SAND2007-1400C

ELECTROKINETICALLY PUMPED LIQUID PROPELLANT MICROTHRUSTERS FOR ORBITAL STATION KEEPING

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Abstract: For most orbital maneuvers, small satellites in the 1-10 kg range require thrusters capable of spanning the micro-Newton to milli-Newton force range. At this scale, electrokinetic (EK) pumping offers precise metering of monergolic or hypergolic liquid propellants under purely electrical control at pressures and flow rates well-suited to microthruster applications. We have demonstrated the use of EK pumps for direct and indirect delivery of hydrazine and hydrogen peroxide monopropellants, respectively, into capillary-based microthrusters with integrated in-line catalyst beds. Catalytic decomposition generates gases which accelerate through a plasma arc-formed converging-diverging nozzle, producing thrust. Specific impulses up to 190 s have been demonstrated for hydrazine in non-optimized nozzles.

Keywords: Monopropellant, capillary nozzle, hydrazine, iridium catalyst, nanosatellite.

1. INTRODUCTION

Advances in the miniaturization of electronics, power systems, and sensors have made small satellites (<10 kg) increasingly popular in the academic and research community as cost-effective alternatives to more conventional large-scale platforms. To be useful, these miniature satellites require propulsion systems which are light, compact, and capable of delivering thrust in the micro-Newton to milli-Newton range. At this scale, microsystem technologies represent a key enabler of spaceborne propulsion.

Mueller [1] provided an overview of a variety of proposed microthruster concepts, ranging from cold gas, resistojet, and liquid propellant designs [2] to solid propellant digital thrusters [3] and plasma or electric schemes. Among these options, liquid monopropellant designs offer a well-rounded balance of efficiency, low mass, small size, low power, and operational flexibility.

2. MONOPROPELLANT THRUSTERS

One of the most common approaches to spaceborne macropropulsion is the hydrazine monopropellant thruster. Liquid hydrazine is pumped through a high surface-area catalyst bed of iridium-coated granular alumina (e.g. Shell-405) where it decomposes energetically to nitrogen, hydrogen, and ammonia gas. These product gases are then accelerated to supersonic velocities by a converging-diverging nozzle to produce thrust. Concentrated hydrogen peroxide is also a suitable monopropellant, decomposing with a silver catalyst to water vapor and oxygen. Because they operate catalytically rather than by combustion, monopropellant thrusters offer the energy density of chemical fuels without the need to carry and handle a separate oxidizer.

2. ELECTROKINETIC PUMPING

For small satellite applications where power and payload are at a premium, electrokinetic (EK) pumps were identified as a promising approach to monopropellant delivery. EK pumps typically consist of a micro-porous dielectric medium such as a particle bed through which fluid flows by electro-osmosis when an electrical potential is applied across the porous structure. These pumps are mechanically simple, involve no moving parts, provide direct voltage control over fluid metering, require no separate valves, and consume less than 100 mW to deliver propellants in the µg/sec to mg/sec mass flow rate range.

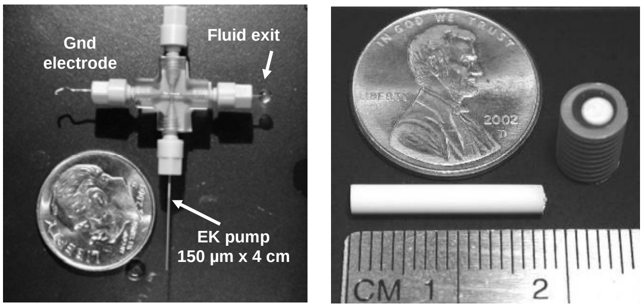

Fig. 1 Packed bed fused-silica capillary EK pump integrated with CapTite™ fittings (left. Sintered-monolith pump element alone and integrated into ¼”-28 threaded fitting (right).

