Literature Study of Field Emission Electric Propulsion Microthruster

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Abstract - *The advancements in propulsion techniques have facilitated notable augmentations in the area of reach of outer space. Despite of the present-day technological limitations and need for the state-of-the-art metallurgical aspects, advanced propulsion systems seem to be very promising in providing high specific impulse to realize the dream of deep interplanetary projectiles. One of such advanced propulsion concepts is Field Emission Electric Propulsion (FEEP) system which is a form of ion thruster using liquid metal i.e. Cesium, Indium or Mercury, as an ion source. The basic concept of the system is field ionization of a given liquid metal and subsequent acceleration of the ions to high velocities by the utilization of a strong electric field. FEEP system offers various unique technical features such as high specific impulse, sub-μN to mN thrust range, instantaneous switch-on/ switch-off capabilities, compact size and better propellant storage characteristics. FEEP system had emerged out as an outstanding candidate as a propulsion system for microthrusters to assist with attitude control and orbit maintenance maneuvers of satellites. In this study, an effort has been made to briefly review FEEP technology and its application potential for commercial and scientific missions.*

Key Words: *Electric Propulsion Systems, Field Emission Electric Propulsion, Advanced Propulsion Concepts, Microthrusters*

1. INTRODUCTION

The passion for reaching deeper in space more efficiently and effectively has led to the boosted development in the field of Electric Propulsion systems. The augmented interest in Electric Propulsion (EP) systems results from a certain number of advantages this system offers with respect to other propulsion system for the same thrust levels [1]. Electric Propulsion technologies, as the name implies, make use of electrical power to accelerate the working fluid i.e. liquid metal propellant by means of electrothermal, electrostatic or electromagnetic processes [2]. The use of electrical power enhances the propulsive performances of the EP thrusters when compared with conventional chemical thrusters in which molecular bond energy is utilized for thrust generation. In chemical propulsion systems the energy is stored within the system while EP systems utilize an external source for the generation of driving force. Unlike as is in chemical propulsion systems, EP systems require a very little mass of propellant to accelerate a spacecraft. Generally, propellant is ejected up to twenty times faster than from a conventional chemical thruster which makes the overall system many times more mass efficient which is measured by the term *Specific Impulse* (I_{sp})[3]. When compared to the EP systems which generally have the values of I_{sp} in thousands of seconds, conventional chemical propulsion systems have I_{sp} values in the mere range of 250-450 seconds.

Owing to the significant propellant savings from the use of EP systems providing high specific impulse (thrust/ propellant flow rate >1000 s), difficult planetary missions with smaller launch vehicles had become possible which greatly influence cost-constrained exploration missions. Low requirement of propellant mass greatly reduces overall spacecraft size and weight. Thus, high specific impulse EP technology represents an obvious design approach for micro-scale spacecraft [4].

EP systems are generally classified in three main categories: Electrothermal propulsion systems (resistojets, arcjets, etc.), Electrostatic propulsion systems (gridded ion engines, Hall-effect thrusters, field-emission thrusters, etc.) and Electromagnetic propulsion systems (magneto-plasmadynamic thrusters, pulsed plasma thrusters, etc.). A particular type of electrostatic propulsion system, called as Field Emission Electric Propulsion (FEEP) systems, has lately been a topic for ongoing research.

Modern Earth observation as well as interplanetary missions demand for ultra-precise attitude and orbit control of spacecraft and satellites. In early 90's, FEEP system was acknowledged as the only prevailing thruster capable of precise thrust modulation in the 1 μN - 1 mN thrust range [5]. Figure 1 represents the specific impulse range and thrust levels for various types of propulsion systems [6].

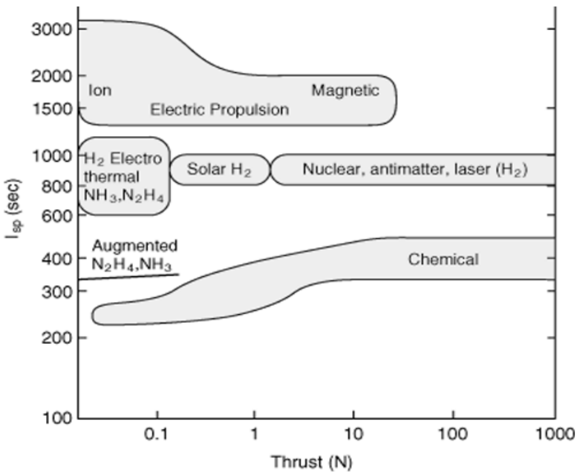

Figure 1: Specific Impulse and Thrust Range of Different Propulsion Systems

FEEP system is a very promising concept that provides specific impulse in the range of 4000 – 11000 s and offers a wide range of application fields including several commercial applications such as small satellite's attitude and orbit control, along with drag free control and precise pointing of scientific spacecraft [7]

It is the purpose of this article to briefly outline the working concept of FEEP system, factors influencing propellant selection and to review its technical developments, current status and potential forthcoming applicability as the future of microthrusters.

