved at the radius R_p. The electron and ion current densities are required to solve Eq. (1). The electron current density is calculated according to the following relation:

$$J_e = J_{eo} \exp(-eU_p/kT_e) \qquad (2)$$

The ion current density depends upon the ratio of Debye length to MP radius and thus will be different for small and large macroparticles.

Small macroparticles

This case corresponds to the low limit of the measured MP size distribution function. In the case of a spherical sheath around a MP and $L_D > R_p$ the ion flux may be calculated using the orbital motion limit[17,18]:

$$J_i=J_{i0}(1 + eU_p/kT_i) \quad (3)$$

Strictly speaking this expression is exact for infinite L_D/R_p ratio. By considering different ion trajectories around the MP, it is possible to calculate the ion flux for a finite L_D/R_p ratio. An influence of this effect was examined in detail in Ref. 16.

In the general case, the capacitance of the MP in the plasma is given by $C=Q_p/U_p= 4\pi R_p\varepsilon_0 G(R_p/L_D)$. The function $G(R_p/L_D)$ is presented in Ref. 16, and for the case $R_p/L_D\approx1$, this function is $G(R_p/L_D)\approx1.8$, while in the orbital motion limit this function is equal to 1.

Taking into account the above expression for MP capacitance and combining Eqs. (1-3), the kinetics of MP charging may be described by the following dimensionless equation (in the orbital motion limit):

$$d\phi/d\tau=(2\pi)^{-0.5}R_p/L_D(1 + \phi - (m_i/m_e)^{0.5}e^{-\phi}) \quad (4)$$

Large macroparticles

In this case, the sheath model near the planar electrode can be used. The ion flux can be calculated from the Bohm expression[19]:

$$J_i=0.4eNC_s \quad (5)$$

The capacitance in this case reads as[20]

$$C = 4\pi\varepsilon_0 R_p^2/L_D \quad (6)$$

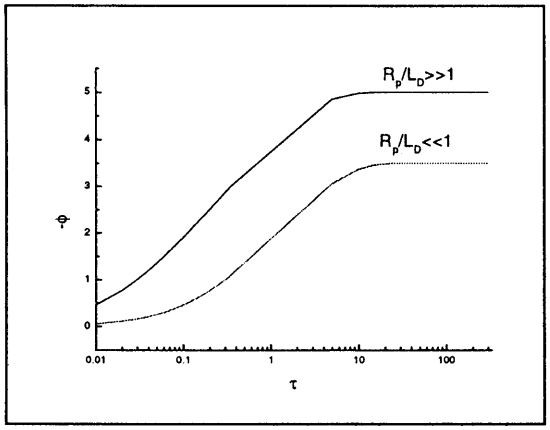

Figure 1. Temporal behaviour of dimensionless macroparticle potential with R_p/L_D as a parameter.

Taking into account the expression for MP capacitance, the kinetics of MP charging may be described by the following dimensionless equation:

$$d\phi/d\tau= (0.4 - (m_i/m_e)^{0.5}e^{-\phi}) \quad (7)$$

The time variation of the dimensionless MP potential is shown in Fig. 1 for two limited cases of $R_p/L_D>>1$ and $R_p/L_D<<1$.

One can see that the charging time is smaller while the steady state potential is larger in the case $R_p/L_D>>1$. The steady state potential increases from about 3.5 in the case of $R_p/L_D<<1$ up to about 5 in the case of $R_p/L_D>>1$. All possible cases realized in a typical PPT are placed between the limits of these two curves. Thus, in the PPT plasma with T=2 eV, MP occurs at a negative potential of about – (7-10) V with respect to the plasma.

Macroparticle charge

In order to calculate possible values of the charge accumulated on the MP we will convert from the dimensionless parameters. The MP charge (in the large MP limit) may be connected with the dimensionless potential as follows:

$$Q_p=4\pi R_p^2 L_D N\phi \quad (8\ a)$$

In the small MP limit, the corresponding expression for the MP charge reads

$$Q_p=4\pi\varepsilon_0 R_p\phi kT_e/e \quad (8\ b)$$

The calculated steady state MP charge as a function of MP radius is shown in Fig. 2 with electron density as a parameter for the large MP limit ($R_p>1\mu m$). It can be seen that the 1 μm MP has a charge of about 10^5 electrons in the case of $N=10^{23}$ m^{-3}. One can see that in this case, MP charge increases with electron density unlike the other case (small MP with $R_p<1\mu m$) when Q_p is independent of the plasma density. In the latter case, the MP charge is a linear function of R_p and can be estimated as $Q_p=2.4\cdot10^3\times R_p$ [μm] where Q_p is in electrons.

