Development of green propellant microthrusters at KAIST

Jeongmoo Huh*, Juwon Kim and Sejin Kwon

Korea Advanced Institute of Science and Technology (KAIST)
South Korea

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Contents

- Introduction
- Microthruster using blended propellant
- Microthruster with micro cooling channels
- Microthruster using high enthalpy propellant (ADN)
- Conclusion
Introduction
Nanosatellites constellation operation

Small satellites constellations plan, Skybox for google, 2016

CubeSat sent from the ISS, Nanosatisfi, 2013

United Nations – ISS CubeSat Deployment 2015
### Required thrust for nanosatellites operations

<table>
<thead>
<tr>
<th>Mission</th>
<th>Mission Time</th>
<th>Thrusting Time</th>
<th>$\Delta V$ (m/s)</th>
<th>Thrust ($\mu$N / kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase altitude from 700 km to 701 km</td>
<td>0.82 hours (half orbit)</td>
<td>10 min</td>
<td>0.53</td>
<td>880</td>
</tr>
<tr>
<td>Boost altitude by 100 km at GEO</td>
<td>1 week (half orbit)</td>
<td>1 week</td>
<td>3.65</td>
<td>6</td>
</tr>
<tr>
<td>Change inclination by 1° at 700 km altitude</td>
<td>0.82 hours (half orbit)</td>
<td>10 min</td>
<td>131</td>
<td>220,000</td>
</tr>
<tr>
<td>De-orbit from 700 km (Hohmann transfer)</td>
<td>0.80 hours (half orbit)</td>
<td>10 min</td>
<td>160</td>
<td>270,000</td>
</tr>
<tr>
<td>Change inclination by 1° at GEO</td>
<td>12 hours (half orbit)</td>
<td>10 min</td>
<td>54</td>
<td>9,000</td>
</tr>
<tr>
<td>Move 10 km ahead at 700 km altitude</td>
<td>3.3 hours (two orbits)</td>
<td>40 min</td>
<td>1.1</td>
<td>460</td>
</tr>
</tbody>
</table>

For orbit transfer, attitude control, and drag compensation of cubesat class nano satellites, 6 $\mu$N – 270 mN thrust is required

→ Development of small scale thruster is essential

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**Propulsion types for microthrusters**

- **Microthruster**
  - Thruster for several μN or mN class thrust generation

<table>
<thead>
<tr>
<th>Type</th>
<th>Reignition</th>
<th>Throttling</th>
<th>System complexity</th>
<th>Specific impulse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mono propellant</td>
<td>Possible</td>
<td>Possible</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Solid propellant</td>
<td>Impossible</td>
<td>Impossible</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>BI propellant</td>
<td>Possible</td>
<td>Possible</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Electrical</td>
<td>Possible</td>
<td>Possible</td>
<td>High</td>
<td>Very high</td>
</tr>
<tr>
<td>Cold gas</td>
<td>Possible</td>
<td>Possible</td>
<td>Low</td>
<td>Very low</td>
</tr>
</tbody>
</table>

Mono-propellant microthruster, An et al., 2006

Bi-propellant microthruster, Huh et al., 2014

Solid-propellant microthruster, Lee et al. 2009
Considerations for microthruster propellant

- **Monopropellant candidates**

<table>
<thead>
<tr>
<th>Propellant</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrazine ((\text{N}_2\text{H}_4))</td>
<td>High specific impulse / toxic / expensive for handling</td>
</tr>
<tr>
<td>HAN ((\text{NH}_3\text{OHNO}_3))</td>
<td>Green propellant / detonable / high viscous / need preheating</td>
</tr>
<tr>
<td>ADN ((\text{NH}_4\text{N(NO}_2)_3))</td>
<td>Green propellant / high viscous / need preheating</td>
</tr>
<tr>
<td>Hydrogen peroxide ((\text{H}_2\text{O}_2))</td>
<td>Green propellant / lower specific impulse / easy decomposition by catalyst</td>
</tr>
</tbody>
</table>

