Thermal Model of MEMS Thruster

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Code 597
Overview

- Introduction
- Statement of Problem
- Approach
- Results
- Conclusion
Introduction

- Innovative science missions call for nanosatellites that are smaller, low-cost, and efficient.
- Nanosatellites require micro-components such as instruments, power, and propulsion.
- Current propulsion technology is not available for this application.
- GSFC is developing monopropellant MEMS thruster, applicable to the nanosatellites.
Monopropellant MEMS (Micro-Electro-Mechanical) thruster goals:
- Thrust: 10-500 µN
- Impulse Bit: 1-1000 µN-s
- Specific Impulse:
  - 130 seconds (Hydrogen Peroxide)
  - 200 seconds (Hydrazine)

MEMS thruster is fabricated of silicon component and glass cover.

Nozzle, plenum, chamber and injector are etched in silicon.

Monopropellants:
- Hydrogen Peroxide, H₂O₂
- Hydrazine, N₂H₄

Catalysts:
- Silver
- Platinum on Aluminum oxide
H$_2$O$_2$ (l) + n H$_2$O (l) → (1+n) H$_2$O(g) + 1/2 O$_2$ (g) + Heat.
Problem: Determine why full decomposition of hydrogen peroxide is not occurring in the MEMS Thruster.

- Suspected Cause: Poor Thermal Design
- Consequences:
  - Lower exit velocity and specific impulse
  - Low performance
Approach to the Problem

- Evaluate applicability of ANSYS software to analyze flow through MEMS passages
- Develop thermal model of the baseline MEMS thruster design
- Determine characteristic design parameters that need to be changed in Baseline MEMS design to increase chamber temperature

Diagram:

- Heat through conduction
- Heat through liquid \( \text{H}_2\text{O}_2 \)
- Heat from radiation
- Heat through vaporization of liquid water
- Heat through gases
- Heat generation
Analysis Tool

- Use ANSYS fluid module to determine the temperature profile and heat loss.
  - ANSYS Computational Fluid Dynamics module: FLOTRAN

- Limitations of FLOTRAN:
  - Single fluid (liquid or gas phase)
  - Either incompressible or compressible flow
  - Incapable of doing chemical reactions
FLOTRAN Validation

- Duplicate the fuel cell model performed analytically and experimentally by MIT
- The results are in good agreement.
- Difference in temperature due to different boundary conditions.

MIT Analysis

GSFC Analysis
Assumptions and Limitation

Assumptions of Thruster Model
- Steady State
- 100% complete decomposition
- Fluid is incompressible liquid hydrogen peroxide
- Thruster Nozzle Not included
- Ambient air convection
- Radiation neglected
  - It will be included in future.

Limitation of Thruster Model
- Fluid Solver (FLOTTRAN) can’t perform chemical reaction, so the temperature may be higher than adiabatic flame temperature
Justification for Deleting Nozzle

- Nozzle have compressible gas. The model is only analyzing incompressible liquid.
- Exit velocity strongly depends on chamber temperature.

\[ v_x = \frac{\gamma R T_o}{(\gamma - 1) M} \left( 1 - \frac{P_x}{P_o} \right)^{\frac{\gamma - 1}{\gamma}} \]

\[ T_x = T_o \left( 1 - \frac{(\gamma - 1) v_x^2}{2\gamma R T_o} \right) \]
Element and Boundary Conditions

- 3D CFD Fluid Element Type in model - FLUID142
- Inlet Pressure Range: 270 Pa to 350 kPa (0.04 psi to 50 psi)
- Outlet Pressure: 0 Pa
- Temperature Fixed at 300 K at entrance
- Exterior Surface exposed to ambient air convection.
- Uniform heat generation in the chamber
Thermal Model of Baseline Design

- Assumption
  - Mass Flow Rate: 385 µg/s
- Calculation
  - Heat Generation: 0.45 W
- Model Prediction:
  - Maximum Temperature: 530 K
Model Validation of Baseline Design

- Two measurements:
  - Temperature on Thruster
  - Decomposition of exhaust products, liquid $\text{H}_2\text{O}_2$ and liquid water, collected on refractometer

- Measured 305 K on glass cover
- Measured 9% decomposition based on exhaust products. It correlates to 315 K.
- Temperatures reasonably close to each other. Possible source of error: Thermocouple is in poor contact with glass cover.