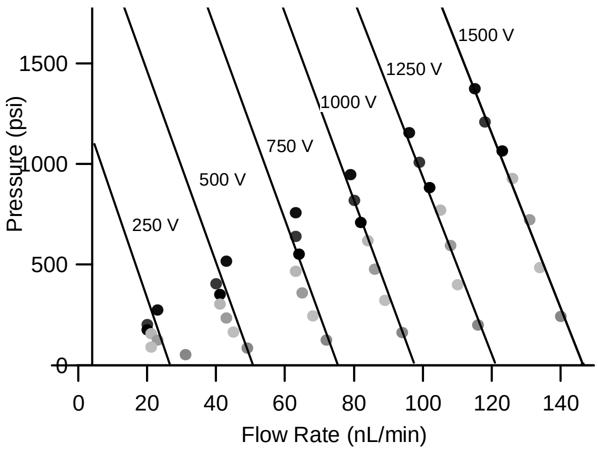

Fig. 2 Capillary electrokinetic pump performance as function of pump driving voltage for a range of downstream flow restrictions (shaded datapoints).

Fig. 1 shows two Sandia EK pump designs. Packed capillary EK pumps have relatively small cross-sectional area (<150 μm ID) yielding flow rates in μg/sec range at pressures up to 50,000 psi. Capillary pumps are fabricated using techniques originally developed for high-pressure liquid chromatography (HPLC) [4]. To optimize pump performance for use with hydrazine and hydrogen peroxide, 0.5 μm zirconium and polydisperse alumina were tested in addition to surface treatments of the more conventional silica particle beds. Fig. 2 shows the pressure and flow performance characteristics of a capillary EK pump with zirconium propoxide modified silica.

Larger, sintered-monolith pumps are best suited for mg/sec flow rates at more modest pressures (1,000 psi). These structures are also formed by slurry packing 0.5 μm silica particles, this time in a high-pressure stainless steel tube. Packed particles are sintered at 1250 C forming a monolith which can then be incorporated into fluidic components. We have successfully demonstrated direct EK pumping of hydrazine with both capillary and sintered-monolith pumps. Indirect delivery of hydrogen peroxide by sintered-monolith pump has also been shown using a free piston to isolate the pump working fluid from the peroxide propellant.

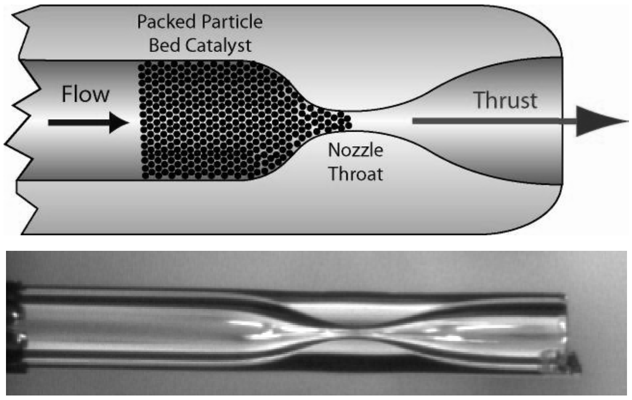

Fig. 3 Schematic of fused-silica capillary thruster and photomicrograph of 340 μm OD capillary nozzle without catalyst formed by arc reflow.

3. NOZZLE & CATALYST FABRICATION

Capillary microthrusters were fabricated using polyamide-clad fused-silica capillary tubing (Polymicro Technologies, Phoenix, AZ) with 360 μm OD and ~100 μm ID. Nozzle geometries were created using a novel plasma reflow process. Capillaries were rotated continuously and their cut ends repeatedly exposed to the electrical arc of a fiber optic fusion splicer (Fiberlign IFS-2001A, Preformed Line Products, Cleveland, OH), progressively forming near-ideal coverging or converging-diverging nozzle geometries after several firings with final throat diameters in the 15-75 μm range.

After forming the nozzles, a dry mixture of 10-15 μm silica and polydisperse iridium (<50 μm) particles were introduced into the capillary and pressed into place behind the nozzle using a thin wire or compressed air to form an integrated catalyst bed. Fig. 4 indicates catalyst position in a completed microthruster and shows a fabricated converging-diverging glass capillary nozzle.

