

Feasibility of Electrostatic Microparticle Thrusters

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Abstract: The paper discusses the feasibility of electrostatic propulsion which uses microparticles as propellant. Two novel thruster concepts are proposed which differ both from electrospray-like colloid thrusters and nano field-emission thrusters, which extract nanoparticles from suspensions. It is shown that particle charging in a plasma is not sufficient for electrostatic acceleration. Moreover, it appears technically difficult to extract charged particles out of a plasma for subsequent acceleration without being discharged. It is proposed to charge particles with low secondary electron emission using an energetic electron beam, e.g. with graphite particles surface potentials of -90 V can be obtained. Another promising concept is charging by contact with needle electrodes at high electrostatic potential (~ 20 kV), which allows for maximum possible specific charges.

Nomenclature

E_p	= electric field strength at the particle surface
e	= elementary charge
ϵ_0	= permittivity of free space
g	= gravitational acceleration at sea-level
I_i, I_e	= ion and electron currents which charge a particle
I_{sp}	= specific impulse
j_e	= electric current density of an electron beam
k	= Boltzmann's constant
m_p, m_i, m_e	= masses of a microparticle, an ion, and an electron
n_i, n_e	= ion and electron number densities
ϕ_p	= surface potential of a particle
q_p	= particle charge
r_p	= particle radius
ρ	= mass density
T_i, T_e	= ion and electron temperatures
U_{acc}, U_n	= acceleration potential, potential of a needle electrode
v_{p0}	= velocity of a particle after acceleration
W_i, W_e	= kinetic energies of a beam ion and a beam electron

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I. Introduction

Present-day ion thrusters feature highest specific impulses and low thrust levels. The exhaust velocity, which is about one order of magnitude above those of chemical engines, allows for an economic use of the propellant mass. On the other hand, the kinetic energy of an exhaust ion scales as the square of its velocity. Due to the limited power provided by solar panels, the achieved thrusts are only in the order of tens to hundreds of mN. The momentum transferred by one ion for a given kinetic energy W_i is $p = (2W_i m_i)^{1/2}$, when m_i is the molecular mass. For this reason, propellants with higher atomic mass numbers, typically xenon (in earlier times also mercury and cesium), are preferred. However, the enhanced momentum per molecule and the higher total thrust is bought with the less efficient use of the propellant mass, i.e. a lower specific impulse or exhaust velocity. The extrapolation of the use of heavy atoms leads to molecules, nano- and microparticles as propellants. Such novel concepts are still in the stage of preliminary investigations. Examples are field emission thrusters which are operated in the ion-droplet mixed regime (colloid thrusters),¹ and nanoparticle thrusters, which extract charged particles from a suspension by means of electric fields.² In this contribution, we consider the possibility of novel thruster concepts which use microparticles as propellant, i.e. solid metal or dielectric particles with diameters of a micrometer or less.

II. Charging of Microparticles

In this section, different ways to charge fine particles are described and compared with regard to the achievable charge-to-mass ratio (specific charge) q_p/m_p . Besides the accelerating potential U_{acc} , the specific charge is the deciding parameter for the exhaust velocity v_{p0} of the particles and the specific impulse $I_{sp} = v_{p0}/g$, which is traditionally defined as the exhaust velocity divided by the gravitational acceleration on Earth.

A. Charging in Plasma

Fine particles immersed in a plasma are typically negatively charged due to the higher electron velocities compared to the ion velocities.^{3,4} Such a system is called a complex (or dusty) plasma. The negative charge repels most of the electrons with the exception of a small fraction in the velocity distribution which has enough kinetic energy to overcome the potential barrier of the particle. At the charge equilibrium the ion current balances the current of these fast electrons ($I_i = -I_e$); this equilibrium potential is known from plasma probe theories as the floating potential. The charge on a particle with radius r_p can be estimated with the commonly used orbital motion limited (OML) theory for spherical probes in a collision-less plasma.⁵ The ion and electron currents are functions of the particle surface potential ϕ and depend on the temperatures T_i , T_e and densities n_i , n_e of ions (mass m_i) and electrons (mass m_e), respectively:

$$I_i(\phi) = 4\pi r_p^2 \frac{en_i}{4} \left(\frac{8kT_i}{\pi m_i} \right)^{1/2} \left(1 - \frac{e\phi}{kT_i} \right) \quad , \quad (1)$$

$$I_e(\phi) = -4\pi r_p^2 \frac{en_e}{4} \left(\frac{8kT_e}{\pi m_e} \right)^{1/2} \exp \left(\frac{e\phi}{kT_e} \right) \quad . \quad (2)$$

From the equilibrium potential $\phi = \phi_p$ the charge can be calculated as $q_p = 4\pi\epsilon_0 r_p \phi_p$, assuming that the particle has the capacity of a sphere in vacuum. A good empirical formula for laboratory argon plasmas with electron temperatures $kT_e = (2 - 4) \text{ eV}$ is, that the particle carries per micrometer of its diameter between 2000 and 4000 electrons on its surface. The surface potentials are independent of the particle size and in the range of -5 to -10 volts.

The attainable charge-to-mass ratios are in the order of $q_p/m_p \approx -0.5 \text{ C kg}^{-1}$ for a $1\text{-}\mu\text{m}$ melamine formaldehyde (MF) plastic particle ($\rho = 1500 \text{ kg m}^{-3}$). A ten times smaller particle ($2r_p = 100 \text{ nm}$) of the same material reaches a hundred times higher ratio $q_p/m_p \approx -50 \text{ C kg}^{-1}$ due to the scaling laws $q_p \propto r_p$ and $m_p \propto r_p^3$. The surface potential of the particle (and consequently q_p and q_p/m_p) strongly depends on the electron temperature T_e , and is approximately proportional to the latter, i.e. $\phi_p \propto T_e$, where the coefficient depends on the ion mass and temperature.

B. Charging with an Electron Beam

The relation $q_p \propto T_e$ suggests to increase the electron temperature in order to obtain higher particle charges. However, no low temperature plasma shows electron temperatures of more than a few eV. More promising is the use of an energetic electron beam. In case of a monoenergetic electron beam with current density j_e and electron energy W_e , Eq. (2) simplifies to

$$\begin{aligned} I_e(\phi) &= \pi r_p^2 \left(1 + \frac{e\phi}{W_e}\right) j_e, & W_e \geq -e\phi, \\ I_e(\phi) &= 0, & W_e < -e\phi. \end{aligned} \quad (3)$$

In the first equation the bracketed expression means the reduction of the geometrical cross section πr_p^2 due to the deflection of the electrons (OML theory). If the electron beam has a sufficiently high current density j_e , then the ion current I_i from the plasma ions becomes negligible ($I_i \ll -I_e$), and the equilibrium particle surface potential ϕ_p follows closely the potential which corresponds to the beam energy:

$$\phi_p \approx -W_e/e. \quad (4)$$

Such an experiment was performed by Walch *et al.*⁶ The plasma was generated with a hot filament discharge in a double plasma machine, where the filaments could be biased negatively up to -120 V to inject 2 mA of fast electrons into the chamber. The particles were dropped from top through the chamber and collected at the bottom with a Faraday cup, which allowed for a measurement of the particle charge. The gas pressure ($< 3 \times 10^{-4}$ Pa) was sufficiently low, so that the fast electrons did not lose their energy by collisions with neutrals. Up to a critical electron beam energy, which is characteristic for each particle material, the particle surface potential followed the filament potential as expected. Above that critical energy, the particle charge decreased due to increasing secondary electron emission at the surface. The maximum surface potentials reported are approximately -90 V for graphite, -60 V for copper, -50 V for silicon, and -40 V for glass particles.