![% Decomposition vs Temperature Graph](image)
Thruster Redesign Parameters

- Fluid Velocity
- Chamber Sizing Analysis
- Thermal Conductivity
- Reaction Time
- Material Volume
- Chamber Length
- Cylinder Model
- Injector Length
- Injector Diameter
**Goal:** Investigate injector size parameters to obtain higher temperature using FLOTRAN

**Thin wall and small diameter provide low thermal loss and create high chamber temperature**

<table>
<thead>
<tr>
<th>Inside Radius (µm)</th>
<th>Outside Radius (µm)</th>
<th>Fluid Length (µm)</th>
<th>Thickness (µm)</th>
<th>Power Generation (W)</th>
<th>Net Heat to Fluid (W)</th>
<th>Solid Conduction (W)</th>
<th>Temp. (K)</th>
<th>Solid/Fluid Heat Transfer Ratio</th>
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<td>5</td>
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<td>0.45</td>
<td>0.0288</td>
<td>0.4220</td>
<td>365</td>
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Chamber Sizing Analysis

- **Goal:** Investigate various lengths of square chamber sizes to obtain high temperature in short time.
- **Important constraint in catalyst bed design:** Residence Time. Various experiments reveal residence time between 0.53 to 0.64 seconds. These numbers correspond to 528 µm to 562 µm based on mass flow rate of 385 µg/s.
- **Square chamber length should be between 528 µm to 1100 µm** to provide faster thermal response time and adequate complete reaction.
Thermal Model of New Design

- **Assumption**
  - Mass Flow Rate: 385 µg/s
  - Chamber Length: 550 µm

- **Calculation**
  - Heat Generation: 0.45 W

- **Model Prediction**
  - Maximum Temperature: 724 K
  - 36.6% increase in temperature from baseline design
## Analytical Comparisons

<table>
<thead>
<tr>
<th></th>
<th>$Q_{\text{Heat}}$ (W)</th>
<th>$Q_{\text{liquid}}$ (W)</th>
<th>$Q_{\text{solid}}$ (W)</th>
<th>$Q_{\text{gases}}$ (W)</th>
<th>Max. Gas Temp (K)</th>
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<tbody>
<tr>
<td><strong>Baseline Design</strong></td>
<td>0.450</td>
<td>0.098</td>
<td>0.321</td>
<td>0.031</td>
<td>607</td>
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<tr>
<td><strong>New Design</strong></td>
<td>0.450</td>
<td>0.034</td>
<td>0.114</td>
<td>0.302</td>
<td>833</td>
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<td><strong>Percent %</strong></td>
<td>-65.3</td>
<td>-64.5</td>
<td>874.1</td>
<td>37.2</td>
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$$\Delta T_g = \left( \frac{c_{pl}}{c_{pg}} \right) \Delta T_i$$
Conclusion

- ANSYS is a reliable tool in analyzing MEMS thruster designs.
- ANSYS has limitations in studying reactive flow:
  - limited to single phase flow (liquid or gas)
  - cannot model chemical reactions in the flow
- Baseline design heat losses to liquid and solid were too large to allow full hydrogen peroxide decomposition.
- Established changes in characteristic design parameters in designing an efficient MEMS thruster
  - The new thruster design should realize a significant improvement in performance because of the increase in the reaction chamber temperature and faster thermal response time.
  - 36.6% increase in temperature
  - Heat addition to gases increased by 874%
Current Work

- Investigate thermal expansion between thin walls and glass
- Perform Stress Analysis on silicon and glass components
- Perform a thermal transient analysis with ANSYS
- Fabricate and test new thruster
- Investigate methods to improve ANSYS modeling capability to include chemical reactions and two-phases flow with University of Vermont
Any Questions?