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Performance of propellant for ultrasonically aided electric propulsion

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ABSTRACT

Ultrasonically aided electric propulsion (UAEP) is a new type of colloid thruster which uses ultrasonic nozzle instead of the traditional capillary or needle emitter. This paper focuses on the effects of propellant upon the performance of UAEP system. Multiple solutions, such as doped formamide, water and tributyl-phosphate were employed and tested as the propellant. The relationships between the spray current and several characteristic parameters of the propellant, such as surface tension coefficient, electrical conductivity, viscosity and doped solute, were experimentally investigated. The experimental results showed that the operation state of UAEP system was greatly influenced by the physical properties of the propellant. The solution of LiCl/tributyl phosphate was selected as the propellant for UAEP.

1. Introduction

Micro-thruster systems capable of delivering smoothly variable thrust in the range from 1 μN to 1 mN are required for the primary propulsion of nano- and micro-spacecrafts [1–3]. Colloid propulsion utilizes an electrostatic-type device to extract ions or charged droplets from a liquid meniscus, which in turn are accelerated through an intense electric field to produce a high exhaust velocity. As with most electric propulsion devices, the mass flow rates that can be attained in this type of device are low [4]. The thrust produced by colloid thruster is therefore not high enough to meet the needs of some space missions in the past [5]. As a result, a large number of electrospray nozzles were integrated into an emitter array to enhance the propellant mass flow rate as well as the total thrust. Busek Inc. successfully tested a colloid thruster with 57 emitters and obtained a thrust of 100 μN [6]. MIT's space propulsion lab has been studying the feasibility of using a planar array of micro-fabricated electrospray emitters for space propulsion applications, and has successfully developed an emitter array with 1025 emitters in an area of 0.64 cm^2 [7]. Restricted by the manufacturing capability, the number of emitters, however, could not be increased without limit. A new integration method of emitter array needs to be developed.

Ultrasonically aided electric propulsion (UAEP), introduced by W. Song, is a novel method to produce a flux of highly charged droplets for space propulsion applications [8]. In a UAEP system, a liquid film is firstly generated on a surface which vibrates at a frequency of 25 kHz or higher. Then, capillary standing waves are induced and gradually form a rectangular pattern by the continuous vibration. After a voltage of several kV is applied, highly charged droplets are extracted from the crests of the standing capillary waves. Therefore, the number of emitters is significantly increased [9–11]. UAEP, categorized as a kind of colloid thruster, is likely to be one of the promising electric propulsion technologies in the future.

The performance of colloid thrusters is greatly affected by the properties of the propellant. In this paper, several

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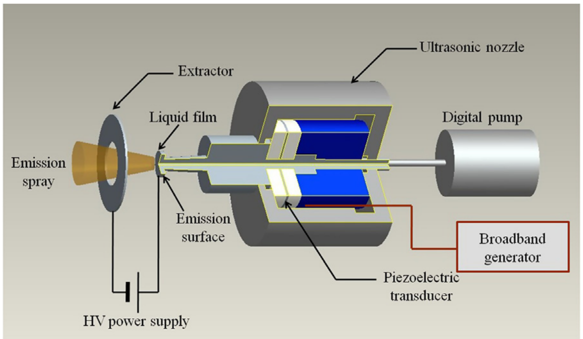

Fig. 1. Basic schematic of UAEP system.

organic and inorganic solutions will be tested as the propellants in the UAEP experimental system. The relationships between the UAEP operation state and the characteristic parameters of the propellant, such as surface tension coefficient, electrical conductivity, viscosity and doped solute, will be experimentally established.

2. Basic principles of UAEP

The configuration of a UAEP system is illustrated in Fig. 1. It consists of an ultrasonic nozzle driven by a pair of piezoelectric transducers, a propellant supply subsystem (usually a digital controlled syringe pump), a broadband function generator, a high voltage power supply and a metal grid which serves as the extractor. Ultrasonic nozzle is regarded as the most important component in the UAEP system. The piezoelectric transducers contained in the ultrasonic nozzle are driven by a broadband function generator, which produces square waves at different frequencies. The pair of piezoelectric transducers acts as the source of mechanical vibration of the ultrasonic nozzle.

