DESIGN AND ANALYSIS OF A COLD GAS PROPULSION SYSTEM FOR STABILIZATION AND MANEUVERABILITY OF A HIGH ALTITUDE RESEARCH BALLOON

COLLEGE OF ENGINEERING & APPLIED SCIENCES SENIOR DESIGN THESIS

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MITCHELL B. BROWNELL
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WESTERN MICHIGAN UNIVERSITY
OBJECTIVE

Design a propulsion system to stabilize a high altitude research balloon and provide means of anti-rotation via yaw control
DESIGN CONSIDERATIONS

• FAA regulations
  • 2.72 kg limit for a single payload
  • 5.44 kg total
• Jet stream
• Temperatures and pressures at altitude
• Amount of thrust needed
• Time of system operation
**Propulsion System Selection**

- Propeller – low-density medium at high altitudes
- Solid Rocket Engines – inability for instantaneous control
- Chemical Combustion – volatile and high-density fuel
- Cold Gas Propulsion – feasible
BASICS OF COLD GAS PROPULSION

- Releasing a compressed gas (N2, CO2, AIR, etc) through a nozzle
  - e.g., Exhausting fire extinguisher while sitting in a rolling chair.
- Nitrogen (N₂) gas was selected
- Nitrogen has an average specific heat
- Abundant, ethically validated
- Hydrogen has a specific heat almost 14x that of Nitrogen but is highly combustible
<table>
<thead>
<tr>
<th>Concept Selection Evaluation</th>
<th>Design for Cold Gas Propulsion System</th>
<th>Western Michigan University</th>
<th>College of Engineering &amp; Applied Sciences</th>
<th>Mitch Brownell</th>
<th>Greg Neff</th>
<th>Ryan Savard</th>
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</thead>
</table>

## Design Concepts

<table>
<thead>
<tr>
<th>Concept Reference Number</th>
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<th>2.a</th>
<th>3.a</th>
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<tbody>
<tr>
<td>Gas/Propellant</td>
<td>Nitrogen</td>
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<td>Carbon Dioxide</td>
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<td>Thruster Material</td>
<td>410 Stainless Steel</td>
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<td>Other Design Notes</td>
<td>Converging</td>
<td>Custom Propellant Tank</td>
<td>Subsonic, Converging/Diverging</td>
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<td></td>
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<td>(High Pressure Converging)</td>
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<td>Custom Tank</td>
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## Rating Summary

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<tr>
<th>OVERALL DESIGN RATING</th>
<th>82.91</th>
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<td>Geometric/Design Rating</td>
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<td>Cost/Quality Rating</td>
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## Design Parameters/Conditions

<table>
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<th>Ref No.</th>
<th>Description of Design Parameter</th>
<th>Importance Factor</th>
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<tr>
<td>1.1</td>
<td>1. Manufacturability/Producability</td>
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<td>2. Thrust Maximization</td>
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<td>3. Gas Delivery System</td>
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<td>4. Design Considerations</td>
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<td>3.1</td>
<td>5. Geometric Characteristics</td>
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<td>3. Gas Delivery System</td>
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<td>2.2</td>
<td>4. Design Considerations</td>
</tr>
<tr>
<td>3.1</td>
<td>5. Geometric Characteristics</td>
</tr>
</tbody>
</table>

### Design Parameters/Conditions

#### 1. Manufacturability/Producability

- **Ease of material access**: 8.0
- **Part Complexity**: 7.0

#### 2. Thrust Maximization

- **Optimization of gas flow**: 8.0
- **Overall Thrust Value**: 8.0
- **Head Loss**: 9.0

#### 3. Gas Delivery System

- **Tank Design/Materials/Analysis**: 9.0
- **Gas Delivery System and Mass Flow**: 7.0
- **Material Properties**: 10.0

#### 4. Design Considerations

- **Ability for CAD/ANSYS modeling**: 10.0
- **Maximization of laminar flow**: 8.0
- **Ideal gas properties for application**: 10.0

#### 5. Geometric Characteristics

- **Size applicable to cube sat**: 10.0
- **Machinibility relative to size**: 6.0
- **Manufactability on application**: 8.0
OVERALL DESIGN

Nozzles
Balloon Mounting Points
Propellant Tank
Frame
Sensor/Equipment Deck
NOZZLE DESIGN PROCESS

Assumptions
Constraints
Operating Conditions

Determine thrust needed to counter rotation.
Determine area ratio of nozzle

Calculate exit velocity of gas

If thrust is too high or too low, adjust mass flow rate appropriately

Apply design to a system using four nozzles.

Confirm calculations using ANSYS Fluent
**Nozzle Design**

- Required thrust – 0.0476 N total, 0.0238 N per Nozzle.

- Velocity calculation – based on a set mass flow rate, the geometry of the nozzle, and the state of the gas.