Exemplarily, we can consider $1\text{-}\mu\text{m}$ and 100-nm graphite particles charged with a 90-eV electron beam. The charge would be approximately 31 000 and 3 100 negative elementary charges, corresponding to $q_p/m_p \approx -4.3$ C kg $^{-1}$ and -430 C kg $^{-1}$, respectively. However, the charge on such small particles could not be confirmed with the experiment in Ref.⁶ because the signal-to-noise ratios in the charge measurements with a Faraday cup were good only for particles bigger than $35\text{ }\mu\text{m}$.

C. Charging by Contact with High Voltage Needle Electrodes

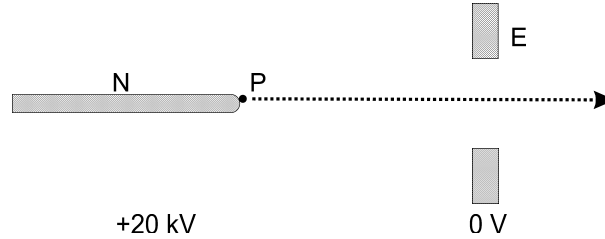


Figure 1. Simplified schematic drawing of the particle charging and accelerating device. The needle (N) charges a particle (P) which is afterwards accelerated towards the electrode (E). The particle leaves the system through the hole in the electrode.

Hypervelocity impact experiments for the simulation of micrometeoroids and their impacts for example on the surface of the moon, space vehicles, and instruments also use electrostatic acceleration of charged microparticles. A successful technique applied there allows for the highest possible specific charges (see Sec. E). The particles are charged by contact with very small spherical or needle-shaped surfaces at high voltage potentials, as indicated in Fig. 1. Shelton *et al.*⁷ applied this technique using as charging electrode a tapered tungsten wire with a diameter of $r_n = 24\text{ }\mu\text{m}$ at the tip, which is maintained at a positive potential of $U_n = 20$ kV. If the microparticle ($r_p < r_n$) touches the needle tip, it acquires the charge

$$q_p = \frac{2}{3} \pi^3 \epsilon_0 r_n \frac{r_p^2}{(r_p + r_n)^2} U_n. \quad (5)$$

With the assumption $r_n \gg r_p$ the electric field strength on the particle becomes $E_p = \pi^2 U / 6r_n$. For example a needle with radius $r_n = 12 \mu\text{m}$ at a potential of $U_n = 20 \text{ kV}$ yields an electric field strength of $E = 2.7 \times 10^9 \text{ V m}^{-1}$. A $1\text{-}\mu\text{m}$ iron particle ($\rho = 7874 \text{ kg m}^{-3}$) would carry 475 000 positive elementary charges and have a specific charge of $q_p/m_p = 18.5 \text{ C kg}^{-1}$. The values for the smaller 100-nm particle are $q_p = +4750e$ and $q_p/m_p = 185 \text{ C kg}^{-1}$.

material	m_p	v_{p0}	$2r_p$	q_p/m_p	q_p	E_p
iron	$10 \times 10^{-16} \text{ kg}$	10 km s^{-1}	$0.62 \mu\text{m}$	$+25 \text{ C kg}^{-1}$	$+15600e$	$2.3 \times 10^9 \text{ V m}^{-1}$
iron	$1.0 \times 10^{-16} \text{ kg}$	10 km s^{-1}	$0.29 \mu\text{m}$	$+25 \text{ C kg}^{-1}$	$+15600e$	$1.1 \times 10^9 \text{ V m}^{-1}$
latex	$0.9 \times 10^{-16} \text{ kg}$	5 km s^{-1}	$0.54 \mu\text{m}$	$+6.3 \text{ C kg}^{-1}$	$+3500e$	$7.0 \times 10^7 \text{ V m}^{-1}$
latex	$0.9 \times 10^{-16} \text{ kg}$	11 km s^{-1}	$0.54 \mu\text{m}$	$+30 \text{ C kg}^{-1}$	$+17000e$	$3.4 \times 10^8 \text{ V m}^{-1}$

Table 1. Experimental parameters for particles from a needle source. Mass m_p and speed v_{p0} were selected from figure data published in Ref.,⁸ the other parameters were calculated. The particles were accelerated with a potential of $U_{\text{acc}} = 2 \text{ MV}$.