2. WORKING CONCEPT

The physical principle governing the operation of FEEP system is the *Field Effect* which refers to the utilization of a strong electric field to generate a spray of charged ions and/or droplets. The potential difference between the electrode and the liquid metal propellant's free surface is balanced by the surface tension of the fluid. As a result, the surface deforms to an equilibrium shape of a cone. The strong field intensity at the tip of the cone causes the formation of a propellant spray or jet or stream, which is composed of ions. This propellant stream is then expelled at high velocities through a micrometric slit emitter with the help of an accelerator followed by charge neutralization of the propellant stream [8].

In general, the FEEP system comprises of a propellant reservoir, a slit emitter, an accelerator, a power source and a neutralizer generally assembled as depicted in Figure 1.

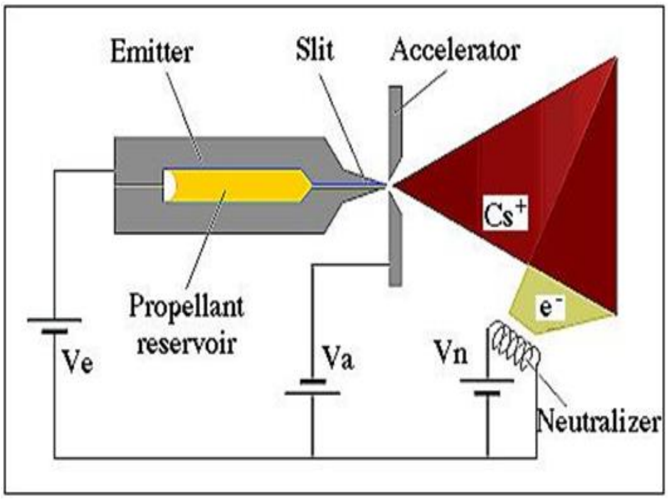

Figure 2: FEEP System Assembly

The cylindrical reservoir which has merely a length of 5 cm and a diameter of 10 cm reserves the liquid metal propellant in it and is connected to the generator (i.e. electric phase). There exist diverse slit emitter configurations such as the needle or the capillary but the governing principle of all configurations is identical. In the slit emitter, liquid metal propellant is fed by capillary forces through a narrow conduit. The slit emitter is made up as two identical halves, usually made from stainless steel, and which are clamped or screwed together. A nickel layer, deposited onto one of the slit emitter halves, outlines the preferred conduit contour and governs conduit's height (i.e. slit height, typically in the range of 1-2 μm) and conduit width (i.e. slit length, ranging from 1 mm up to about 7 cm) [9]. Slit emitters had been developed to enhance the emitting area of the thruster which led to yield higher thrust levels while diminishing the issue of irregular behavior observed during the use of single emitters. The slit emitter usually carries a positive potential while the accelerator is at negative potential. The electric field, thus generated between the slit emitter and accelerator, acts on the liquid metal propellant.

The accelerating electrode (accelerator) consists of a metal plate where two sharp edges are machined, positioned directly in front of the slit emitter. When thrust is required, a strong electric field is generated by the application of high voltage difference between the slit emitter and the accelerator using a power source. Figure 2 depicts the baseline relationships for voltage and needle curvature [10].

Under such condition, the free surface of the liquid metal propellant encounters local instabilities due to the collective effects of the electrostatic force and the surface tension leading to the formation of series of protruding cusps or "Taylor cones". The atoms at the tip of these Taylor cones spontaneously ionize when the electric field reaches a value in the range of 10^9 V/m, an ion stream is extracted by the electric field. An external source of electrons which is also called as a neutralizer is employed in the system to provide a stream of negatively charged ion to maintain electrical neutrality of the propellant stream and the thruster assembly [11].

3. MINIMUM VOLTAGE REQUIREMENTS

A critical minimum electric field is required for the ion emission to positively take place. Experimentally, emission has been demonstrated at an extractor electrode distance of 200 μm and a 10 kV potential, although any combination that develops an electric field of approximately 10^9 V/m causes ions to begin streaming for indium tipped emission [11]. As the tip radius of curvature decreases, the local electric field increases; ion emission occurs at voltage U_0

Mathematically,

$$U_0 = \ln (2d_{te}/r_c) \sqrt{(r_c\sigma/\varepsilon_0)}$$

Where, r_c is the needle radius of curvature and d_{te} the tip to electrode distance. Figure 3 represents the relationships for voltage and needle curvature [12].

