

Contamination Test of a Cesium Field Ion Thruster

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Field emission electric propulsion is the technological application of the principle of liquid metal ion sources as thrusters in electric space propulsion. This paper describes the influence of the residual gas atmosphere on a slit-type field ion thruster with liquid cesium as propellant obtained during a long-term test of about 100 days, occasionally simulating the vacuum conditions outside a spacecraft in low Earth orbit. Major deviations of the current-voltage emission characteristic due to gas adsorption and the related contamination of the slit area of the ion thruster have been found, as well as a recovery effect initiated by high current ion emission.

Introduction

FIELD emission electric propulsion (FEEP) is the technological application of the principle of liquid metal ion sources as thrusters in electric space propulsion.¹ In the FEEP system, the ions being expelled are created directly from the surface of liquid cesium (Cs) exposed to vacuum by means of a high electric field resulting from suitable voltages applied to an emitting electrode geometry. When the surface of a liquid metal is subjected to a high electric field, it is distorted into a cone or a series of cones. When the apex field reaches values of the order of 10^9 Vm^{-1} , metal atoms are ionized either by field evaporation or field ionization; the ions are accelerated and expelled from the emitter by the same electric field that has ionized them, therefore, creating the thrust.

The main advantages of a propulsion system based on the field emission principle are emitter clustering capability, continuous thrust throttling, operational simplicity, and the possibility to operate in both the continuous and the pulsed mode.² Therefore, the FEEP system seems to be suitable not only for north-south stationkeeping of geostationary satellites and drag compensation, but also for fine attitude control purposes. Because of its low induced disturbances when firing, FEEP can offer great advantages in particular for missions such as astronomy missions that require fine pointing.

A flight demonstration of the entire FEEP system is now regarded as the next milestone toward the qualification of an operational system. This very first space test will be performed throughout in a low Earth orbit (LEO), considering unmanned spacecraft (e.g., EURECA II) or satellites (AOTS) only.³ The influence of the constituents of the near Earth space vacuum therefore is evident, considering even the intrinsic local atmosphere of any spacecraft, which results from outgassing processes induced by solar radiation as well as from intermittent operation of chemical thrusters.⁴⁻⁷

Recent investigations have demonstrated the outstanding importance of both the residual gas atmosphere and the emitter preparation technique on the emission performance of a FEEP thruster.^{8,9} In order to simulate comparable conditions as mentioned above in a terrestrial experiment, a long-term contamination test of a field ion thruster has been performed over a period of about 100 days.

Experimental Procedure

The electrode configuration of the field ion thruster is shown in Fig. 1. A plane accelerator electrode with an aperture

of width $2b$ is mounted in a distance a of the emitter slit edge. The emitter and accelerator are kept at voltages $+U_E$ and $-U_{ACC}$ vs ground potential. The data for the emitter-accelerator geometry with an emitter slit length of $1.5 \times 10^{-2} \text{ m}$ are as follows: $a = 6 \times 10^{-4} \text{ m}$; $2b = 4 \times 10^{-3} \text{ m}$; $d = 1 \times 10^{-2} \text{ m}$; $w = 1.5 \times 10^{-6} \text{ m}$. In order to investigate the emission performance, a thruster was inserted into an ultra-high-vacuum (UHV) system. After bakeout, liquid nitrogen (LN_2) cooled surfaces together with a titanium getter pump allow for an ultimate total background pressure of some 10^{-10} mbar . Mass spectroscopic analysis of the residual gas atmosphere is carried out by means of a quadrupole mass analyzer. Cs of high purity is supplied to the emitter by a completely closed Cs-feeding system, which operates mainly by capillary forces. Additionally, positive pressure feeding of Cs may be performed by means of a micrometer driven Cs pump. The emitter and the Cs-feeding system are outgassed by radiative and resistive heating.

Results and Discussion

Because of the very high chemical reactivity of the alkali metal Cs, the influence of the residual gas atmosphere on the emission performance of a slit emitter is evident. The chemical reactions of Cs with the most serious atmospheric constituents $^{18}\text{H}_2\text{O}$, $^{32}\text{O}_2$, and $^{44}\text{CO}_2$ throughout result in crystalline substances (see Table 1) with rather high melting temperatures (indicated in parentheses).