Nozzle and catalyst structures were coupled to propellant delivery capillaries and electrokinetic pumps using CapTite™ modular capillary fittings (Sandia National Labs, Livermore, CA) as depicted in Fig. 4. Also visible in Fig. 1 (left), these polymer fittings (Ultem, PEEK) were developed in-house to provide chemically-inert, easily reconfigurable microfluidic interconnects with minimal dead-volume and pressure capability up to 5000 psi or more.

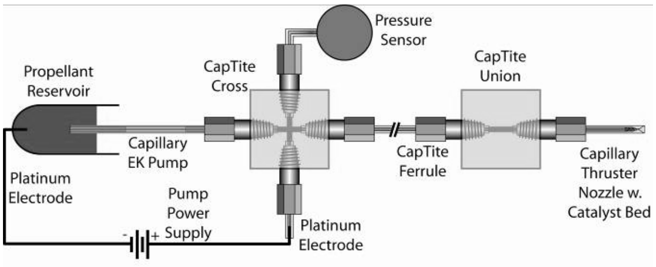

Fig. 4 Complete microthruster system assembly with CapTite™ fluidic interconnects, packed-bed capillary EK pump, and capillary thruster nozzle.

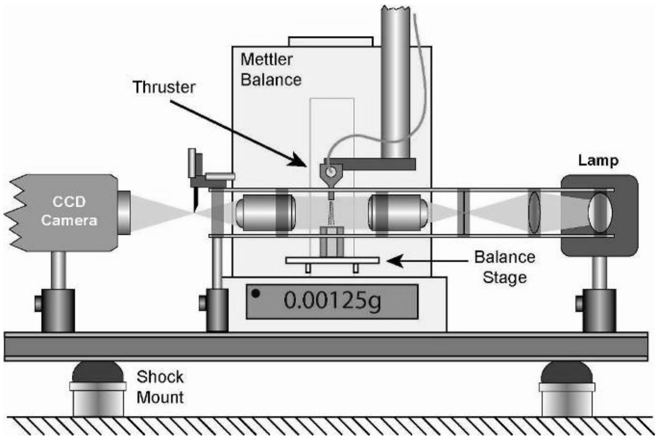

Fig. 5 Schematic of thrust measurement and visualization apparatus including precision balance, vibration isolation platform, and optical train for Schlieren microscopy.

4. THRUST MEASUREMENT

Fig. 5 shows the measurement apparatus used for flow visualization and thruster performance studies. A precision balance (XP-205, Mettler-Toledo, Columbus, OH) was adapted to achieve 0.1 µN thrust force resolution with the thruster impinging onto the balance. A Schlieren optical setup installed above the balance allowed visualization of the thrust plume during measurements, and Labview software provided time-correlated acquisition of thrust force, pressure, and flow rate data. Fig. 6 shows a Schlieren video still taken during thrust measurement and a high-magnification image of a hydrazine thruster in operation. In most cases, a resistive heater positioned near the catalyst bed of the capillary was used to initiate catalysis. Once "lit," hydrazine decomposition typically provided sufficient excess heat to sustain the reaction, even causing the catalyst to glow visibly red-orange at flow rates greater than about 1 µL/min.

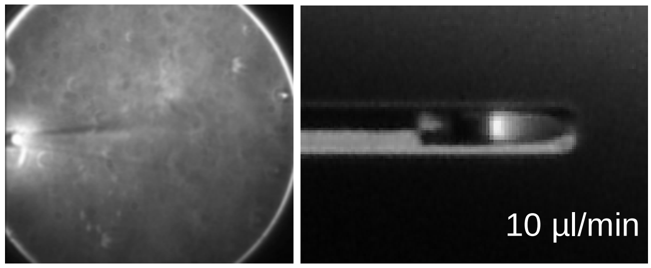

Fig. 6 Schlieren image of thrust plume (left) and photomicrograph of hydrazine capillary (360 µm OD) thruster with glowing catalyst bed (right).

