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Fabrication of a liquid monopropellant microthruster with built-in regenerative micro-cooling channels

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ABSTRACT

This paper reports a feasibility study of regenerative micro-cooling channels in a liquid microthruster composed of thermally fragile materials. Glass, which is among the most thermally insulating materials, has been used as microthruster fabrication material to suppress excessive heat loss in micro scale thruster. However, the frangibility of glass has remained a challenge to be solved. To thermally manage the fragile structure, the use of regenerative micro-cooling channels in a microthruster is suggested in this work, and the feasibility was tested through design, fabrication and experimental performance of a glass microthruster with microchannels. Nine photosensitive glass layers were wet etched and integrated to fabricate the microthruster. Before integration of the layers, a fabricated Pt/Al_2O_3 catalyst was inserted into the chamber of the microthruster for propellant decomposition. Hydrogen peroxide (90 wt%) was used as a monopropellant and served as the working fluid for regenerative cooling. A liquid microthruster with micro-cooling channels was successfully fabricated with a photosensitive glass MEMS process. Experimental performance tests were conducted while measuring the microthruster chamber pressure, chamber temperature, and surface temperatures. The test results showed normal operation of the microthruster, which had an estimated thrust of approximately 48 mN and temperature efficiency of approximately 41%. The decreasing surface temperatures of the microthruster during thruster operation successfully validated the cooling effect of the micro-cooling channels and demonstrated their practicality for the regenerative cooling of liquid microthrusters.

1. Introduction

MEMS technology has resulted in many imaginary suggestions becoming reality. This is also valid for space technology. Nanosatellites that weigh 1–10 kg have been proposed [1–8] and provide significant advantages, including extreme cost effectiveness, as compared with traditional satellites, which have the drawback of high costs of launch vehicles. Limitations on the functionality of small-scale satellites, owing to their restricted mass and volume, can be supplemented through constellation group operations involving several small-scale satellites. It is expected that operating constellations of small satellites will result in higher reliability for entire satellite systems, improved revisit times, and the possibility for more versatile mission operations. Those operations are feasible only after meeting the prerequisites associated with down-sized thruster development for attitude control, drag compensation, and orbital transfer. The required thrust depends on the satellite weight and mission profile [9,10].

Electrical and chemical propulsion are possible for micropropulsion. Electric propulsion has a high specific impulse but requires high electric power, which may be an excessive burden on small-scale satellites. Chemical propulsion has the advantage of high energy density, and it consumes little electrical power. From these choices, many microthruster studies have examined chemical propulsion by using monopropellants [11–19], bipropellants [20–22], solid propellants [23–39], and cold gases [40–42].

Monopropellant thrusters are among the most appropriate micropropulsion options because they are simpler than bipropellant thrusters and possess re-ignition and throttling abilities, which are difficult to implement in solid propellant thrusters. Monopropellant thrusters also have higher specific impulses than cold gas thrusters.

Most microthrusters have been fabricated using silicon [29–36]. However, some studies have attempted to use low thermal conductivity materials, such as glasses [37–39] and ceramics [11,12,20], to prevent heat energy losses stemming from the large

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surface-to-volume ratios of small-scale thrusters. Cheah et al. [43] have fabricated a vaporizing liquid microthruster using a high-temperature co-fired ceramic (HTCC) and have found that using HTCC as the structural material is more efficient and consumes less electrical power than silicon. Wu et al. [11] have successfully manufactured a monopropellant microthruster based on low-temperature co-fired ceramic (LTCC) tape technology and have demonstrated that the thruster operates normally. However, under certain thermal stresses, the combustor wall cracks, and the level of thrust decreases. In [44], a monopropellant microthruster fabricated using glass and a decomposed propellant using a catalyst coated on a spherical support is described, but cracking has been observed near the catalyst chamber wall of the microthruster, where the highest thermal stresses occur. Low thermal conductivity materials have been good choices for conserving the heat energy of thermal devices. However, the thermal frangibility and brittleness of some materials have remained challenges to solve.

In this work, the use of regenerative cooling channels added to a liquid monopropellant microthruster is suggested as an alternative for thermal management of a microthruster structure fabricated by using a thermally fragile material. Glass, as one of the fragile and best low-conduction materials, was selected as a micro-fabrication material for this study. The suggested microthruster was fabricated using a photosensitive glass MEMS fabrication process. The feasibility of regenerative cooling using micro-channels was evaluated through the design, fabrication and performance testing of a glass microthruster with built-in regenerative micro channels.