- Hydrogen peroxide is one of the suitable propellant for a microthruster
- Simple system without additional heater installation and high pressure device
- Economical cost for thruster development and testing using green propellant
Previous work of monopropellant thruster

- Insufficient propellant decomposition due to
- Chamber structure failure
- Catalyst washed away in high temperature and pressure
- Additional heater needed to overcome excessive heat loss in microthruster

*Hitt D L et al. 2001 Smart Mater Struct 10 1163-75
***Jundu P et al. 2013 J Microelectromech S 22 406-17
**Takahashi K et al. 2006 In: Proc. of the 23rd Sensor Symp., pp 513-6
Research objectives

- Find the possibility of use of high energy content by propellant blending to overcome the excessive heat loss in micro scale thruster.
  - Find effect of blended propellant on thrust stability and response characteristics.

- Investigate the feasibility of using micro cooling channels in micro thruster to deal with thermal stress and structure failure.
  - Find effect of micro cooling channels on performance of a liquid monopropellant microthruster.

- Feasibility test of use of ionic propellant to increase microthruster performance.
  - Overcome drawback of ionic propellant using H2O2 for chamber preheating.
Microthruster with blended propellant
Designed thruster drawing

Component layers for the microthruster
# Specification of designed thruster

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F )</td>
<td>50 mN</td>
</tr>
<tr>
<td>( I_{sp} )</td>
<td>117 s</td>
</tr>
<tr>
<td>Chamber pressure</td>
<td>5 bar</td>
</tr>
<tr>
<td>Propellant mass flow rate</td>
<td>0.034 g/s</td>
</tr>
<tr>
<td>Catalyst capacity</td>
<td>2 g/s/cm(^3)</td>
</tr>
<tr>
<td>Catalyst volume</td>
<td>0.0196 cm(^3)</td>
</tr>
<tr>
<td>Catalyst</td>
<td>Pt / Al(_2)O(_3)</td>
</tr>
<tr>
<td>Support size</td>
<td>40 ~ 45 mesh</td>
</tr>
<tr>
<td>( L/D )</td>
<td>1.5</td>
</tr>
<tr>
<td>Ullage volume</td>
<td>Approximately 8% of chamber volume</td>
</tr>
</tbody>
</table>
Fabrication material considerations

- Micro fabrication materials for a microthruster

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>125 W/m K</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>25 W/m K</td>
</tr>
<tr>
<td>HTCC</td>
<td>20 W/m K</td>
</tr>
<tr>
<td>LTCC</td>
<td>3 W/m K</td>
</tr>
<tr>
<td>Glass</td>
<td>1 W/m K</td>
</tr>
</tbody>
</table>

- Lowest thermal conductivity with glass
- Advantages of high aspect ratio machinability
- Cost-effectivity, chemical resistance and transparency
Microthruster fabrication process

Quartz wafer → Photosensitive glass

310 nm UV

Cr Mask

UV Exposure

Heat Treatment

Etching

Polishing

Bonding

Lithography procedure
Manufactured components

Component layers for the thruster
Thruster fabrication results

- Optical microscope image

Micro nozzle exit with 0.01% error and nozzle throat with 5%
Thruster fabrication results

- Optical microscope image

Drawing of designed micro injector

Fabricated micro injector

Micro injector fabrication with approximately 10% error
Considerations for catalyst fabrication

- **Catalyst – Platinum**
  - Good performance
  - Melting temperature 2041 K
  - Durable at high temperature and pressure

- **Support – Alumina pellet**
  - High surface mass ratio (~ 255 $m^2/g$)
  - Thermally, physically robust
  - Strong adhesion with metal
  - 40 ~ 45 mesh (425 µm – 325 µm) size $\gamma$-alumina
Pt/Al₂O₃ fabrication procedure

