Interstellar Electrical Propulsion by Means of Pure Ionic Emission

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Abstract

• Electrospray-based propulsion is a simple, compact, and efficient propulsion method capable of achieving very high specific impulse. Current Space Propulsion technologies—systems that propel spacecraft in the vacuum of space after leaving Earth's atmosphere--produce limited specific impulses, limiting the maximum duration of current interstellar space travel. This study explores the viability of using an electrospray-based Space Propulsion system to achieve a specific impulse high enough to enable the completion of space missions lasting many years longer than what is currently possible

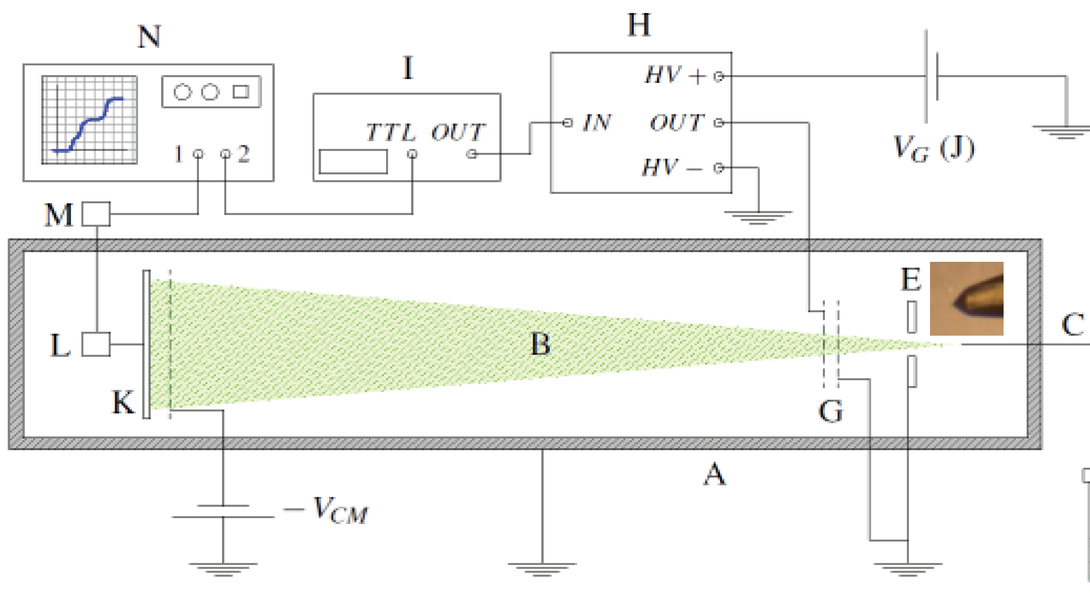
• Measurements and calculations were performed using the Time of Flight (TOF) technique to study and compare the performance of 4 Ionic Liquid (IL) propellants in an electrospray-based thruster. A vacuum chamber was constructed in which to generate the ion beam studied using TOF. An electrometer-amplifier was designed and constructed in order to process the beam signal, and data were acquired using an oscilloscope connected to a computer. Data analysis was accomplished using Excel and MATLAB software

• Results showed relatively high specific impulses for all 4 Ionic Liquids tested, which was expected. The total electric potential energy may be enhanced by applying voltage post-acceleration. For instance, 8 kV may be applied after accelerating the beam with the 2 kV used in this experiment. This would increase our highest specific impulse result from approximately 1700 s to 4000 s. This is very promising compared to other electrical propulsion systems like electrothermal hydracine resistojet and arcjet thrusters, which typically yield specific impulses of approximately 300 and 600 s, respectively

Methods & Materials

Experiment

• The Ionic Liquid propellant is placed in a reservoir (D) which is pressurized with respect to the zero-pressure vacuum chamber (A) and applied a voltage with respect to a grounded extractor (E) using a high voltage source (F)
• Silica capillary needle (C) feeds the liquid from reservoir to vacuum chamber. The applied voltage at reservoir generates the electrospray beam (B) from the needle's tip
• An electrostatic gate (G) is subjected to high voltage pulses generated by a pulsar (H). The pulsar is powered by an external high voltage input power supply (J) and generates pulses via input from a low voltage pulse from a waveform generator (I)
• The beam of ions is collected on the collector plate (K). An electrometer (L) – amplifier (M) is housed on the other side of the plate and receives the current signal collected. It processes this signal and outputs it directly to an oscilloscope (N). The oscilloscope is connected to a PC with which the signal is recorded for further analysis