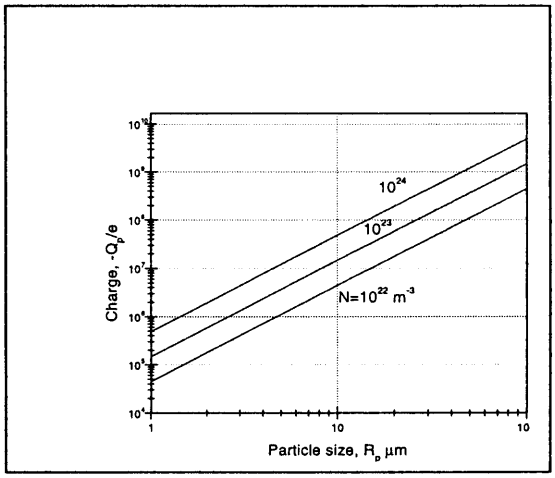

Figure 2. Macroparticle charge dependence on the radius with electron density as a parameter. T_e=1.5 eV.

Momentum transfer

The primary forces on the MP in the PPT discharge are two: (i) a drag force due to collision with neutral atoms and ions and (ii) a force due to the presence of the electric field in a current carrying plasma. In order to predict the MP velocity, we simply integrate the equation of motion from some starting point. Given the solution for plasma density and velocity distribution in the cavity, we evaluate the forces that act on an individual MP. The equation of motion of an individual MP may be written as:

$$d(M_pV_p)/dt=F_d+Q_pE \qquad (9)$$

The mass M_p of the MP traveling in the plasma may be changed as a result of macroparticle ablation (see next section).

The first term is the total drag force and the second term is the electric force, which depends upon the electric field in the plasma and the MP charge. An average electric field E in the plasma may be calculated from Ohm's law for known current density j namely: $E=j/\sigma$. We will consider a diffuse discharge on the anode and therefore $j=I/\pi r_a^2$. In partially ionized plasmas, there are Coulomb collisions of the MP with ions since the MP is charged. These collisions may result in a force, called ion drag[21]. In low-density plasmas with large ratio of Debye length to MP radius, it was found that the momentum transfer due to ions which are collected by a MP cross section is much less than that due to ions scattered but not collected[22]. It should be noted that if the Debye length is much less than or about the MP size, the momentum transfer is determined by the MP cross section[22]. Thus, in typical PPT conditions, ion and neutral drag have equal cross sections. Analyses of the MP size distribution and range of possible plasma densities (10^{21}-10^{24} m^{-3}) shows that both free molecular and continuum regimes can be realized.

Small MP (free molecular regime). In the free molecular regime (i.e. $R_p<<\lambda_c$) the drag force can be written as[23]:

$$F_d = (\pi\rho)^{0.5}R_p^2/2\beta\{(s+\exp(-s^2)/2s + (s^2+1-1/4s^2)\sqrt{\pi}\,\mathrm{erf}(s)\} \qquad (10)$$

where $\beta=m/2kT$ and $s=2V_p/(\sqrt{\pi}(V-V_p))$.

Large MP (continuum regime). In this case the drag force which acts on the isolated MP placed into a plasma moving with velocity V is determined by the expression[24,25]:

$$F_d=C_D\pi R_p^2\rho(V-V_p)^2/2 \qquad (11)$$

where C_D is the drag coefficient that depends upon Reynolds number. For instance, in the case of $Re\leq 1$ $C_D=24.8/Re$ (Refs. 24, 25). Estimation shows that in the PPT plasma, the Reynolds number is about $10^{-3}V$, where V is the plasma velocity [m/s]. The calculation of the MP velocity in the continuum regime as a function of time with normalized plasma velocity as a parameter is plotted in Fig. 3a for the case $R_p=1$ μm. It can be seen that the maximum possible MP velocity is about 230 m/s. In experiments it was found that some MP's have a velocity of about 200 m/s (Ref.5).

