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► To cite this version:

J. Mitterauer. LIQUID METAL ION SOURCES AS THRUSTERS FOR ELECTRIC SPACE PROPULSION. Journal de Physique Colloques, 1987, 48 (C6), pp.C6-171-C6-176. 10.1051/jphyscol:1987628 . jpa-00226831

HAL Id: jpa-00226831

<https://hal.science/jpa-00226831>

Submitted on 1 Jan 1987

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LIQUID METAL ION SOURCES AS THRUSTERS FOR ELECTRIC SPACE PROPULSION

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Abstract: Electric space propulsion systems are characterized according to their inherent features and specified domains of application in space missions. Particularly the Field Emission Electric Propulsion (FEEP)-system using a liquid metal ion source as a thruster is described and recent results on its emission performance are presented.

1. INTRODUCTION

Space propulsion by mass expulsion actually can be performed by conversion of chemically stored thermal energy on the one side or electric energy on the other side into kinetic energy of the expelled mass. In the case of chemical propulsion, the amount of energy released is limited by the energy content of the chemical propellants. Chemical propulsion is therefore energy limited but not power limited; compared with electric propulsion, chemical propulsion is characterized by relative high thrust and low exhaust velocity.

In the case of electric propulsion, electric energy normally being converted from solar radiation energy is used to supply or augment the kinetic energy necessary for mass expulsion. Bearing in mind the practical limitations of electric power and propellant mass on board of the spacecraft, electric propulsion is therefore power limited but not energy limited. Compared with chemical propulsion, electric propulsion is characterized by relative low thrust and high exhaust velocity.

The application of electric propulsion to space missions is restricted by its inherent characteristics, i.e. above all high exhaust velocity, high specific electric power and high operating voltage. From these primary characteristics there result derived characteristics for space applications: Low propellant mass (typically about 10% of that required with advanced chemical propellants), low thrust level, long operating duration due to the low thrust (typically $5 \cdot 10^3$ h), electrical power conversion and finally the necessity of ion beam neutralization in the case of electrostatic systems in order to avoid electrostatic charging of the spacecraft.

On the other hand, the inherent characteristics of electric propulsion offer specified domains of their application in space missions:

- Orbit control or stationkeeping of geostationary satellites
- Disposal of spent or failed satellites from geostationary orbit
- Atmospheric drag compensation of low orbit spacecraft
- Interplanetary space missions with high energy demand
- Control of spacecraft charging

The slit emitter module

The slit emitter module in principle consists of two symmetrical highly polished metal plates of the shape depicted in Fig.1. In one or both of the emitter halves there is milled a recess to be of use as a reservoir of the liquid metal supplied to the emitter module by a feeding capillary tube. On certain regions of one of the inside faces there is sputter deposited a layer of nickel with a thickness of the order of 10^{-6} m. When the two halves are tightly clamped together they are separated by the thickness of this layer, thus forming a narrow slit through which the liquid metal can flow and be transported to the edges of the slit by the action of capillary forces. The material used for the emitter fabrication is stainless steel and, more recently, Inconel X750 which has shown better wetting characteristics for caesium, the liquid metal used for most of the emitter tests because of its superior wetting characteristics, low melting point and high atomic mass.

Thruster, propellant system and power conditioning unit

The FEEP thruster basically comprises the emitter which is kept at a positive voltage, the accelerator, kept at negative voltage and which is used as a counter-electrode to establish the field needed for ionization and finally the neutralizer in order to avoid electrostatic charging of the spacecraft. As illustrated in Fig.2, the complete FEEP system comprises:

- One or more thrusters and neutralizers
- A propellant system
- A power conditioning unit

The proposed neutralizer for the future development is a plasma bridge neutralizer fed also by caesium which can be operated with very low mass flow rates of approximately only 4% of the main flow rate or less. The propellant tank is a metallic bellows device pressurized for caesium expulsion by heated zeolite. The power conditioning unit consists of a thruster dedicated power supply module utilizing advanced technology in power conversion.