Dielectric particles can also be charged with this technique, but they have to be coated with a conducting material. In the Heidelberg Dust Accelerator⁸ latex particles were successfully used. Table 1 shows some of the experimental values for iron and latex particles. The latex particles had a narrow size distribution, and most of the particles were accelerated to speeds between 5 and 11 km s^{-1} . The size distribution of the iron powder was broad, resulting in speeds from less than 1 km s^{-1} to more than 10 km s^{-1} .

D. Charging in Quadrupole Traps

Quadrupole traps together with electron and ion beams have been used to charge microparticles for subsequent acceleration,⁹ and for the study of charging processes^{10–12} and particle fragmentation.¹³ The trap allows to keep the particle in the beam and to determine very accurately its specific charge by a measurement of the grain oscillation frequency. Vedder⁹ was able to reach positive charge-to-mass ratios of up to 400 C kg^{-1} applying a (positive) ion beam. Negative charging is limited due to secondary electron emission (see Sec. E). Electron beams with energies where the secondary electron emission yield is higher than unity produced positive surface potentials in the range of just a few volts.

E. Upper Limits for the Particle Charge

The electric charge on a microparticle is limited by certain processes which become important at very high electric field strength on the particles surface.¹⁴ For negative charges electron field emission begins at $|E_p| > 10^9 \text{ V m}^{-1}$. For positive charges field evaporation destroys the particle, if $|E_p| > 10^{10} \text{ V m}^{-1}$. In case of materials with low tensile strength or even fluffy grains, charges of both signs are able to fragment the particles (“Coulomb explosion”)¹³ already at lower field strengths.

The specific charge q_p/m_p , which is the crucial parameter for electrostatic acceleration, can be related to the electric field at the surface $E_p = q_p / 4\pi\epsilon_0 r_p^2$, assuming spherical particles. By means of the particle mass $m_p = \frac{4}{3}\pi r_p^3 \rho$, one obtains the specific charge as

$$\frac{q_p}{m_p} = 3 \frac{\epsilon_0 E_p}{r_p \rho} \quad . \quad (6)$$

This equation can be used to calculate the maximum possible specific charge, which depends on the particle size and density and the critical electric field strengths for positive and negative charges. Table 2 shows the charge-to-mass ratios for some combinations of size and material assuming the above mentioned critical field strengths for all the particles.

III. Acceleration of Charged Microparticles

In order to make the particles useful for propulsion, they have to be accelerated by an electric field. The desired specific impulse $I_{\text{sp}} = v_{p0}/g$, i.e. the particle exhaust velocity v_{p0} , determines the required

material	ρ	$2r_p = 1.0 \mu\text{m}$	$2r_p = 0.1 \mu\text{m}$
latex	1100 kg m^{-3}	$(-48 \dots + 480) \text{ C kg}^{-1}$	$(-480 \dots + 4800) \text{ C kg}^{-1}$
MF	1500 kg m^{-3}	$(-35 \dots + 350) \text{ C kg}^{-1}$	$(-350 \dots + 3500) \text{ C kg}^{-1}$
graphite	2200 kg m^{-3}	$(-24 \dots + 240) \text{ C kg}^{-1}$	$(-240 \dots + 2400) \text{ C kg}^{-1}$
iron	7874 kg m^{-3}	$(-6.7 \dots + 67) \text{ C kg}^{-1}$	$(-67 \dots + 670) \text{ C kg}^{-1}$

Table 2. Estimated range of the possible specific charges for particles with different materials and sizes. The critical electric field strengths have been assumed cautiously to be 10^9 V m^{-1} for negative and 10^{10} V m^{-1} for positive charges.¹⁴

acceleration voltage U_{acc} by means of the equation

$$\frac{1}{2} m_p v_{p0}^2 = |U_{\text{acc}} q_p| \quad . \quad (7)$$

In the following the challenges and attainable specific impulses are discussed.