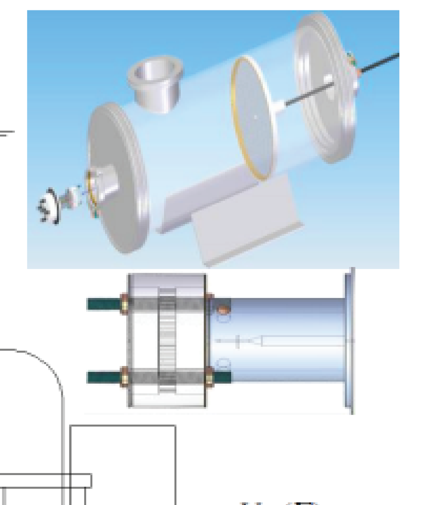
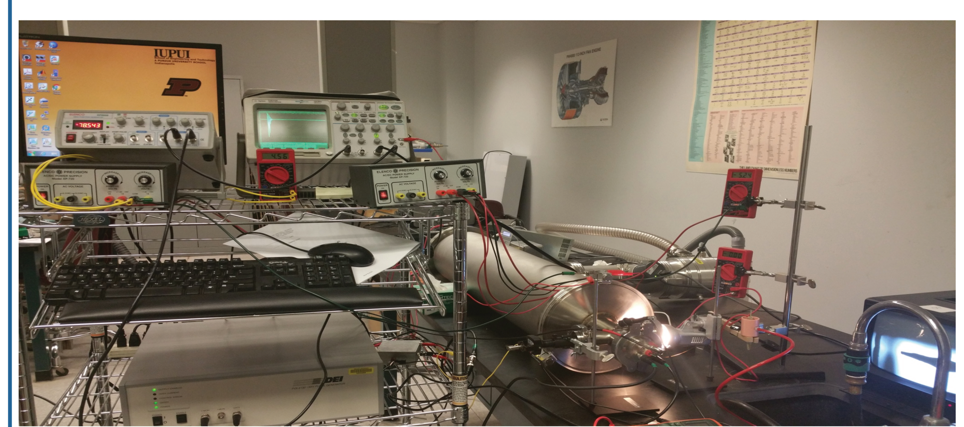
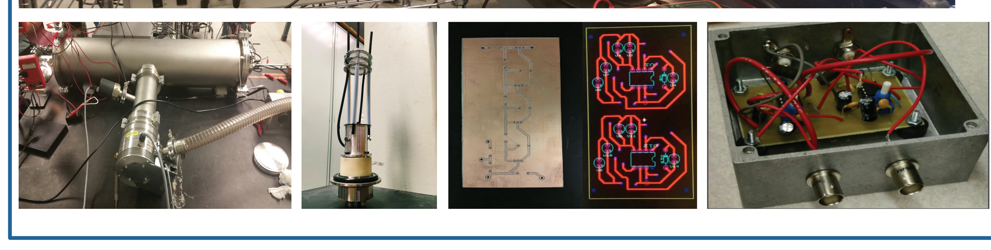


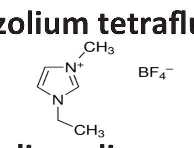
Figure 2: Experiment Setup



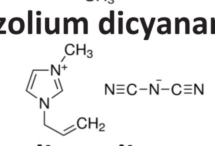


Ionic Liquids

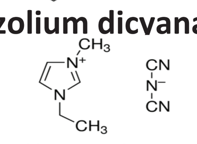
• **1-Ethyl-3-methylimidazolium tetrafluoroborate (EMI–BF_4)**



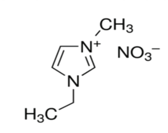
• **1-Allyl-3-methylimidazolium dicyanamide (AMI-DCA)**