Once these substances were deposited in a considerable amount on the free Cs surface at the emitter slit edge, irreversible contamination connected with partial or even complete throttling of the hydrodynamic Cs flow at the micron-size slit orifice may occur; thermal volatilization of these contaminants is out of scope due to the range of the melting temperatures. Throttling of the Cs flow by solid contaminants results in an enhanced flow impedance of the emitter slit itself. The voltage necessary to sustain a given value of emission current depends on the flow impedance of the emitter slit, resulting in a voltage enhancement with increasing impedance.^{1,8,9}

In order to evaluate the surface contamination due to adsorption of molecules originating from the residual gas at-

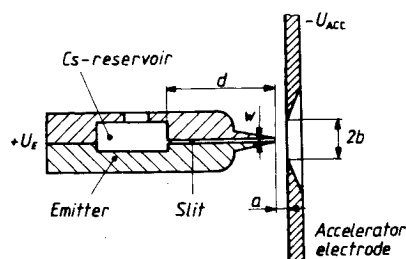


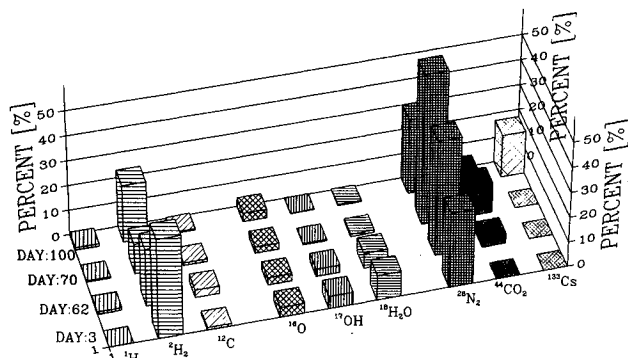
Fig. 1 Sectional view of the emitter-accelerator configurations.

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Table 1 Reaction products of Cs with H₂O, O₂, and CO₂

Cesium oxide	Cs ₂ O	(490°C)
Cesium peroxide	CsO ₂	(433°C)
Cesium peroxide	Cs ₂ O ₂	(594°C)
Cesium hydroxide	CsOH	(272°C)
Cesium carbonate	Cs ₂ CO ₃	(610°C)

**Fig. 2** Set of mass spectra of the residual gas atmosphere.

mosphere, the equilibrium condition for evaporation and condensation is used; the particle flux density ν is given by

$$\nu = p(2\pi mkT)^{-1/2} \quad (1)$$

where p is the saturation vapor pressure at the temperature T and m is the mass of the molecules. Considering a surface particle density N of about 10^{19} m^{-2} for a monomolecular surface layer and assuming an accommodation coefficient of unity, the time t necessary for the adsorption of a monolayer of contaminants is given by

$$t = \nu^{-1} \quad (2)$$

For an equilibrium temperature $T = 300 \text{ K}$ (i.e., approximately the melting temperature of Cs) and inserting the partial pressure p of the contaminating gaseous constituents in mbar, from Eqs. (1) and (2), there results

$$t(\text{H}_2\text{O}) = 2.79 \times 10^{-6} p^{-1} \text{ s}$$

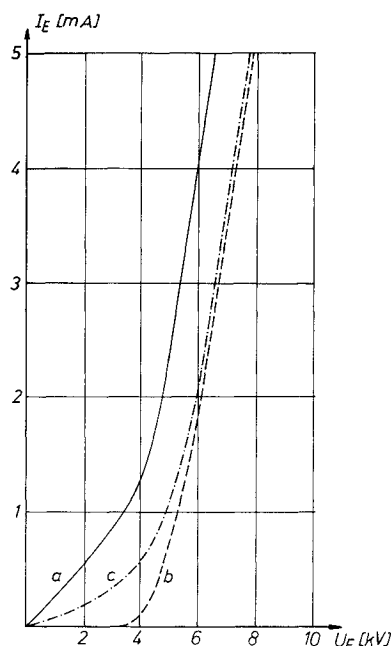
$$t(\text{O}_2) = 3.72 \times 10^{-6} p^{-1} \text{ s}$$

$$t(\text{CO}_2) = 4.36 \times 10^{-6} p^{-1} \text{ s} \quad (3)$$

Mass spectra of the residual gas atmosphere characterizing typical phases of the contamination test cycle are outlined in Fig. 2, showing the percentage of the constituents on the total pressure. Only $^{18}\text{H}_2\text{O}$ and $^{44}\text{CO}_2$ are really contaminants; $^{32}\text{O}_2$ is nearly completely absent throughout. The abundance of the mass peaks ^1H , ^{12}C , ^{16}O , and ^{17}OH is contributed to molecular dissociation (H_2O , CO_2) by electron bombardment within the ion source of the quadrupole mass analyzer. Finally, the occurrence of ^{133}Cs depends on the adsorption of Cs on the LN_2 -cooled surfaces as well as on chemical gettering of H_2O by Cs.