5. EXPERIMENTAL RESULTS

Fig. 7 shows specific impulse performance (I_{sp} in thrust force per propellant weight flow rate, i.e. seconds) of a capillary microthruster with hydrazine delivered by syringe pump at various flow rates. Where macroscale hydrazine thrusters have typical specific impulse values around 220 s, the efficiency of this microthruster is significantly lower, particularly at low flow rates. Most likely this discrepancy arises because the nozzle throat is relatively large (tens of microns), requiring a higher mass flow rate to produce sonic (choked) flow in the throat and supersonic exit velocities. Optimization of nozzle size and geometry should enable higher specific impulse values. Fig. 8 shows a time sequence of thrust experiments with hydrazine delivered by direct EK pumping. Pump flow rate is increased from a baseline of 16 µL/min to 27, 51, 67, and 82 µL/min with corresponding increases in pressure and thrust.

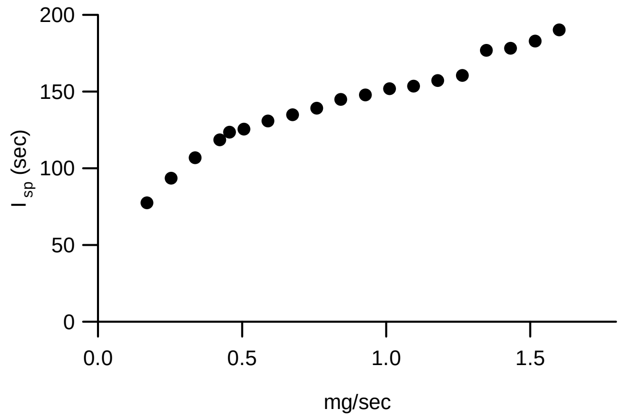

Fig. 7 Hydrazine capillary thruster specific impulse (thrust / gravimetric flow rate of propellant) as function of pumping rate.

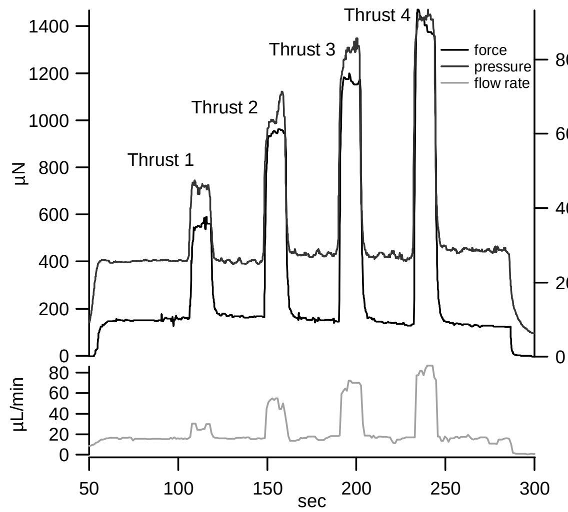

Fig. 8 Flow rate (bottom), thrust (middle), and propellant pressure (top) of a hydrazine microthruster with time-varying EK pump drive.

6. CONCLUSIONS & FUTURE WORK

Direct electrokinetic pumping of hydrazine through capillary microthrusters with integrated iridium catalyst beds and plasma arc-formed nozzles has been demonstrated. These preliminary designs have yielded thrust forces in a range from 10 µN to as much as 3 mN with characteristic specific impulse numbers averaging about 125 s depending on hydrazine flow rate. Including pump and miniature high-voltage power supply, the entire liquid propellant microthruster subsystem is estimated to weigh less than 10 g and occupy less than 5 cm^3.

Future work will seek to optimize capillary-based designs for improved specific impulse, minimum impulse bit, catalyst/nozzle lifetime, and repeatability of fabrication. Alternative architectures are also under evaluation including the low-temperature co-fired ceramic (LTCC) and lithographically patterned quartz microthruster designs shown in Fig. 9.

Fig. 9 2.5 cm long silver-catalyzed hydrogen peroxide LTCC thruster (left), 10 x 14 mm iridium-catalyzed quartz hydrazine thruster with femtosecond laser-drilled inlet port (right).

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