• **1-Ethyl-3-methylimidazolium dicyanamide (EMI–DCA)**



• **1-Ethyl-3-methylimidazolium Nitrate (EMI-NO_3)**



Time of Flight (TOF) Technique

• Calculation of propulsive characteristics achieved by exploiting the Conservation of Energy:

$$q\Phi = \frac{1}{2}mv^2$$

as ions are accelerated by the electric potential, Φ, the potential energy is transformed to kinetic energy.
• A zero-reference time is chosen with respect to the pulsing on the gate for when ions arrive inside the chamber, and the distance L they travel is recorded:

$$t_{of} = \sqrt{\frac{mL^2}{2q\Phi}}$$

• Using this allows for the calculation of mass flow rate & thrust:

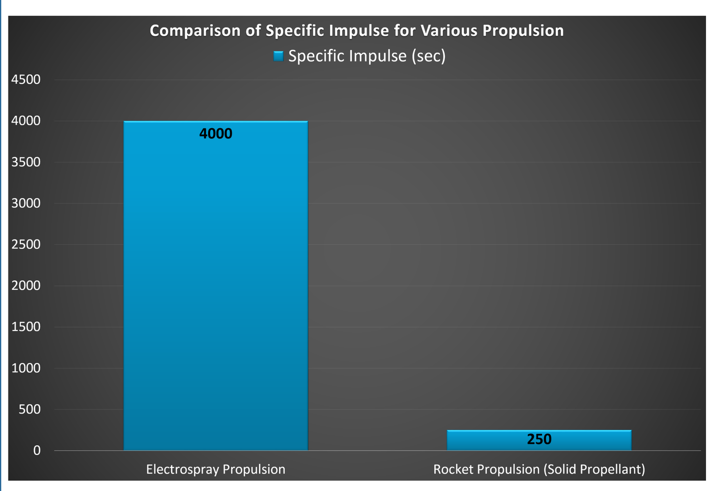
$$\partial m' = -\frac{m}{q}\partial I = -\frac{2\Phi}{L^2}t^2\partial I \qquad \partial T = -\partial m'v = -\frac{2\Phi}{L}t\partial I$$

Introduction

• Characteristics of Space Propulsion:
  • Thrust (T) : Propulsion of the system
  • Specific Velocity (v) : Indicates the system's performance
• High specific impulse is critical for long-range mission capability
• Study seeks to investigate the implementation and performance of an electrospray-based propulsion system
• Goal: Obtain the highest possible specific impulse for the smallest possible flow rate
• 4 different Ionic Liquid propellants will be used and their performance compared

$$\text{Impulse} = \frac{\text{Velocity (v)}}{\text{Gravity (g)}}$$

$$\text{Specific Impulse} \propto \frac{\text{Efficiency it uses propellant}}{\text{to generate thrust}} \propto \text{velocity}$$