When the UAEP system operates, a slightly conductive liquid propellant is transported to the tip of the ultrasonic nozzle by the liquid supply subsystem. Under the action of surface tension, a thin liquid film is formed on the emission surface at the nozzle tip. When the nozzle starts to vibrate, capillary standing waves are induced on the surface of the liquid film. By regulating the mass flow rate of the propellant and the vibration amplitude at a proper level, the capillary standing waves reach a critical stable condition. Under this condition, emission of charged droplets will not take place until an external electric field is applied or the vibration amplitude is further increased. When a high voltage is applied between the emission surface and the extractor, highly-charged droplets will be extracted from the crests of the capillary standing waves. The droplets are accelerated and move towards the extractor, which generates continuous thrust. As each crest of the standing waves are equivalent to an emitter in a traditional colloid thruster, the number of the UAEP emitters is greatly increased. As a result, a higher thrust can be achieved.

Being viewed from the microscopic perspective, the formation of a charged droplet in the UAEP system can be observed as shown in Fig. 2. It should be noted that the emission process takes place under a high electric field. As shown in Fig. 2(a), one of the crests of the capillary standing wave is moving upward. Due to the effect of the electric field, a number of charges move towards the extractor and accumulate at the tip of the crest. When the crest reaches its peak position, as shown in Fig. 2(b), the crest tip becomes sharper and the number of charges rises up to the maximum. In this situation, the tip of the crest is considered as an equivalent of a Taylor-cone in a cone-jet mode, which is firstly studied by Taylor [12]. As shown in Fig. 2(c), the stability of the crest tip is affected by the surface tension force, electrostatic force and inertial force. The relationship among these forces is represented in Eq. (1).

$$\vec{F}_{sur} = \vec{F}_e + \vec{F}_i \tag{1}$$

where $\vec{F}_{sur}$ is the surface tension, $\vec{F}_e$ the electrostatic force generated by the electric field between the extractor and the emission surface, and $\vec{F}_i$ the inertial force determined by the acceleration and mass of the crests during the vibration. The electrostatic pressure P_e, which is proportional to the electrostatic force F_e, can be calculated as

$$P_e = \frac{\varepsilon_0 E^2}{2} \tag{2}$$

where E is the local electric field intensity on the wave surface and ε_0 the vacuum permittivity. When the crest starts to recede, the surface tension is overcome by the electrostatic force and inertial force. As a result, a charged droplet is extracted from the crest of the capillary standing waves. Because of the inertial force, the required electrostatic force is much lower than that of the traditional electrospray.

3. Experimental system

To investigate the influence of propellant ingredient on the UAEP system, an experimental facility was developed. The schematic diagram of the experimental system is illustrated in Fig. 3.

The experimental system is operated in the atmosphere. An ultrasonic nozzle with a vibration frequency of 120 kHz is employed in the experimental system. A broadband ultrasonic generator and a digital syringe pump are used to transmit the electrical signal and the propellant to the ultrasonic nozzle, respectively. This power generator operates over a power range from 0 W to 5 W, with a regulation precision as low as 0.01 W. The digital syringe pump can control the propellant's flow rate in a wide range, which is from 0.001 ml/min to 30 ml/min (0.001–30 sccm). The SPELLMAN SL 30P30 HV power supply is used to provide a voltage from 0 V to 30 kV. The spray current is recorded by the KEITHLEY 6485 electrometer with a recording range from 20 fA to 20 mA. The prototype thruster consists of an ultrasonic nozzle, an extractor and several insulation parts are mounted on a PTFE stand. The UAEP prototype thruster and its emission process are shown in Fig. 4. An annular extractor is employed to obtain a clear view of the spray. As shown in Fig. 4(b), extracted from the liquid film on the