4. PROPELLANT SELECTION AND CONSIDERATIONS

Several researches and studies have been carried out to highlight and summarize the various physical, chemical, electrical and mechanical characteristics of an ideal propellant for FEEP system [13]. The selection of the ideal propellant is intensely influenced by numerous crucial features like low melting temperature, lowest ionization potential, low surface tension, high atomic mass, non-toxicity and related environmental concerns with the handling and storage of the propellant [14, 15].

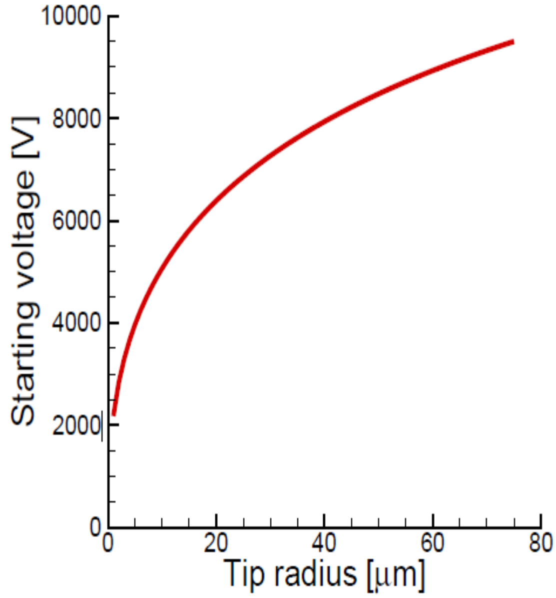

Figure 3: Minimum Electrode Potential vs. Needle Tip Radii of Curvature

A European Space Agency (ESA) panel in 1980 initially identified the minimum acceptable atomic mass for any potential propellant as that of cesium with a mass of 133 AMU but a lower secondary standard of 100 AMU was also adopted in successive years [16]. Subjected to an intense electric field and to undergo a pure *Field Effect*, the propellant must emit individual ions rather than droplets or clusters [17]. The choice of a hazardous, toxic, explosive liquid such as Cesium as propellant considerably upsurges the ground system financial burden to safely handle and contain carcinogens [18].

A large number of different liquid metals or alloys can be selected to be used as propellant in FEEP system. Alkali metals with high atomic weight i.e. Cesium, Rubidium, etc. may deliver commendable performance in terms of thrust efficiency and power-to-thrust ratio. These propellants have a low ionization potential, low melting point and have extraordinary wetting capabilities. These characteristics result in lower power losses in heating, melting and ionization and due to their capability to utilize capillary forces for feeding purposes eliminating the need of pressurized tanks or valves. Alkali metals have minimal attitude to form ionized droplets or clusters, thus increasing the mass efficiency significantly. A beam of singly-ionized cesium or rubidium atoms, produced by field evaporation at the tip of the slit emitter, generates the thrust. Table 1 tabulates and compares the physical properties of few preferred liquid metals as propellant for FEEP system.

Table 1: Physical Properties of Few Liquid Metals

Name	Rubidium	Indium	Cesium	Mercury
Atomic Number	37	49	55	80
Atomic Weight (u)	85.467	114.818	132.9	200.592
Element Category	Alkali Metal	Post-transition Metal	Alkali Metal	Post-transition Metal
Melting Point (°C)	39.3	156.6	28.5	-38.829
Boiling Point (°C)	688	2072	671	356.73
Density (g/cm^3)	1.532	7.31	1.93	13.564
First Ionization Energy (kJ/mol)	403	558.3	375.5	1007.1
Second Ionization Energy (kJ/mol)	2632.1	1820.7	2234.3	1810

The chosen propellant should melt at readily achievable temperature without acquiring a substantial power demand. Normally, this has been around 100-300°C. The propellant should have a low vapor pressure to allow the propellant to be emitted in a stream instead as a non-accelerated mist. This dispersion lowers mass efficiency and increases deposition rates upon the spacecraft itself. The capillary flow rate along the surface of a needle needs to be large enough to allow constant emission at relatively higher currents of 100μA [19].

Physical characteristics such as ionization energy, work function and surface tension contribute to the initial potential needed to induce field effect. Lower beginning voltages reduce power and secondary equipment mass requirements. The propellant should flow readily along capillary feed systems and maintain liquid films from which emission occurs. It must be able to wet the reservoir feed system and slit emitter materials very efficiently [20].