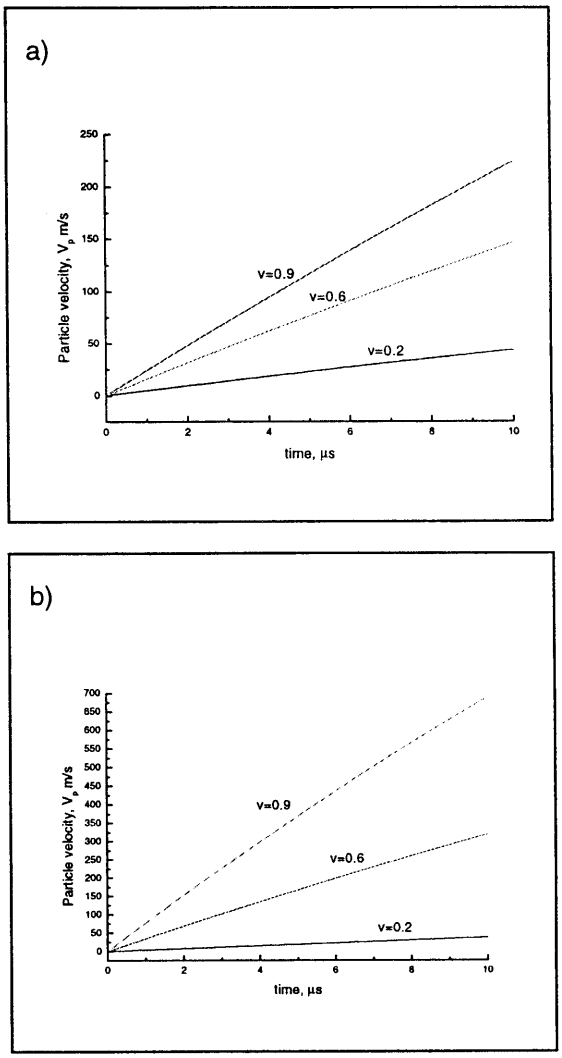

Figure 3. *Temporal behaviour of the macroparticle velocity with dimensionless plasma velocity as a parameter. $T_e=1.5$ eV, $N=10^{23}$ m^{-3}. a) $R_p=1$ μm, b) $R_p=0.1$ μm.*

Smaller MP's may have a larger velocity as shown in Fig. 3b for the case of $R_p=0.1$ μm, calculated in the free molecular regime. One can see that the MP velocity depends upon the residual time in the discharge. Thus, those MP's generated towards the end of the pulse are expected to have a smaller velocity.

The ratio of MP velocity to the plasma velocity dependence on the MP radius is shown in Fig. 4 with plasma density as a parameter. These calculations are performed for the case of MP residual time equal to the discharge pulse, i.e for t=10 μs. One can see that small MP's in the dense plasma can approach the plasma velocity and can be entrained by the plasma jet. However, the large MP's are generally slower and flow substantially behind the plasma jet.

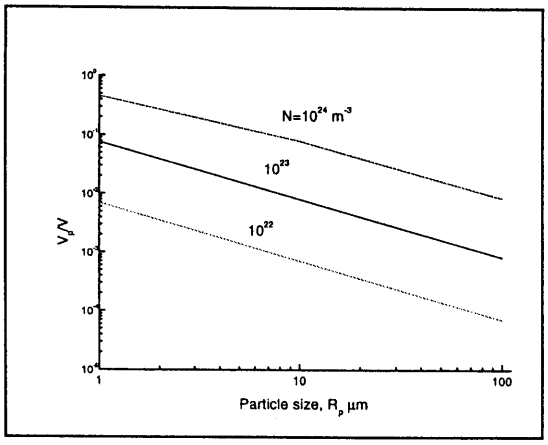

Figure 4. Normalized macroparticle velocity dependence on the macroparticle radius with plasma density as a parameter. T_e=1.5 eV, Δt=10 μs.

It should be noted that, due to ablation, the MP radius decreases in the course of interaction with the plasma and thus MP-plasma interaction may change from initially continuum to free molecular. An effect of MP ablation is considered in the next section.

Heat transfer

As the particle moves through the plasma it is heated by neutral, electron and ion fluxes and is cooled by radiation. An additional cooling mechanism is due to decomposition of the dielectric material under high temperature. We will consider the situation where the thermal time constant is much shorter than the MP residual time. In this case, the MP has a uniform temperature throughout its volume and inward heat conduction from the surface may be neglected. The resulting energy balance reads:

$$\frac{4}{3}\pi R_p^3 \rho C \frac{dT_p}{dt} = 4\pi R_p^2 (Q_{i,e} + Q_n - Q_r - Q_d) \qquad (12)$$