A corresponding set of current-voltage characteristics is shown in Fig. 3, defining the emission performance of the thruster by the dependence of the emission current I_E on the emitter voltage U_E for a constant value of the accelerator voltage $U_{\text{ACC}} = -5 \text{ kV}$.

The surface conditions of a new emitter prior to Cs feeding mainly result from the bakeout procedure. On day 3 after the

**Fig. 3** Set of current-voltage characteristics of the thruster.

start of the test cycle, the total pressure was $1 \times 10^{-9} \text{ mbar}$; with a share of 10% of H_2O , $t(\text{H}_2\text{O}) = 2.8 \times 10^4 \text{ s}$ results from Eq. (3). Bearing in mind this rather long time scale and considering the time necessary to cool down the emitter and the Cs-feeding capillary from an outgassing temperature of about 450°C to a feeding temperature of 35°C is approximately 10^4 s , less than one monolayer of H_2O is adsorbed until Cs feeding. Outstanding wetting properties therefore result; the current-voltage characteristics of an uncontaminated emitter properly wetted by Cs is shown in Fig. 3a.

Because of specific circumstances, immediately after a first experimental period (i.e., from days 3 to 4), the emitter was kept in a standby position for about 60 days at ambient room temperature. During this period, the LN_2 supply to the cold surfaces as well as the Ti-getter pump were out of operation. On day 62, a total pressure of $6 \times 10^{-9} \text{ mbar}$ was measured; the amount of H_2O and CO_2 was 6 and 4%, respectively. From Eq. (3) there follows $t(\text{H}_2\text{O}) = 7 \times 10^3 \text{ s}$ and $t(\text{CO}_2) = 1.7 \times 10^4 \text{ s}$. Assuming for simplicity equal vacuum conditions for the whole standby period, the number N_m of monolayers built up during 60 days results to $N_m(\text{H}_2\text{O}) = 740$ and $N_m(\text{CO}_2) = 300$.

After this standby period, initiation of emission was not possible merely by switching on the supply voltages. Imposing yet a slightly positive pressure by operation of the Cs pump, emission starts from several distinct emission sites originating from localized mechanical penetration of the solid crust of contaminations at the emitter slit orifice. Increased conditioning of the emitter occurs with time after continuous emission at a maximum emission current of 5 mA for about 1 h. Figure 3b shows the current-voltage characteristic of the emitter after this reconditioning procedure on day 62; compared to the initial characteristic depicted in Fig. 3a, up to an emitter voltage of about 4 kV emission is nearly completely suppressed; furthermore, the whole curve is shifted towards higher values of the emitter voltage. Both features indicate some throttling of the Cs flow, presumably due to remnants of the solid contaminants even after reconditioning.

For a period of 10 days the equipment was now continuously supplied with LN_2 . Numerous emission experiments were performed during this period; the total pressure of the residual gas atmosphere was in the range between about $5 \times 10^{-10} \text{ mbar}$ and $5 \times 10^{-9} \text{ mbar}$. A typical mass spectrum on day 70 at a total pressure of $9 \times 10^{-10} \text{ mbar}$ shows a percen-

tag of H_2O of 1% and a strongly increased amount of CO_2 of 12%, the latter mainly due to desorption from stainless steel surfaces by Cs-ion bombardment. From Eq. (3) there follows $t(\text{H}_2\text{O}) = 2.8 \times 10^5 \text{ s}$ and $t(\text{CO}_2) = 4.4 \times 10^4 \text{ s}$; within the rather short idle periods between emission experiments, contamination therefore is negligible.

Reconditioning proceeds further during the second experimental period, as it is shown in Fig. 3c, which was obtained on day 70. Although there is no remarkable change in the high current regime, the shape of the current-voltage characteristic in the low current regime approaches the initial slope outlined in Fig. 3a. Because of the good vacuum conditions, no additional contamination had occurred, while still existing contaminations had been removed by the emission process itself.

For a second time, the thruster was kept in standby position without LN_2 supply for 30 days. On day 100 a total pressure of $7 \times 10^{-8} \text{ mbar}$ was measured with contributions of H_2O and CO_2 of 0.5 and 4.5%, respectively, but with an enhanced share of Cs of 17%, which results from the high Cs emission rate during the preceding experimental period. The reduced percentage of H_2O and CO_2 obviously is due to chemical reactions with Cs; this is corroborated by an enhanced amount of H_2 . From Eq. (3) there follows $t(\text{H}_2\text{O}) = 9.3 \times 10^3 \text{ s}$ and $t(\text{CO}_2) = 1.5 \times 10^3 \text{ s}$; the numbers of monolayers built up during 30 days result to $N_m(\text{H}_2\text{O}) = 280$ and $N_m(\text{CO}_2) = 1730$.