A. Particles Charged in Plasma

1. Plasma with low Degree of Ionization

Plasmas, which are generated by electron-neutral collisions, like dc glow discharges, thermionic discharges, capacitively or inductively coupled rf discharges, and electron cyclotron resonance (ECR) plasmas produced with microwaves, show ionization degrees of only a few percent or less. If the microparticles are charged in such a plasma, the acceleration cannot be done in the plasma for the following reason. If an acceleration electrode is at low potential, it collects ions and electrons from its disturbed vicinity like a Langmuir probe. Due to the extremely low mobility of the particles, the electron current would be much higher than the current of the particle charges, and only a vanishing portion of the power would be deposited in the microparticle motion. A high voltage electrode instead would lead to a secondary discharge or electrical breakdown with the same effect. This means, that the plasma has to be switched off or the microparticles have to be moved out of the plasma in order to be accelerated.

After a switch-off of the plasma the particle charge can possibly be conserved, but only if the gas pressure is very low and the particles are not densely packed.¹⁵ In a microgravity experiment, where these conditions were not fulfilled, the remaining charge after the switch-off was two orders of magnitude below the initial charge.¹⁵ Furthermore, if there is remaining neutral gas, the electric field for acceleration would generate again a glow discharge or an arc discharge.

Moving the particles out of the plasma for further acceleration can be performed in two different ways. The first possibility is using a grid, which limits the plasma like in an ion-thruster. The particle would traverse the positive space charge in the plasma sheath, and would therefore at least partially be discharged.^{4,16} Some of the particles would collide with the grid, loose the charge and become useless for propulsion. The second possibility is extracting the particles through a diffuse edge of the plasma, i.e. where no walls limit the plasma. The particle would see an always quasineutral plasma with decreasing density. This was the case in the already mentioned experiment,⁶ where the particles kept the entire expected charge (admittedly, the plasma played there only a subsidiary role in the entire charging process).

$2r_p$	q_p	q_p/m_p	I_{sp} at $U_{\text{acc}} = 2 \text{ kV}$	U_{acc} for $I_{\text{sp}} = 50 \text{ s}$
$1.0 \mu\text{m}$	$-2500e$	-0.5 C kg^{-1}	4.5 s	250 000 V
$0.1 \mu\text{m}$	$-250e$	-50 C kg^{-1}	45 s	2 500 V

Table 3. Expected parameters for MF particles charged in an argon plasma ($kT_e = 3 \text{ eV}$).

To judge if charging in plasma is suitable for electrostatic propulsion of microparticles, Table 3 shows the specific impulses for an acceleration potential of 2 kV, which is typical for ion thrusters. Only the small 100-nm particles reach a value which lies at least in the order of magnitude of cold gas thrusters. A modest specific impulse of $I_{\text{sp}} = 50 \text{ s}$ requires for the above mentioned 1- μm plastic particles already an accelerating voltage of $U = 250 \text{ kV}$.

2. Fully Ionized Plasma

A nearly fully ionized (low-temperature) plasma can be produced with cesium vapor and a hot tungsten surface similar to the technique applied in early cesium ion thrusters¹⁷ and Q machines.¹⁸ The advantage is, that no neutral gas would impose a limit on the acceleration field strength because of electrical breakdown. It appears possible to apply an intermittent acceleration voltage to appropriately designed electrodes in the plasma, accepting the unavoidable side effect of the run-off of the plasma to the electrodes and the related currents. The disadvantages are, that cesium is a highly corrosive alkali metal which limits the lifetime of the thruster, and that the electrons have only the temperature $T_e (= T_i)$ of the tungsten surface, typically 2000 K or 0.2 eV. Due to Eqs. (1) and (2) and the resulting approximate relation $\phi_p \propto T_e$, the particles carry only 270 elementary charges per micrometer of diameter.