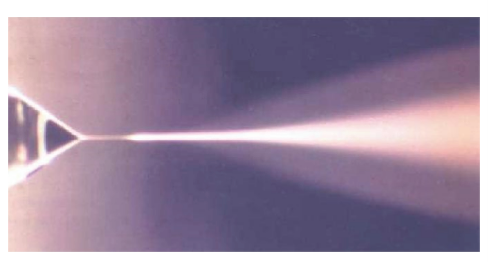
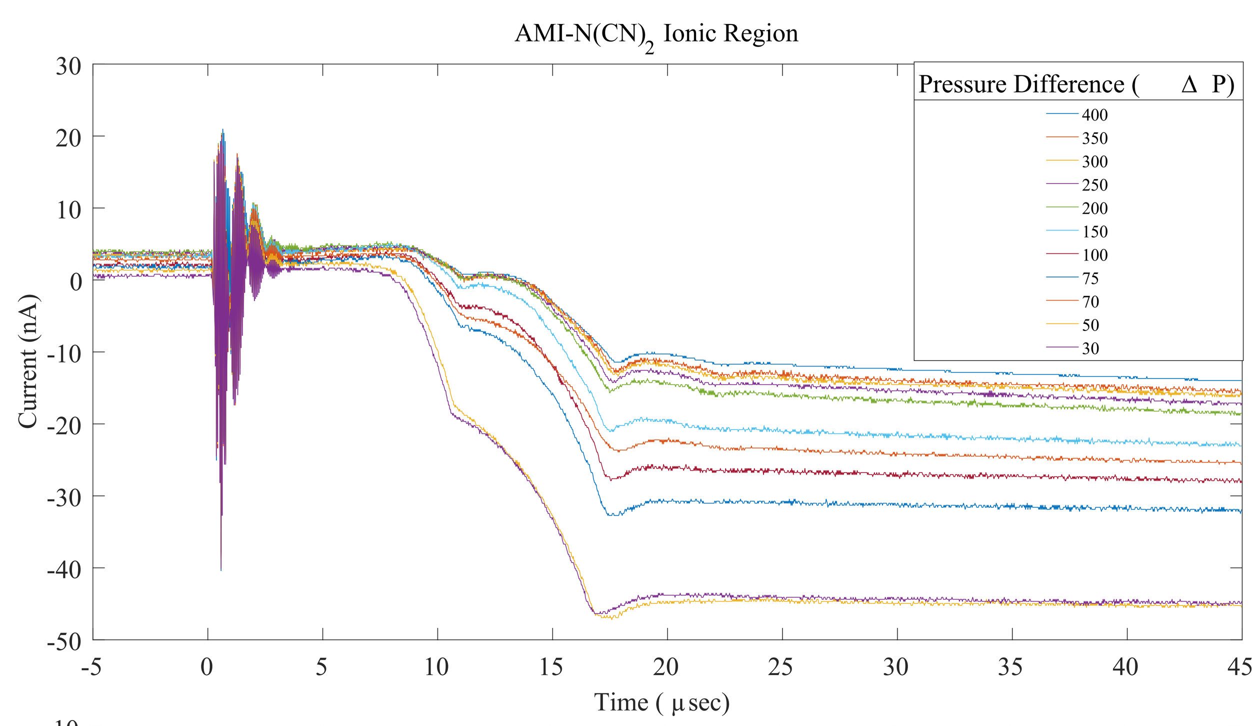