The ion and electron fluxes are equal after the MP reaches steady state charge. Therefore, the gross energy input by ions and electrons to the MP is given by the current density and the sum of the energy carried by each species:

$$Q_{i,e} = j_f(R_p)(2kT_e + kT_e + eU_p(t)) \qquad (13)$$

where $U_p(t)$ is the time dependent MP potential (see sec. A).
The neutral atoms heat transfer may be calculated using the Newtonian model:

$$Q_n = \alpha \Delta T \qquad (14)$$

In the general case, the coefficient of heat transfer is a complex function of MP size, gas flow temperature and velocity, heat conductivity, specific heat and density. The relation between the coefficient of heat transfer and the above parameters was determined by a similarity law[24]. For the convective heat transfer between a body and gas flow, the following similarity can be used:

$$Nu = \alpha R_p / \lambda \qquad (15)$$

When the particle is not moving relative to the plasma, the Nusselt number Nu equals 2 (Ref. 31). The dependence of atomic thermal conductivity on temperature is given by: $\lambda = 2.4 \cdot 10^{-4} T^{3/4}$ W/mK (Ref. 31). The radiative flux is given by the Stefan-Boltzmann law:

$$Q_r = \sigma \xi T^4 \qquad (16)$$

The heat flux associated with material decomposition can be calculated as:

$$Q_d = V_d \Delta H \qquad (17)$$

Where[26] $\Delta H = 5.8625 \times 10^4$ cal/mole in the case of Teflon. The ablation rate can be estimated at equilibrium using Knudsen's law:

$$V_d = P_o / \rho \sqrt{m_a / (2\pi kT)} \qquad (18)$$

where P_o is the equilibrium pressure of Teflon (see Refs. 1,4). The rate of the MP radius change is determined by the ablation rate V_d:

$$dR_p/dt = -V_d \qquad (19)$$

The initial condition reads as: $R_p(t=0) = R_{po}$.
The calculated temporal variation of the MP temperature is shown in Fig. 5 with MP radius as a parameter. It can be seen that small MP's are heated substantially up to 1000 K during a short time period, while large MP's are only slightly affected by the plasma. Heating of the MP leads to significant ablation as plotted in Fig. 5. One can see that small MP's (~1 μm) completely ablate if their residual time is larger than 0.5 μs.

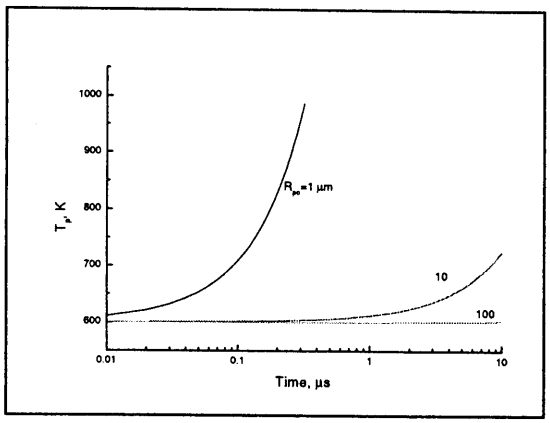

Figure 5. Temporal dependence of the macroparticle temperature with the macroparticle radius as a parameter. T_e=1.5 eV, $N=10^{23}$ m^{-3}.

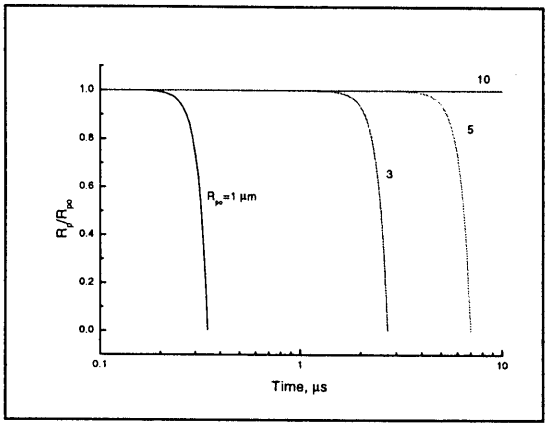

Figure 6. Macroparticle radius versus time with the initial macroparticle radius as a parameter. T_e=1.5 eV, $N=10^{23}$ m^{-3}.

Discussion

One of the important possible applications of the PPT is for attitude control of small satellites, which are part of a group of close-flying satellites. In this case, interaction of the integrated plasma plume from the PPT with another spacecraft becomes an important issue. An experimental investigation has shown that the plasma plume contains a substantial fraction of macroparticles that originated from the dielectric as well as from the electrodes. The presence of such particles in the interacting plume may be a source of local damage to the spacecraft. The potential for MP damage upon their collision with spacecraft surfaces depends upon the MP directed velocity. The present calculation shows that the MP velocity depends mainly upon MP size and residual time in the discharge. Those small MP's emitted at the beginning of the discharge pulse may have a velocity of 200 m/s. Thus, one can expect a relatively broad range of MP velocity from zero up to a few hundred m/s depending on the point of MP formation and the MP size. Another useful outcome from the MP velocity calculation is the possibility to estimate some characteristic time of MP flux ejection. Since MP velocity is generally smaller than the plasma velocity and due to the broad range of MP velocities, the effective time of MP ejection from the thruster is much larger than the pulse duration. For instance, our estimation shows that the large MP's (~100 μm) exhaust from the thruster only after several seconds.