$2r_p$	q_p	q_p/m_p	I_{sp} at $U_{acc} = 2$ kV	U_{acc} for $I_{sp} = 50$ s
1.0 μm	$-240e$	-0.05 C kg^{-1}	1.4 s	2.6 MV
0.1 μm	$-24e$	-5.0 C kg^{-1}	14 s	26 kV

Table 4. Expected parameters for MF particles charged in a fully ionized cesium plasma ($T_e = T_i = 2000$ K).

Table 4 shows, that the attainable specific impulses are significantly lower than in a plasma with electron temperatures ranging from 2 to 4 eV. The 100-nm particles reach a specific impulse $I_{sp} = 50$ s, comparable to a cold gas system, if an acceleration voltage of 26 kV is applied.

B. Particles Charged by an Electron Beam

The already mentioned experiment performed by Walch *et al.* with an electron beam from a biased hot filament was operated at a very low gas pressure ($< 3 \times 10^{-4}$ Pa) and low plasma density, so that the charging was dominated by the fast electrons.⁶ The background gas and the plasma, which is generated by the fast electrons, are actually unnecessary for the charging process. The difficulties mentioned in Section A related with the background gas can therefore be avoided using no gas. Acceleration can be performed with additional ring or cylinder anodes. To impede that the electrons gain energy in the field of the accelerator anodes, a magnetic field can be used, which directs the electrons onto the counter electrode at zero potential. A gyroradius $r_{ce} = 1$ mm for a 90-eV electron is already obtained for a weak magnetic field of $B = 32$ mT, and should be small enough to guide the electrons along the magnetic field lines. The microparticles, on the other hand, are not magnetized due to their much lower specific charge. They can cross the magnetic field lines and follow the accelerating electric field.

$2r_p$	q_p	q_p/m_p	I_{sp} at $U_{acc} = 2$ kV	U_{acc} for $I_{sp} = 50$ s
1.0 μm	$-31\,000e$	-4.3 C kg^{-1}	13 s	29 kV
0.1 μm	$-3\,100e$	-430 C kg^{-1}	130 s	290 V

Table 5. Expected parameters for graphite particles charged with an electron beam ($W_e = 90$ eV).

Graphite particles charged with the electron beam technique can be accelerated to much higher speeds than the plasma charged particles, as Table 5 shows. Specially the smaller particles (100 nm) reach the exhaust velocity of cold gas thrusters, if an acceleration potential of only 290 V is used.

C. Particles Charged with Needles

When the particles leave the needle electrode source, they have already been accelerated by the potential difference between the needle and hole electrode. In case of the Heidelberg Dust Accelerator,⁸ a subsequent acceleration with 20 kV or 2 MV was accomplished, but this is not necessary.

In Table 6 the performance of the particle source without and with an additional accelerating system is shown. The source alone surpasses cold gas thrusters in specific impulse, and with a further 180-kV acceleration the microparticle thruster becomes comparable with chemical thrusters.

material	m_p	$2r_p$	q_p/m_p	I_{sp} at $U_{acc} = 20$ kV	I_{sp} at $U_{acc} = 200$ kV
iron	10×10^{-16} kg	$0.62 \mu\text{m}$	$+25 \text{ C kg}^{-1}$	100 s	316 s
latex	0.9×10^{-16} kg	$0.54 \mu\text{m}$	$+30 \text{ C kg}^{-1}$	110 s	346 s

Table 6. Expected specific impulses for particles from a needle sources. The values for $U_{acc} = 20$ kV correspond to the source without further acceleration, the designation $U_{acc} = 200$ kV means the sum of 20 kV needle potential plus a 180 kV additional accelerator potential.

