PROSPECTS OF MICROSTRUCTURED LIQUID METAL ION SOURCES (MILMIS) FOR FIELD EMISSION ELECTRIC PROPULSION (FEEP)

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Abstract

Liquid metal ion sources (LMIS) have a wide range of applications in focused ion beam technology. A special type of LMIS is the liquid metal ion thruster developed at the European Space Research and Technology Centre (ESTEC) for field emission electric propulsion (FEEP). Combining this technology with the microfabrication techniques developed in the new technical field of vacuum microelectronics, there results the concept of "Microstructured liquid metal ion sources (MILMIS)".

The most simple method to create a MILMIS is in situ wicking and wetting of a porous sintered metal emitter from a liquid metal reservoir. A pilot experiment on such a MILMIS with cesium has been performed in order to prove its capability as a FEEP-thruster for steady-state and pulsed operation.

Introduction

At the European Space Research and Technology Centre (ESTEC), a field emission electric propulsion (FEEP) system based on the liquid metal ion source (LMIS)-principle with cesium as the propellant progressively has been developed and evolved from a single-pin emitter, through linear arrays of stacked needles to the presently favored slit emitter module. Homogeneous high current ion emission from a micron-sized slit has been demonstrated successfully, allowing the occurrence of a linear series of equally spaced emitting sites with a distance of less than 10^-3 m and a linear current density of more than 5x10^-4 Am^-2. Compared with other electric propulsion systems, FEEP is characterized by the highest values of power-to-thrust ratio (5.5x10^-9 W N^-1) and of specific impulse (6x10^5 s).

The work mainly was dedicated to a system operated in a continuous mode; recent tests have proved that the FEEP system can easily be operated in a pulsed mode with a very high pulse repeatability.

This has opened a new range of applications for FEEP, i.e., drag compensation and attitude and orbit control of scientific spacecraft for astronomy missions, earth observation, interferometry in space, and microgravity experiments. All these missions require a very fine attitude (milli arc seconds) and orbit control (relative positioning of several satellites to millimeter accuracy). This is a domain of application on which the FEEP system can claim several advantages compared with chemical or other electric propulsion systems, i.e., continuous thrust, throttling, small impulse bit, instantaneous switch-on/switch-off capability, mechanical and electrical simplicity, and thruster clustering.

However, the use of condensable liquid metal propellants such as cesium has caused reluctance on the part of potential users because of their concern over spacecraft contamination and launch-safety issues. Nearly all these areas of concern are eliminated, or at least substantially moderated, by the use of inert gas propellants such as xenon. Unfortunately, these propellants are not practicable for a FEEP-system.

Nevertheless, for the future there appear interesting prospects for electric propulsion using LMIS-thrusters. Contamination problems are moderated for spacecraft without solar energy conversion power supplies; that applies especially to prospective spacecraft with nuclear electric propulsion (NEP) systems, e.g., the SP-100 Flight Experiment or the NERVA Derivative Reactors, which may show reduced launch-safety issues concerning liquid metal propellants. Such planned nuclear power systems can provide electric power in space from tens to hundreds of kilowatts, and with advanced conversion systems, into some tens of megawatts, which
is necessary for energetic, high-velocity-change interplanetary missions.

A crucial requirement for the use of LMIS for NEP is the production and development of the present linear slit emitter module towards a high power LMIS-thrust. The conversion of the linear array of emission sites into a two-dimensional large-area emitter array, using a microstructured substrate which is wetted by a liquid metal film, recently has been proposed within the concept of "Miniaturized liquid metal ion sources" with prospective terrestrial and space applications.

However, NEP is not the only space application for microstructured liquid metal ion sources.

The FEEP linear slit emitter is a semi-miniaturized liquid metal ion source and represents an ultimate development in precision mechanics, demonstrated by a value of about $10^{-6}$m for both the slit width and the round-off radius of the emitter slit edges. The application of microfabrication technology to the development of vacuum field-effect devices offers an interesting alternative to the present slit emitter technology. The development of microfabrication techniques to form miniaturized field-electron and field-ion sources has resulted in a new class of efficient, low voltage, cold electron and ion sources and the emergence of a rapidly growing new technical field that has come to be known as vacuum microelectronics.

The idea of adapting this technology to LMIS for micro-thrust-propulsion or spacecraft surface-charge neutralisation therefore is obvious.

**Liquid Metal Ion Sources**

In a liquid metal ion source (LMIS) the ions being expelled are not created by electron bombardment of a gas or of a metal vapor, but they 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. With increasing applied voltage, the radius of curvature at the apex of these cones becomes smaller and smaller, and therefore the liquid electric field at the tip becomes larger and larger.