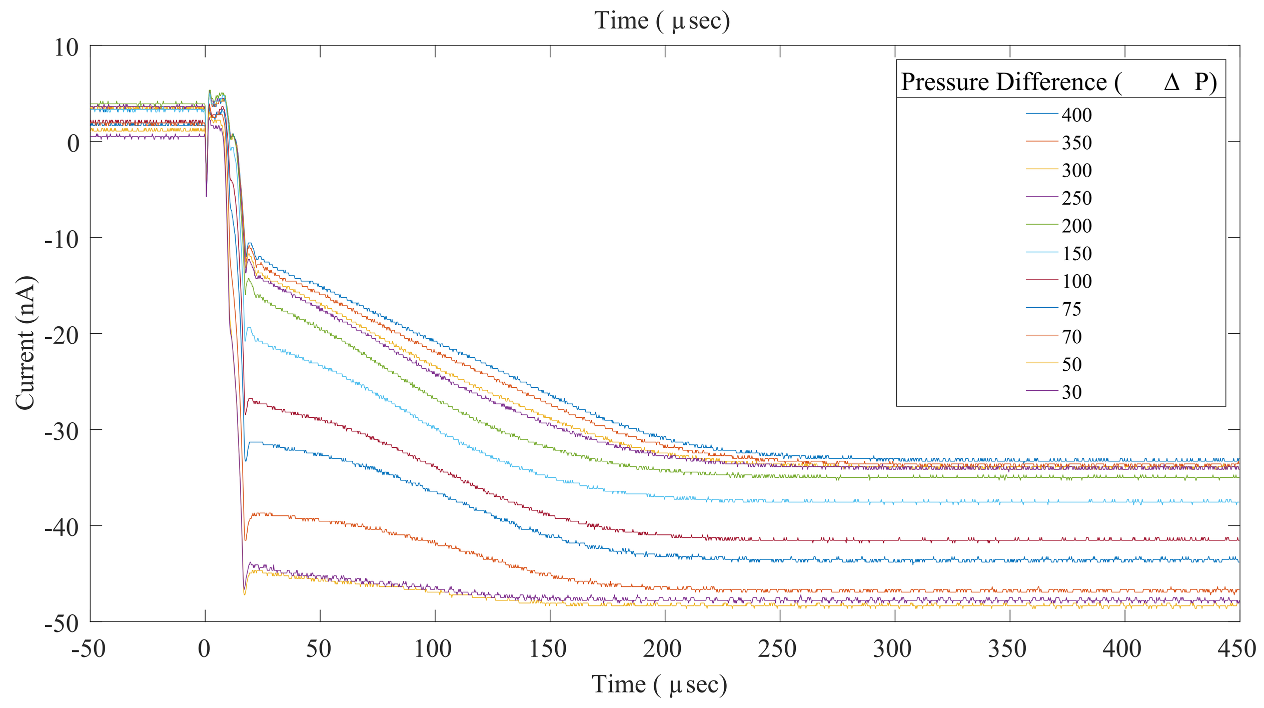
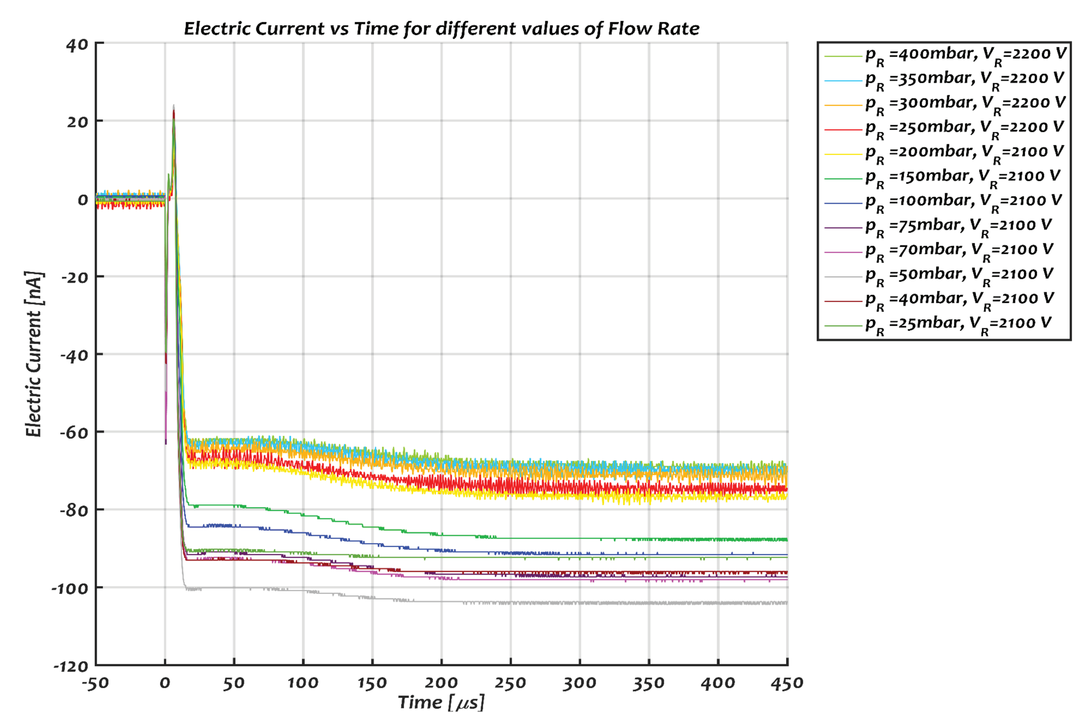