1) Before loading
   - Wash 40 – 45 mesh γ-alumina with water
   - Dry at 300 °C for 1 hour

2) Loading active-material
   - Use H₂PtCl₆·6H₂O as precursor
   - Evaporation method

3) Calcination
   - Evaporate water
   - Eliminate impurities at furnace

4) Reduction
   - With hydrogen gas at high temp
Fabricated catalyst and SEM results

Pt/Al$_2$O$_3$ catalyst (40 – 45 mesh, 355 – 425 µm)

Scanning electron microscopy (SEM) results

Platinum on alumina support
EDS results of catalyst

Energy dispersive X ray spectroscopy (EDS) results of the fabricated catalyst

<table>
<thead>
<tr>
<th>Element</th>
<th>Wt %</th>
<th>At %</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>26.22</td>
<td>47.07</td>
</tr>
<tr>
<td>Al</td>
<td>45.2</td>
<td>48.12</td>
</tr>
<tr>
<td>Pt</td>
<td>27.67</td>
<td>4.07</td>
</tr>
<tr>
<td>Cl</td>
<td>0.91</td>
<td>0.74</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>
Thruster integration procedure

1. Thermal Bonding
2. Catalyst insertion
3. UV Bonding

Fabricated Pt/Al$_2$O$_3$ catalyst
Thruster fabrication results

Integrated thruster
Experimental setup

- With sufficient propellant supplying response time
- Teflon tube with 1/16”, 1/32” diameter
- Additional valves for flow control and pressure drop to prevent capillary phenomenon

Diagram showing the experimental setup for the micro thruster performance test.
Thruster test setup

- Thruster
- Stand
- Sensor
- Plate
- Feeding line
Blended propellant preparation

- **Target performance**
  - Specific impulse higher than that of 98wt% H₂O₂
  - Minimum temperature at range of decomposition temperature higher than hydrazine(N₂H₄)

→ 30 O/F ratio was considered for 90wt% H₂O₂ and ethanol blending
Experimental test using blended propellant

Auto-ignition of blended ethanol by decomposed hydrogen peroxide

Plume condensation, visible only in the low ambient temperature
Repeatability test of the microthruster with unblended hydrogen peroxide 1.7 ml/min

- **Repeatability test using pure 90wt% H$_2$O$_2$**
- **Four pulse operation with 10 sec each pulse operation**
- **Repeatability successfully observed**
Test results with same flow rate

Thrust curve by ethanol-blended H$_2$O$_2$ and pure H$_2$O$_2$ at the same flow rate of 1.7 ml/min

- Comparison between pure H$_2$O$_2$ and blended H$_2$O$_2$
- Equal volume flow rate for each case, 1.7ml/min for 10 sec
- Improved thrust, specific impulse, and rising time

*Huh et al. 2014 J Micromechanics and Microengineering 24 104001
Test result of different volume flow rate

- Different propellant flow for same thrust generation
- Propellant flow changes following theoretical specific impulse 125s / 105s ~ 2.0ml / 1.7ml
- Different stability in the same thrust generation
Standard deviations of acquired thrust

Standard deviation for three cases; difference between

(A) Actual thrust and average thrust
(B) Average thrust and steady thrust
(C) Steady thrust and actual thrust

Notice)
- Averaged by low pass filter
- Steady thrust of 30 mN
- For 1,000Hz sampling rate at steady state

Case (A), (C): The highest value in blended case
→ Actual thrust instability increased by propellant blending

Case (B): The lowest value in blended case
→ Average thrust became more stable by propellant blending
Microthruster with cooling channels
Experimental test results

Structural failure due to thermal shock

→ Low thermal conductivity of glass was good to conserve thermal energy, but fragility of glass was left as challenge
Regenerative cooling method for rocket

- Coolant flows inside tube of rocket structure
- Coolant is also used as propellant
- No performance degradation
Designed thruster with cooling channels