Due to the possible electrostatic nature of MP interaction with a spacecraft, the MP charge may play an important role. A spacecraft interacts with a plasma jet so as to become electrically charged to assure zero net current just like the MP. Thus, since the spacecraft has some negative potential with respect to the plasma, the MP may interact with the electric field in the thin sheath around the spacecraft. In some cases, the MP may be reflected in the sheath without mechanical collision with the surface. This effect has a positive role since the electrostatic nature of MP interaction with surfaces in space is not then connected with any mechanical damage. Thus it is important to estimate the possibility of such MP-surface interactions. Previously this effect was studied for the case of vacuum arc generated macroparticles[10,11]. It was obtained both theoretically and experimentally for typical conditions that the electrostatic nature of the MP interaction with surfaces (without mechanical touching) is possible. It happens in those cases when a MP approaches the surface with a grazing angle such that the MP kinetic energy will be smaller than the potential electrostatic energy. The possibility of this effect may be estimated using the following integral expression:

$Q_p U_s > M_p V_{pn}^2/2$

For instance, if the spacecraft potential U_s is about 10 V, a 1μm MP may be electrostatically reflected if its normal velocity component is less than 4 m/s.

Another important outcome from the present study is prediction of the MP complete or partial decomposition due to interaction with the plasma during the discharge pulse. This means that the size distribution of MP's exhausted from the PPT is different from the original MP distribution. According to our calculation, the difference is more significant in the range of small MP's. Thus, any measurements of the MP flux in the plasma plume involve some combination of the original MP distribution and that from MP - plasma interaction rather than the size distribution of MP's emitted from the Teflon. It is important to note also that the MP decomposition

may be a substantial volume source of the neutral component of the discharge plasma. However, since there is an uncertainty in the original MP size distribution, the significance of the last effect cannot be estimated accurately.

Conclusion

We have shown that the plasma may affect particulate contamination from the plume of a PPT. During flight, a MP may become charged, heated and accelerated. It was found that the charging time depends upon MP size and is generally smaller in the case of small MP's. We have found that a 1μm MP has a charge of about 10^5 electrons in the case of an electron density of about 10^{23} m^{-3}. The primary forces acting on the MP in the PPT discharge are two: a drag force due to collision with neutral atoms and ions, and an electric force due to the presence of the electric field in a current carrying plasma. The maximum possible velocity of a 1 μm MP is about 230 m/s, which is close to that estimated in experiment. Only small MP's (~0.1 μm) can be entrained by the plasma jet, while large MP's are generally slower and flow substantially behind the plasma jet. Small MP's (<1 μm) may completely decompose during a 1 μs pulse.

Acknowledgments

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Nomenclature

V_p = MP velocity
R_p = MP radius; R_{po} = initial MP radius
Δt = residual time of MP in discharge
L_D = Debye length
λ_C = mean free path
T_e =electron temperature
T_i = ion temperature
T = neutral gas temperature
V = plasma velocity
v = plasma velocity normalized by the sound speed
m_a = atom mass
C_s = sound speed
ε_o = permittivity of vacuum
ε = dielectric permittivity of Teflon
$J_e(r)$ = electron current density in the sheath around MP
$J_i(r)$ = ion current density in the sheath around MP
J_{eo} = electron thermal flux at the plasma-sheath interface
J_{io} = ion flux in the absence of a field at the plasma-sheath interface
U_p = MP potential with respect to the plasma
ϕ = normalized MP potential, eU_p/kT_e
τ = Dimensionless time, L_D/C_s
N = plasma density at the plasma-sheath interface
Q_p = MP charge
M_p= MP mass
F_d = total drag force
E = electric field
j = current density
σ = plasma conductivity
I = discharge current
ρ = specific density
C = specific heat
$Q_{i,e}$ = heat rate due to ion and electron flux
Q_n = neutral atom heat flux
Q_r = radiation cooling rate
Q_d = cooling rate due to decomposition of material
Nu = Nusselt number.
σ = Stefan-Boltzmann constant
ξ = particle emissivity
V_d = ablation rate
ΔH = ablation heat
ΔT = temperature difference between the plasma and the MP
T_p = MP temperature
α = heat transfer coefficient.
P_o = equilibrium pressure
U_s = potential drop in the near spacecraft surface sheath
V_{pn} = normal component of the MP velocity.

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