When the local field reaches values of the order of $10^{4}$Vm$^{-1}$, atoms of the metal tip are ionized either by field evaporation or field ionization. With the proper polarity, 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. The charged particles leaving the liquid metal surface as an ion beam are replenished by the hydrodynamical flow of the liquid metal. The liquid metal more or less is converted directly into an ion beam without the transitional vapor phase which is common in the technology of other ion sources; therefore ionization operates with high power efficiency.

Because the radius of curvature at the apex of such a cone is about $10^{-7}$m or less, for interelectrode spacings of some $10^{-3}$m applied voltages of some $10^{3}$V are sufficient to obtain the required high electric fields. A rough criterion for onset of ion emission is given by the assumption that electrostatic forces and surface tension forces are in balance.

Stable and exceedingly bright ion emission with a rather low energy spread from an extremely small apex region of the liquid metal cone characterizes the ion beam and result in some unique applications which never may be met by other ion sources. Single-site ion emission with currents up to several $10^{-6}$A may be obtained with a brightness in excess of $10^{7}$Acm$^{-2}$sr$^{-1}$.

![Fig.1](image_url)

**Fig.1**: Schematic diagram of different types of liquid metal ion sources: (a) pin or needle type; (b) tube or capillary type; (c) elongated slit type. Left: shape of the liquid metal tip without electric field. Right: distortion of the liquid metal tip by an electric field due to a positive emitter potential $+U_e$ and a negative accelerator potential $-U_{acc}$ versus common ground.
In LMIS, ion beams can be created from liquid metal wetted needles (or arrays of needles) or from capillaries into which the liquid metal is allowed to flow. As in the case of the slit emitter, the capillary is elongated to a long slit of nearly rectangular cross section, allowing therefore the occurrence of a series of emitting cones, each of them contributing to the ion beam. This different types of ion beam emitters schematically are outlined in Figure 1.

An alternative concept is the impregnated-electrode-type LMIS \(^1^1\) with a porous ion emission tip made of a refractory metal. Typically the porous tip is formed by sintering tungsten powder; this porous material is machinable and it is easy to fabricate multiple ion-emission points. The ion source has a cylindrical reservoir for liquid metal, which also serves as a heater for melting the metal to be ionized.

Figure 2 shows the structure of three kinds of impregnated-electrode-type LMIS: Source A is the prototype, source B has most of its porous tip surface covered for ionizing high vapor pressure metals, and source C has multi-point emission tips for high current operation.

It has been shown that sintered porous materials can be used to control the liquid flow as well as a means for reducing the surface area of liquid metal, and thereby reducing the vaporization rates of volatile liquid metal atoms from the surface \(^1^2\). After successful extraction of metal ion beams from more than ten elements with currents up to approximately 5x10^-4A, efforts were made to increase the total ion current by increasing the number of emission sites. Using this approach, germanium ion currents of about 4x10^-3A were obtained from a source equipped with a linear array of eight ion emission points equally spaced at a distance of 1.4x10^-2m \(^1^2\). The corresponding linear current density of about 4x10^-1Am^-1 is comparable with the results for a slit emitter using Cs as liquid metal \(^2\).\(^3\).

**Large-area microstructure liquid metal ion sources (MILMIS)**

As mentioned before, within the new technical field that has come to be known as vacuum microelectronics, microfabrication techniques have been developed to produce micron-sized cones, wedges, and microvolcanos as well as linear and two-dimensional arrays of these microstructures \(^1^0\). Such a substrate with an array of cones or wedges covered by a liquid metal film and opposed to a planar counter-electrode is of considerable interest, as such a device complies with a recent theoretical study on large-area LMIS \(^1^4\). In this case, the originally planar liquid metal surface which is thought to be distorted into a sharply peaked structure by hydrodynamically driven instabilities, will be superseded by the array structure covered with liquid metal with the apices of the cones or wedges as preferential emission sites.

The most simple method to create such an array structure covered with liquid metal is in situ wicking and wetting of a porous sintered metal from a liquid metal reservoir; this method has been applied to a lithium LMIS for inertial confinement fusion experiments \(^1^2\). The similarity of this concept to the impregnated-electrode-type LMIS is obvious; the only difference is in using the intrinsically roughness of the sintered metal surface instead of machined points as potential emission sites.

**Pilot experiment on a cesium-MILMIS**

In order to prove the applicability of the concept of MILMIS to cesium which is the liquid metal propellant exclusively used with FEEP, a pilot experiment just recently has been performed with a 5mm diameter Cs-MILMIS inserted instead of a 1.5cm-ESTEC slit emitter into the ultra-high vacuum facility used in previous FEEP experiments \(^3\).

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**Fig.2:** Three kinds of impregnated-type-liquid metal ion sources \(^1^2\). A: prototype; B: for high vapor pressure metals; C: for multi-point emission. The diameter of the reservoir is 2mm, and the length is 20mm.