The main advantages of a propulsion system based on the field emission principle are:

- Mechanical, electrical and operational simplicity
- Emitter clustering capability
- Continuous thrust throttling from zero to maximum
- Active control of the spacecraft potential by the neutralizer

Fig.1: Slit emitter module
in original size

Fig.2: Basic design of
the FEEP-system

II. THE FIELD EMISSION ELECTRIC PROPULSION SYSTEM

In 1972, the European Space Agency (ESA) started the development of an advanced concept of electric propulsion based on the field emission principle; the application of this principle in liquid metal ion sources (LMIS) has resulted in a high specific impulse ion thruster called FEEP (Field Emission Electric Propulsion). This activity has been carried out at the European Space Research and Technology Centre (ESTEC) in Noordwijk under the ESA Technological and Research Programme /1/. Major activities in research and development sponsored by ESA furthermore are being pursued at the Société Européenne de Propulsions (F), at the Fulmer Research Institute (UK), at the University of Pisa (I) and finally at the Technical University of Vienna (A).

The field emission principle

In a field emission electric propulsion system the ions being expelled are created directly from the surface of a liquid metal 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 which protrude more and more from the surface with increasing field strength. The onset of ion emission occurs when the applied total voltage between the emitter and accelerator electrode is in excess of a critical value which is called the onset voltage. When the field reaches values of the order of 10^7Vm^{-1} , atoms of the metal tip are ionized either by field evaporation or field ionization; the free electrons are rejected into the bulk of the liquid metal while the ions are accelerated and expelled from the emitter by the same electric field which has ionized them, creating therefore the thrust. Because the radius of curvature at the apex of such a cone is of the order of 10^{-7}m or less, applied voltages of the order of 10^3V are sufficient to obtain the required high electric fields.

Considering one of the most advanced physical models of the ion emission process /2/, field evaporation is claimed to be the dominant mechanism of ion formation, but it also was found that thermal evaporation followed by field ionization may make a significant contribution to the total ion current. Field ionization, unlike field evaporation, can occur also in a region of the order of 10^{-7}m wide above the apex of an emitting cone, where thermally evaporated neutral atoms and clusters (also emanating from the shanks of the cone) were attracted by polarization forces. Contrary to field evaporation, the field ionization mechanism gives rise to singly charged ions only. Bearing in mind finally the obviously inherent feature of this mechanism to emit beneath atomic ions and molecular ions of minor percentage /3/ even charged clusters and microdroplets (the diameter of the latter ranging between 10^{-7}m to 10^{-6}m), a new scope for speculation on vapor production processes is offered. Experimental evidence on neutral emission support the view that virtually all of the neutral mass is emitted as microparticles /3/, /4/, /5/. These are interpreted as aggregates of neutral atoms carrying a surface charge such that the inward surface tension forces approximately are balanced by the outward electric forces. It is known that for microparticles with diameters less than about $2 \cdot 10^{-7} \text{m}$ the effective surface tension decreases as a result of the gross curvature of the liquid surface /5/. One would expect therefore that microparticles in this range would be unstable and would dissociate under the outwards electric forces, contributing probably to the supply of neutral atoms and clusters mentioned above.

The typical FEEP thruster performance is summarized in Table 1:

Range of emitter length	3 to 8cm
Emitter slit width	$1,1 \cdot 10^{-4} \text{m}$
Range of emitter voltage	1 to 10kV
Range of accelerator voltage	-4 to -8kV
Thrust per unit length	$3 \cdot 10^{-4} \text{Ncm}^{-1}$
Power to thrust ratio	$5,5 \cdot 10^4 \text{WN}^{-1}$
Specific impulse	$6 \cdot 10^4 \text{Nskg}^{-1}$
Mass efficiency	60%
Power efficiency	98%

III. EMISSION PERFORMANCE OF THE FEEP SYSTEM

Recent investigations have demonstrated the outstanding importance of both the residual gas atmosphere and the emitter preparation technique on the emission performance of FEEP thrusters /4/,/6/. In addition, very recently, the capability of FEEP thruster operation in the pulsed mode has been demonstrated, thus opening the possibility of utilising this system for new domains in application like extreme fine positioning of spacecraft /7/.