2. Design and fabrication of the microthruster

2.1. Propellant considerations

Monopropellant is a propellant that releases energy through an exothermic decomposition reaction by a catalyst and produces high-temperature gases that can be converted to kinetic energy at a nozzle. Hydrazine(N_2H_4), hydrogen peroxide(H_2O_2) and ionic propellants, such as HAN(NH_3OHNO_3), ADN($NH_4N(NO_2)_2$), have been generally used as monopropellants. Hydrazine is the most commonly used storable monopropellant with high specific impulse. However, it is difficult to handle because of its high toxicity, thus requiring additional costs for safety equipment during development and operational processes. As green propellants, HAN and ADN are good alternatives for monopropellant thrusters, but they have high viscosity, thus potentially causing large feeding pressure losses and making them inappropriate as microscale thruster propellants. In addition, ionic propellants require preheating for propellant decomposition, which is another disadvantage for their use as microthruster propellants, owing to difficulties in supplying electrical power on nanosatellites. Hydrogen peroxide is also a green propellant with several advantages, such as high density, storability, and non-toxicity, thus allowing for cost-effective handling processes. It is also easily decomposed by a catalyst, without initial preheating, into environmentally friendly oxygen and water vapor. The decomposition process for hydrogen peroxide follows the equation:

$$2H_2O_2(l) \rightarrow 2H_2O(g) + O_2(g) + \text{Heat}$$

The heat energy generated depends on the concentration of H_2O_2 and is 2884.47 kJ/kg for a concentration of 100 wt% H_2O_2. Hydrogen peroxide above 90 wt% concentration has often been used as a monopropellant [12,17,19,45] and has a decomposition temperature of approximately 1022 K. 90 wt% hydrogen peroxide was selected as a monopropellant for this study. By using hydrogen peroxide as a monopropellant, the microthruster will be expected to have advantages of operation flexibility as well as simplicity and reliability, because thrust generation depends only on the supplied propellant flow rate.

2.2. Catalyst preparation

Catalyst for decomposing propellants have been of primary interest, especially for micro-scale monopropellant thrusters, owing to low propellant decomposition efficiencies with low reaction temperatures that stem from the excessive heat energy losses of microthrusters. Most previous work has shown that propellant decomposition efficiency and thrust generation are insufficient when a catalyst coated on the inner surface of the microthruster chamber is used [14,44,46]. Direct insertion of the catalyst coated on a porous support into the microthruster chamber as suggested by Lee et al., has improved propellant decomposition efficiency in a microthruster [17]. In this work, a propellant decomposable catalyst was fabricated by using both an active material and support for the catalyst direct insertion method, as recommended in previous studies.

Among the alternatives for catalyst active material, such as Ag [12], MnOx [47,48], Ir [49], and Pt, which have been widely used for hydrogen peroxide decomposition, Pt was selected as the active material. Pt is well known to be a good catalyst for H_2O_2 decomposition [19,45,50,51], and its melting temperature is 2041 K, which is significantly higher than the adiabatic temperature of rocket-grade hydrogen peroxide. As a catalyst support, γ-alumina was chosen as recommended in a previous study [17]. The γ-alumina has a high surface-to-mass ratio of approximately 255 m^2/g. In addition, it is thermally and physically robust and strongly adheres to metals [45,49,52].

For Pt/Al_2O_3 catalyst fabrication, the alumina support size was determined by considering the channeling effect, which is the propellant flow through the voids between the catalyst supports depending on the size of the catalyst support. If the catalyst support is too small, inducing flow and a moderate pressure drop through the catalyst bed are difficult. However, with a catalyst support that is too large, the propellant flows through the voids between the catalyst supports without spending sufficient reaction time in the catalyst bed. The γ-alumina support size was specified to have a 40–45 mesh size, on the basis of other experimental studies on the ratio of catalyst support diameters to chamber diameters [19,45,53].

Pt/Al_2O_3 catalyst fabrication began by preparing a γ-alumina pellet. The γ-alumina pellet was ground and washed through a size 40- to 45-mesh sieve (corresponding to sizes of 425- to 355-μm) before the loading process. After washing the γ-alumina, 10 wt% H_2PtCl_6 $6H_2O$ was used as a precursor to wet impregnation for platinum loading on the alumina support. After the wet alumina in the solution was dried at 90 °C for 12 h in a convection oven, calcination was carried out at 500 °C in a furnace for 3 h. Finally, a reduction process was performed with hydrogen gas at 500 °C in a furnace for 3 h to revitalize the active material. The fabricated catalyst is shown in Fig. 1. To determine the wt% of the platinum, energy-dispersive X-ray spectroscopy(EDS) was used, thus yielding a value of 28 wt% based on the alumina support, which is near the intended weight percent of the platinum (30 wt%). The EDS result is shown in Fig. 2.

2.3. Design of the microthruster with cooling channels

A liquid microthruster with micro-cooling channels was designed considering the feasibility of fabricating several planar wafers by using a MEMS fabrication process. The objective thrust of a microthruster can be determined on the basis of the requirements on nanosatellite attitude control and orbital maintenance. For estimated thrusts ranging from 100 μN to 100 mN for nanosatellite