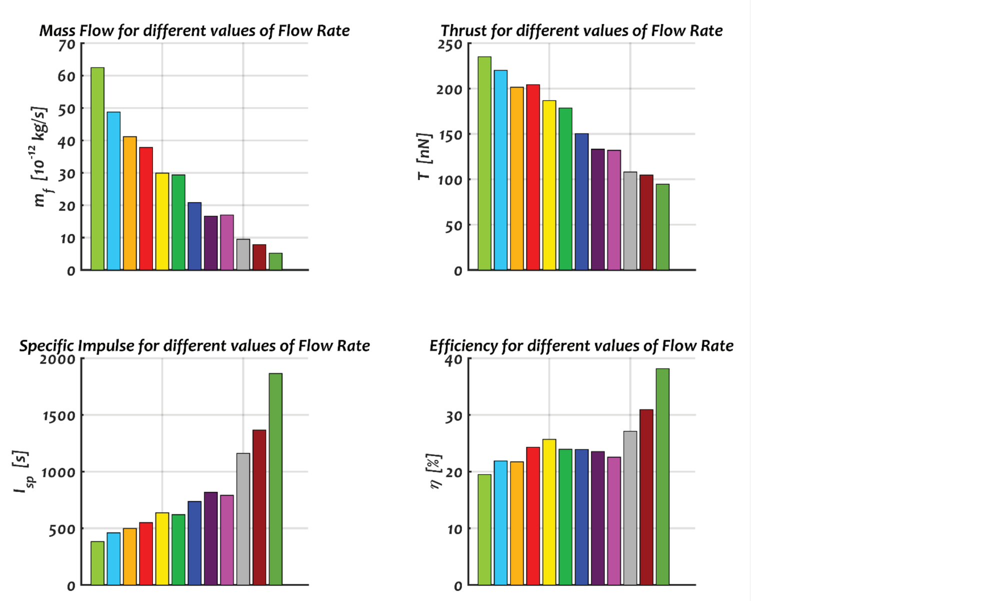
Figure 1: Electrospray of Methanol

Results









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Romero-Sanz I, Bocanegra R., Fernández de la Mora J., and Gamero-Castaño M. (2003.) "Source of heavy molecular ions based on Taylor cones of ionic liquids operating in the pure ion evaporation regime." Journal of Applied Physics. 94:3599-05.

Conclusion

The graphs above show Ionic Liquids:
1. EMI-BF_4 (*Results*, top left)
2. AMI-N(CN)$_2$ (*Results*, bottom left)
3. EMI-N(CN)$_2$ (*Results*, right)

The 4th Ionic Liquid, EMI-NO_3, is not shown as it produced an unstable Taylor cone yielding inconsistent data.

The 3rd Ionic Liquid, EMI-N(CN)$_2$, produced the most desirable propulsive characteristics and is shown with greater detail in *Results*.

Discussion:
• At constant voltage, a pressure differential between the reservoir and the chamber is used as independent variable ranging from 400 mbar to 25 mbar. This pressure differential is directly proportional to the flow rate as calculated by Poiseuille's law and can be used as a means to control the propulsive characteristics of the liquid. The bar charts reveal a positive correlation between pressure differential and mass flow rate, as expected, and higher mass flow rate is correlated with higher thrust but lower specific impulse. Also, within the voltage and pressure differential range of the experiment, higher specific impulse is accompanied by higher efficiency. For the EMI-N(CN)$_2$ liquid, the highest specific impulse of about 1700 s is achieved under pressure differential of 25 mbar (50.4 pl/s), although a 4000 s specific impulse can be achieved by applying 10 kV of post-acceleration voltage.
• The ion beam is stopped periodically by the high-voltage pulse. Ions graphs show several steps in the rise of the signal, which are caused by ions with different charge-to-mass ratios arriving at the collector. The first visible step corresponds to the fastest ions with highest charge-to-mass ratio (e.g. EMI^+). The second visible step is one cation with one neutral particle (e.g. [EMIBF$_4$]EMI$^+$). After the ionic regime, we enter the mixed regime followed by the droplet with cluster composed of m anions and n cations.
• Experiments changing the voltage applied at the reservoir and constant pressure differential were conducted using EMI-N(CN)$_2$. The results show that increasing voltage leads to lower mass flow rate and thrust but higher specific impulse and efficiency. Applying an additional 400 V at 75 mbar pressure differential, the specific impulse increased from about 1500 s to 2500 s.

Conclusion:
Propulsive parameters of the four ionic liquids are characterized:
• Positive correlation between pressure differential and mass flow rate
• Positive correlation among voltage applied at the reservoir, specific impulse, and efficiency
• Pure ionic propulsion might be able to achieved via small pressure differential and high voltage applied at the reservoir

As a single ionic thruster, our emitter is incapable of generating enough thrust for the spacecraft to be viable for long-range missions. Future studies will stablish a larger TOF system of many joint ionic thrusters (multiplexing). Also, more experiments will be conducted to further study characteristics of different ionic liquids under varying parameters (pressure differential, voltage applied at the reservoir, relative height between the needle and the reservoir vial).