Although the total pressure of the residual gas atmosphere was higher by about one order of magnitude, due to the lower share of H_2O during this period, the growth of CsOH is much less than observed previously during the first standby period; this is evident if one compares the figures for $N_m(\text{H}_2\text{O})$, i.e., 280 vs 740. Emission even starts immediately after switching on the supply voltages; no mechanical support was necessary by means of the Cs pump. The initial state of the current-voltage characteristic as it is shown in Fig. 3a is nearly attained.

Finally, the role of CO_2 as a serious contaminant of Cs is reduced considerably, as even the accumulation of about 1700 monolayers does not affect the emission performance; while the critical number of monolayers of H_2O for complete throttling of the Cs flow is somewhere between 300 and 700. The outstanding role of H_2O as the most serious contaminant therefore is supported.

Relations to Space Environment

Originating mainly from Space Shuttle flights, information on the concentration of neutral and charged constituents as well as on the total pressure of the Shuttle environment⁴⁻⁷ exists. At 300-km altitude, the atmospheric pressure will be of the order of 10^{-7} mbar . However, during the first days in orbit, a spacecraft will contaminate this environment by desorbing gases⁴; eventually a long-term local environment, which is a function of the vapor pressure of spacecraft materials, will be established. During Shuttle flights, ambient pressures of 10^{-6} mbar have been measured close to the cargo bay after 1 day in orbit, reducing to 10^{-7} mbar progressively. Thruster firings during maneuvers cause a short-term increase up to 10^{-4} mbar .⁵ Partial pressures of H_2O and CO_2 of 10^{-6} mbar and 10^{-7} mbar , respectively, close to the Shuttle surface have been observed.⁶ Following thruster firing, emitted H_2O , N_2 , and H_2 have been found.⁷

Comparing these data with the results of the present analysis of total and partial pressures during the contamination test, there exists a particularly qualitative similarity of the residual gas atmosphere within the test chamber to vacuum conditions presumably to be expected during a space test of a FEPP thruster in LEO.

Although the partial pressures of the contaminants H_2O and CO_2 sometimes are orders of magnitude greater in the Shuttle environment,⁶ during the relatively long standby periods (60 days and 30 days) of the present test, there occurs an accumulation of a quantity N_m of monolayers of contami-

nants, which corresponds to a deposition in space at enhanced partial pressures and with a reduced time scale. The most important feature of the test therefore does not result in a time scale for reconditioning of the thruster, but it results much more in the evaluation of the quantity N_m of monolayers of potential contaminants in space sufficient for serious contamination of the thruster by chemical reactions with Cs together with an even serious degradation of the emission performance.

Conclusions and Recommendations

Generally the results of the present experiment suggest the following conclusions.

1) Within the contaminants H_2O and CO_2 , which are both present in a terrestrial space simulation vacuum chamber and in the near Earth space vacuum, H_2O by far is the most serious one. This is supported by a critical number N_m of monolayers for throttling of the Cs flow by solid chemical compounds, which for H_2O is somewhere between 300 and 700; while even an accumulation of about 1700 monolayers of CO_2 has no remarkable influence on the emission performance.

2) Once a FEPP thruster is supplied with Cs at extremely clean surface conditions (removing H_2O extensively by high-temperature bakeout in UHV) and is wetted properly by Cs, reconditioning by the combined action of positive pressure Cs feeding and the ion emission itself is possible even after complete throttling of the Cs flow at the emitter slit edge by chemical compounds resulting from reactions of 300 to 700 monolayers of H_2O with Cs.

Furthermore, with respect to a flight demonstration of a FEPP thruster in space, recommendations offered are as follows.

1) Whether the initial Cs supply to the emitter will be carried out on ground or in orbit, the Cs feeding has to be performed always at UHV conditions, as any reconditioning after imperfect wetting inside the emitter slit and the Cs supply system is not practicable.

2) In case the Cs supply system anticipated for the space test operates with capillary feeding only, additional positive pressure feeding is recommended in order to dispose of mechanical emitter reconditioning after any serious contamination occurring casually.

3) Monitoring of the most serious contaminants in the environment close to the thruster is recommended in order to prevent contamination at the emitter slit edge by periodic firing of the emitter.

4) The pulsed mode of operation of the thruster seems to be superior to the continuous mode, as the former allows for a periodic ablation of contaminations from the free Cs surface by the emission itself.

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