Regenerative cooled microthruster components

Thruster specification

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust</td>
<td>50 mN</td>
</tr>
<tr>
<td>Chamber pressure</td>
<td>2 bar</td>
</tr>
<tr>
<td>Propellant</td>
<td>90wt% H₂O₂</td>
</tr>
<tr>
<td>Specific impulse</td>
<td>72 sec</td>
</tr>
<tr>
<td>Propellant flow rate</td>
<td>0.07 g/s</td>
</tr>
<tr>
<td>Catalyst capacity</td>
<td>1.08 g/s/cm³</td>
</tr>
<tr>
<td>Catalyst volume</td>
<td>0.065 cm³</td>
</tr>
<tr>
<td>Catalyst</td>
<td>Pt / Al₂O₃</td>
</tr>
<tr>
<td>Catalyst support size</td>
<td>40 ~ 45 mesh</td>
</tr>
</tbody>
</table>
Microthruster main profile and channel

Component layers for the microthruster

Injector

50 µm

Nozzle

262 µm

370 µm

Injector

3.5 mm

4.5 mm

5.6 mm

5.5 mm

0.5 mm
Component layers for the regenerative micro thruster
Thruster fabrication results

- Optical microscope image

Micro cooling channel

Micro nozzle

Micro injector
Thruster integration procedure

1. Thermal bonding
2. Sensors installation
3. Catalyst insertion
4. UV bonding

Fabricated Pt/Al₂O₃ catalyst
Thruster fabrication results

Integrated microthruster with regenerative cooling channels
Experimental setup

Experimental setup for the microthruster test
Experimental test result
Test results

- Lower chamber temperature, pressure, and surface temperatures by regenerative cooling channels
- Estimated thrust generation decreased by 10% with excessive cooling effect
Test results comparison

- Relieved thermal shock by 64% with cooling effect
Microthruster using ADN-based propellant
ADN(Ammonium dinitramide)-based propellant

- Approximately 200–300°C preheating is required for the ADN decomposition by catalyst

<table>
<thead>
<tr>
<th>Propellants</th>
<th>LP1846 (HAN - based)</th>
<th>LMP-103S (ADN - based)</th>
<th>Hydrazine (N₂H₄)</th>
<th>95 wt.% H₂O₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>1.4</td>
<td>1.3</td>
<td>1</td>
<td>1.4</td>
</tr>
<tr>
<td>Specific impulse (s)</td>
<td>262</td>
<td>255</td>
<td>239</td>
<td>182</td>
</tr>
<tr>
<td>Density Isp (g·s/cm³)</td>
<td>376</td>
<td>332</td>
<td>241</td>
<td>256</td>
</tr>
<tr>
<td>Adiabatic Temperature (K)</td>
<td>2,171</td>
<td>2,054</td>
<td>1,183</td>
<td>1,154</td>
</tr>
</tbody>
</table>

LMP-103S
(Ammonium dinitramide 63% Methanol 18.4% Water 13.95% Ammonia 4.65%)
ADN microthruster

- Primary injection of H2O2 for chamber preheating (~ 300°C) and ADN decomposition

Successful catalytic combustion of ADN
Conclusion
Conclusion

- A liquid monopropellant microthruster using green propellant was successfully fabricated and operated.
  - Thruster fabrication using photosensitive glass MEMS process
  - Pt/Al$_2$O$_3$ catalyst fabrication for propellant decomposition
  - Sufficient propellant decomposition efficiency and thrust generation

- Use of high energy content to overcome the excessive heat loss at micro scale thruster was successfully validated.
  - Improved average thrust stability, but degraded actual thrust stability

- Cooling channel feasibility and effectiveness was validated in micro liquid propellant thruster for structural thermal management.
  - 10% thrust degradation and 64% relieved thermal shock with excessive cooling effect of micro channel

- Use of ionic liquid (ADN) in microthruster was tried and successfully decomposed without additional heater installation.
  - Use H2O2 for chamber preheating instead of additional thermal device.
Thank you