Among all the requirements for alternative propellant to Cesium, reliability is the most critical. Arcing or flashover may result in irreversible damage to the whole FEEP system, thus further declining the reliability and lifetime.

In last decades, many studies and experiments has been conducted to utilize Indium as propellant due its high atomic mass, low ionization potential and its good wetting properties. The Indium FEEP is built by the Austrian Research Centre in *Seibersdorf* (Austria). Indium can be handled in atmosphere with minimum to no risk which greatly simplifies testing and also eases complex sealing procedures prior to launch. Another noteworthy advantage of Indium as propellant is the fact that Indium is solid during launch due to its melting point at 156°C. Indium offers extensive improvements in usability with only mild degradation in performance, and is therefore considered a better candidate in propellant selection. Indium provides an additional characteristic that Indium's exposure to air does not result in explosion or hazardous out-gassing [21].

5. DEVELOPMENTS AND CURRENT STATUS

The history of EP systems has spanned over a century and filled with significant discoveries. The benefits of electric over chemical propulsion were first pointed out by Robert H. Goddard in 1906 [22]. Field emission driven by electrostatic forces has been studied for decades, first being analyzed by Schottky in 1923 [23]. Field-ion emission from metal surfaces was examined initially by Tsong and Muller [24].

Along the last decade, FEEP is being tested and developed by *Centrospazio* under ESA funding. Much experimental data on FEEP emitter performance is already available, especially in the 1-100 μN thrust range [25]. The electrical efficiency of FEEP is about 98 %, vs. much lower values of all other electric engines. NASA's Jet Propulsion Laboratory (JPL) and ARCS have concentrated on scaling the ion emission to the $150\mu N$ thrust range.

FEEP has been base-lined for LISA3 (Laser Interferometer Spaceborne Antenna, low-frequency gravitational wave detector, a Cornerstone mission in ESA's Horizon 2000+ programme), OMEGA4 (Orbiting Medium Explorer for Gravitational Astrophysics, a JPL proposal for the NASA MIDEX programme) and GG-Galileo Galilei5 (a small satellite for testing the equivalence principle, under pre-phase A study at ASI), and has been considered for several other missions including ESA's Darwin and GAIA, etc.

A dedicated field emission thruster called In-FEEP based on space-proven miniaturized Indium Liquid-Metal-Ion-Sources (LMIS) had been under development since 1995. Developed more than 20 years ago, Indium LMIS were first successfully tested on-board of the Russian MIR space station in 1991 and have since flown on a number of satellites as part of a spacecraft potential control and mass spectrometer device [26].

LISA (Laser Interferometer Spaceborne Antenna) Pathfinder is an ESA spacecraft, equipped with FEEP subsystem, to be launched in 2015. It will not use ion thrusters as its primary propulsion system, but will use both colloid thrusters and FEEP for very precise altitude control [27]. The LISA Pathfinder FEEP Subsystem has been developed to embark two different FEEP thrusters technologies currently under qualification in Europe: one using slit-shaped emitter with Cesium as propellant and the second using a needle-shaped emitter with Indium as propellant. The LISA Pathfinder Micro-Propulsion subsystem comprises of three main parts, called Micro Propulsion Assembly (MPA): each one consisting of one FEEP Cluster Assembly, one Power Control Unit (PCU) and one Neutralizer Assembly (NA). The FEEP Cluster Assembly consists of a self-contained unit of 4 FEEP thruster assemblies, which include propellant reservoir, mounted on a support structure [28].

Many aspects of electric-propulsion technology still need to be mastered and the European effort in the coming years will concentrate on these areas. Space agencies, satellite prime contractors and equipment manufacturers in Europe have already identified electric propulsion as a key technology for the future of space missions.

6. INHERENT TECHNOLOGICAL LIMITATIONS

Owing to the fact that FEEP systems are capable of producing thrust forces in the range of few μN to mN only, the application of FEEP systems has been restricted to serve as a secondary propulsion system and they are dependent on chemical propulsion systems for positioning them into orbit.

The other noteworthy technological restriction of FEEP systems is the requirement of electricity-producing equipment onboard. The operation of FEEP system requires a very large potential difference which has to be generated onboard. The inevitable requirement of such equipment significantly increases the size and weight of the overall propulsion system.

7. CONCLUSIONS

FEEP system has offered and secured a promising application field on small-to-medium sized spacecraft, with mass ranging from a few hundred to about 1000 kg and orbital altitudes of 700 km or higher. In comparison with other EP systems, FEEP system delivers the highest thrust-to-power ratio and best specific impulse. Continuous research and developments are contributing to build confidence in the use of FEEP technology. In the nearby future, FEEP will eventually enter the operational scenario and contribute to broaden the field of applications of electric propulsion.

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