Emission site distribution and specific thrust

If the slit emitter is filled with liquid metal and the surfaces of the slit are uniformly wetted, a homogeneous linear liquid tip of semicylindrical shape is assumed to exist at onset conditions. Enhancing the electric field, this tip is distorted; equidistant spaced emitting sites are originating along the extension of the emitter slit, each of them contributing to the ion beam.

In order to maintain these conditions, the emitter is heated and outgassed at an ultimate background pressure of about $5 \cdot 10^{-10} \text{mbar}$ and then is supplied with caesium of extreme purity. Complete and perfect wetting is obtained, resulting in an instantaneous firing of the emitter and being characterized by a nearly homogeneous distribution of equidistant emission sites, the linear density of the latter being about 1200 cm^{-1} . The measured spacing of about $7,5 \cdot 10^{-4} \text{m}$ is in good agreement with calculations according to a standing wave theory of surface instabilities /6/.

Fig.3: Equilibrium configuration of a liquid metal conductor in an electric field of cylindrical symmetry
 (a) Electrode configuration
 (b) Axially symmetrical varicose mode of the liquid metal

The mathematical treatment of this problem has been discussed in some detail /8/,/9/, considering especially standing wave perturbations with no time variations. Among these, the analysis of a cylindrical case seems to be of special relevance to the slit emitter, where it is assumed that the initial shape of the linear liquid metal tip just before emission onset is of semicylindrical geometry. One considers an infinitely long circular cylinder of radius r made of liquid metal to be placed in a hollow metal cylinder of radius R as it is outlined in Fig.3(a). The initial pre-perturbation equilibrium condition is given

$$\epsilon_0 E_0^2 / 2 = \sigma / r \quad (1)$$

where E_0 is the initially uniform electric field at the surface of the liquid cylinder and σ the surface tension of the liquid metal. A small perturbation r' of the radius is applied which is assumed to be sinusoidal in both θ and z ; Laplace's equation then is solved for the resulting perturbed potential Φ'

$$\Phi' = H(r') \exp(jm\theta) \exp(jkz) \quad (2)$$

where $H(r')$ is a Hankel function. For the mode $m = 0$ which is the normal axially symmetrical varicose mode shown in Fig.3(b) there exist two solutions

$$k_1 r = 2 \quad \text{and} \quad k_2 r = 0,2 \quad (3)$$

Considering the relation

$$k = 2\pi/\lambda \quad (4)$$

the resulting wavelengths of the varicose mode are

$$\lambda_1 = \pi \quad \text{and} \quad \lambda_2 = 10\pi \quad (5)$$

In order to decide which of the two perturbation wavelengths may apply, a comparison was made between the results of a standing wave approach for the plane case /10/ and the present values; as the smaller wavelength λ_1 corresponds quite well with the former results, this value was selected for the further considerations.

The capability of such a thruster to operate at rather high values of the specific emission current of $5 \cdot 10^{-3} \text{ Acm}^{-1}$ and more without any current saturation was demonstrated successfully /6/. The calculated specific thrust of about $7 \cdot 10^{-4} \text{ Ncm}^{-1}$ resulting for this specific current is considerably above the values measured for a comparable thruster at ESTEC.

Pulsed operation mode

The need for ultra-fine attitude control of spacecraft for future scientific missions and the unique combination of low thrust and extremely fast switching capability offered by a FEEP thruster had stimulated the interest on the FEEP system performance when operated in the pulsed mode; therefore several dedicated experiments have been carried out to assess the emission characteristics of a FEEP thruster operating with a pulsed power supply unit/7/:

The pulse characteristics of voltage and current follow quite closely the corresponding values of FEEP thrusters operated in the continuous mode. Several pulse frequencies ranging from 50 to $5 \cdot 10^{-4} \text{ Hz}$ have been explored; the minimum pulse length which can be achieved is in the range of 10ms with emission currents of about $3 \cdot 10^{-3} \text{ A}$; this is equivalent to a thrust level of $3 \cdot 10^{-6} \text{ N}$ and an impulse bit of $3 \cdot 10^{-8} \text{ Ns}$ which is far beyond the capabilities of any chemical propulsion system.

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