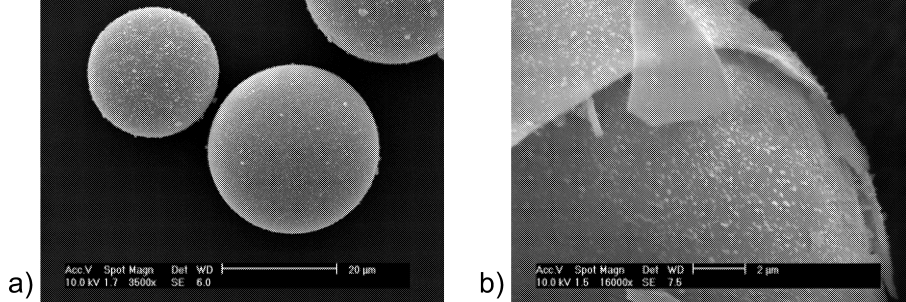


Figure 2. Hollow microspheres. The scanning electron microscope pictures show (a) the perfect spherical shape and (b) the thin walls of a broken particle.

IV. Propellant Material

A. Prefabricated or On-board Synthesized Particles

Particle formation in reactive and etching plasmas, e.g. with methane, silane and acetylene, are well known,¹⁹ so that one can think about the production of particles on board. The generation of the plasma where the particles are formed consumes additional energy which debits the efficiency of the thruster, and causes additional weight for the plasma reactor and necessary electronics. But there are also some advantages over prefabricated particles. Clumping of stored particles and congestion of tank and ducts as possible troubles would easily be avoided. However, we think that it is untimely to discuss the concept of on-board production in detail before a thruster does work with well-defined model particles.

B. Hollow Particles

Hollow glass microspheres (“microballoons”) are known as a low prized filler in composite materials like light weight concrete. Figure 2(a) shows the nearly perfect spherical shape of the microspheres. The particle in Fig. 2(b) was intentionally broken to show the very thin walls, which are approximately 300 nm thick. The lower over-all mass density of a hollow microparticle can yield higher specific charges. Analog to Eq. (6) the charge-to-mass ratio can be recalculated for a hollow sphere with wall thickness $d \ll r_p$ and the particle mass $m_p = 4\pi r_p^2 d \rho$:

$$\frac{q_p}{m_p} = \frac{\epsilon_0 E_p}{d \rho} . \quad (8)$$

It is noteworthy that the charge-to-mass ratio is not dependent of the particle radius, and it is now the wall thickness d which determines the specific charge. A comparison of Eqs. (6) and (8) gives that a hollow sphere yields a higher specific charge, if $d < \frac{1}{3} r_p \rho_f / \rho_h$, where ρ_f and ρ_h are the densities of the filled and the hollow spheres.

Unfortunately, a hollow glass microsphere with 300-nm walls has therefore only a better charge-to-mass ratio than a glass pearl bigger than $1.8\text{-}\mu\text{m}$. But hollow microspheres made of another material and with a modified method of production might have even thinner walls and be better suited as propellant.

V. Conclusion

In this article we made an attempt at a better understanding of the basic technical and physical aspects with respect to the feasibility of electrostatic microparticle thrusters. We have shown that particle charging

in a plasma is for two reasons not practicable. First, the attainable charge-to-mass ratios are too low for the considered particle sizes. Manageable acceleration potentials would yield specific impulses comparable to cold gas thrusters, which then are to be preferred because of their compactness and simpleness. Second, there are no ready-to-use techniques for extracting the particles out of the plasma which preserve the particle charge.

Two different charging mechanisms have been considered, which give the ideas for two novel microparticle thruster concepts. The first one charges the particles negatively with an energetic electron beam. The beam energy is adjusted with regard to the secondary electron emission of the particle material, so that the impacting beam electrons do not produce too many secondaries which would discharge the particle. This technique yields about ten times higher charges than charging in plasma, if materials like graphite with low secondary electron emissions are chosen. The second proposed concept uses high voltage needle electrodes to charge conducting particles positively or negatively, and is known from accelerators for the simulation of micrometeoroids. Here, charging and acceleration are both done in one small electrode assembly. This concept allows for highest specific charges, which are only limited by field evaporation, electron field emission, and coulomb explosion in case of fluffy grains. While the existing dust accelerators are not optimized for high ejection rates, a thruster would probably use a miniaturized needle array instead of a single needle electrode. We plan to perform preliminary experiments for both concepts in the near future.

Acknowledgments

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