**Fig.3:** Schematic sectional view of the emitter-accelerator configuration of the MILMIS. 1: porous metal disc; 2: emitter body; 3: cesium reservoir; 4: accelerator electrode; 5: accelerator grid.
Experimental facilities

A sectional view of the emitter-accelerator configuration of the MILMIS is shown in Figure 3. A porous metal disk (1) of 5mm diameter and 2mm thickness made of sintered Inconel with a grain size between 1-5x10^{-5}m and a grain density of about 400mm^{-2} is pressed tightly into the stainless steel emitter body (2). Cesium is supplied to the reservoir (3) on the rear of the porous metal insert by a totally closed Cs-feeding system involving capillary forces. The accelerator electrode is a stainless steel plate (4) with a tapered aperture; on the rear there is stretched a stainless steel grid (5) with a mesh width of 2mm. The interelectrode distance (grid to porous emitter surface) is 2mm.

The emitter-accelerator unit is mounted on a pivoting cradle, the axis of rotation being coincident with the emitter surface. Tilting the emitter-accelerator unit by 90°, the distribution of emission sites on the emitter surface may be observed by means of a high resolution microscope system within a tubular extension re-entrant window attached to the vacuum facility.

Heating of the emitter is by means of a coil-shaped tungsten filament, allowing both radiation heating for normal emitter operation (30-100°C) as well as electron bombardment heating for outgassing the emitter at 450°C before Cs-supply. The total pressure within the vacuum facility without operation of the MILMIS is of the order 10^{-7}mbar.

![Fig.4: Schematic of the electric circuitry of the MILMIS. ACC: accelerator; E: emitter; CS: cold shroud; C: high voltage capacitor; Rs: low-inductance shunt; UE: emitter voltage; UACC: accelerator voltage](image)

![Fig.5: Current-voltage characteristic of the MILMIS depending on the emitter temperature Te. The dash-dotted line shows the corresponding characteristic for a 1.5cm-ESTEC slit emitter.](image)
comparison, the current-voltage characteristic typical for a 1.5cm-ESTEC slit emitter LMIS with a slit width of 1.2x10^-m is also indicated in this diagram. Although the principal shape is similar, the whole characteristic is shifted to considerable higher values of the total voltage.

This may be mainly due to the quite different emitter geometry showing an enhanced interelectrode distance for the MILMIS; furthermore, there exists a remarkable influence of the flow resistance of the emitter for liquid Cs on the current-voltage characteristic. The latter is corroborated by the dependence of the current-voltage characteristic on the emitter temperature, as with enhanced temperature the viscosity of Cs and therefore the flow resistance decreases.

Emission site distribution: The individual emission sites on the emitter surface are characterized by a more or less bright glow. An analysis of photomicrographs with an image field of 0.5mm diameter shows approximately 50 emission sites at a total emission current level of about 1x10^-A; therefore results for the total emitter surface with 5mm diameter a number of about 5000 individual emission sites with an average emission current of 2x10^-A.

Assuming for simplicity that each grain at the sintered emitter surface is a potential emission site, with a grain density of 400mm^-3 there results a calculated number of 8000 potential emission sites; the efficiency of the micro-structured emitter surface to maintain individual emission sites therefore is about 60%.

High current pulse operation: Pulse operation of the MILMIS is obtained by applying a negative high-voltage pulse to the accelerator, while the emitter is connected to a low-inductive high-voltage capacitor C with a capacity of 2000pF at a charging voltage U_C of 10-12kV; the steady state emitter current is about 1-3x10^-9A. The high voltage pulse is supplied by a coaxial cable pulse generator; the pulse voltage U_{ACC} is between 5-15kV, the pulse width is 6x10^-7s with a rise time of about 1x10^-7s.

The resulting high current pulse discharge shows a damped oscillation with a frequency of approximately 4.2MHz and a duration of about 6x8x10^-7s. Depending on both the charging voltage and the pulse voltage, the maximum peak current is between 9x10^-9A and 1.4x10^-9A with a maximum increase of 1.7x10^-9A^-1.

These results prove the capability of the MILMIS to operate in a pulsed mode at a current level which is orders of magnitude above that for steady-state operation, and with an increase of current which also exceeds by orders of magnitude the values obtained hitherto for a conventional slit emitter.

Conclusions

Although just a pilot experiment on a MILMIS with a porous sintered emitter has been performed, several important conclusions can be drawn from this experiment.

(1) Similar to an impregnated-electrode-type LMIS, the porous sintered emitter of a MILMIS can be used to control the flow as well as to reduce the surface of the liquid metal, and thereby reducing the vaporization rate of volatile liquid metals like cesium.

(2) Compared with the slit emitter module, the MILMIS is simple to fabricate in any size and shape.

(3) The MILMIS easily can be subdivided into individual sections for independent operation or as spare thrusters.

(4) The MILMIS is qualified to pulsed power technology applications. An interesting feature would be a thruster for prospective nuclear electric propulsion.

References