- ANSYS simulation – modeled the geometry and specified inlet and outlet conditions

- If the velocity being produced did not produce enough thrust, either the mass flow rate was increased or the nozzle area ratio was increased

- Initial assumption of incompressible flow was confirmed through fluid flow analysis in ANSYS

\[
F_{air} = \rho_{air} V_{air}^2 A \\
V = \frac{\dot{m}}{\rho A} \\
T = \dot{m}V
\]
# RESULTS

<table>
<thead>
<tr>
<th></th>
<th>Hand Equations</th>
<th>Ansys</th>
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<tbody>
<tr>
<td>Velocity (m/s)</td>
<td>35.3</td>
<td>36.1</td>
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<tr>
<td>Thrust (N)</td>
<td>0.024</td>
<td>0.0256</td>
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<tr>
<td>Inlet Diameter (mm)</td>
<td>6.35</td>
<td></td>
</tr>
<tr>
<td>Outlet Diameter (mm)</td>
<td>1.5875</td>
<td></td>
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<tr>
<td>Inlet Pressure (Pa)</td>
<td>689475</td>
<td>1185</td>
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<tr>
<td>Temperature (K)</td>
<td>231</td>
<td>231</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>10.17</td>
<td>10.17</td>
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</table>
Graphical Nozzle Profiles

Density
GRAPHICAL NOZZLE PROFILES

TEMPERATURE
Graphical Nozzle Profiles

Pressure
GRAPHICAL NOZZLE PROFILES

MESH
PROPELLANT TANK DESIGN PROCESS

- Constraints
  - Operating Conditions
  - Nitrogen gas selection

- Volume & mass calculations

- Geometric Designs & Material Selection

- Modification of preliminary designs to for maximum Safety Factor

- Elimination of materials, geometric designs

- Stress/Displacement evaluation via FEA
Tank Design Requirements

• Lightweight material
• High Strength (i.e., high strength to weight ratio)
• Compatibility of pressure vessel manufacturability
• Low stress concentration (geometric factor)
• Compact, non-robust design
• High safety factor due to application
BASELINE VESSEL PROPERTIES

• Density of nitrogen propellant at operating conditions
  • 275.8 bar (4000 psi, 27.6 MPa), -60 °C (Ideal Gas)
• Nozzle mass flow rate: 0.0014 kg/s, 5 minutes continuous thrust
• 0.336 kg of N₂ gas (design mass)
• Using density relationship, vessel volume of 0.00088 m³ (0.88 L)
• Rough geometric boundary: (10 cm diameter, 18 cm length)
## Concept Summary

<table>
<thead>
<tr>
<th></th>
<th>Concept 1</th>
<th>Concept 2</th>
<th>Concept 3</th>
<th>Concept 4</th>
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</thead>
<tbody>
<tr>
<td>Overall Length (cm)</td>
<td>16.54</td>
<td>17.78</td>
<td>14.22</td>
<td>15.24</td>
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<tr>
<td>Overall Diameter (cm)</td>
<td>10.16</td>
<td>10.16</td>
<td>10.16</td>
<td>10.16</td>
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<tr>
<td>Displacement Volume (cm³)</td>
<td>1139</td>
<td>1065</td>
<td>1145</td>
<td>1056</td>
</tr>
<tr>
<td>Volume of Material (cm³)</td>
<td>115.5</td>
<td>140.2</td>
<td>140.1</td>
<td>141.4</td>
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<tr>
<td>Volume Inefficiency (%)</td>
<td>13.65</td>
<td>13.16</td>
<td>12.23</td>
<td>13.39</td>
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<tr>
<td>Tank Material</td>
<td>Carbon Fiber</td>
<td>Carbon Fiber</td>
<td>304 Stainless Steel</td>
<td>Titanium</td>
</tr>
<tr>
<td>Wall Thickness (cm)</td>
<td>0.25</td>
<td>0.13</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>1630</td>
<td>1630</td>
<td>8050</td>
<td>4430</td>
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<tr>
<td>Mass, excluding gas (kg)</td>
<td>0.28</td>
<td>0.25</td>
<td>1.13</td>
<td>0.64</td>
</tr>
</tbody>
</table>

Western Michigan University
CHosen Tank Concept

Overall Geometric Layout

FEA Loading

MAX
1475 MPa

MIN
34 MPa

FEA Von-Mises Stress Results
**CHosen Tank Concept**

**FEA Displacement Results**
- **MAX** 0.01127 mm
- **MIN** 0.0000 mm

**FEA Safety Factor Results**
- **MAX** 15
- **MIN** 2.45
Frame Design Process

Constraints Operating Conditions
Frame sizing was determined based on design of attached components.
Solidworks Designs & Material Selection

Frame design optimized for optimal system performance
Elimination of materials, geometric designs
Stress/Displacement evaluation via FEA
# Material Selection

<table>
<thead>
<tr>
<th>Material</th>
<th>AL 6061-T6</th>
<th>Ti-6Al-4V</th>
<th>17-7 Stainless Steel</th>
<th>High Modulus Carbon Fiber</th>
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<tbody>
<tr>
<td>Density (g/cc)</td>
<td>2.7</td>
<td>4.43</td>
<td>7.8</td>
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<td>Rockwell Hardness</td>
<td>40</td>
<td>36</td>
<td>38</td>
<td>10.16</td>
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<tr>
<td>Tensile Strength, Ultimate (MPa)</td>
<td>310</td>
<td>950</td>
<td>1240</td>
<td>1056</td>
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<tr>
<td>Tensile Strength, Yield (MPa)</td>
<td>276</td>
<td>880</td>
<td>1030</td>
<td>141.4</td>
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<tr>
<td>Elongation at Break (%)</td>
<td>17</td>
<td>14</td>
<td>3-7</td>
<td>N/A</td>
</tr>
<tr>
<td>Modulus of Elasticity (GPa)</td>
<td>68.9</td>
<td>113.8</td>
<td>204</td>
<td>215</td>
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<tr>
<td>Modulus/weight ratio</td>
<td>2.6</td>
<td>2.53</td>
<td>2.54</td>
<td>13.44</td>
</tr>
<tr>
<td>Mass of Frame (grams)</td>
<td>398.72</td>
<td>572.71</td>
<td>1818.4</td>
<td>380</td>
</tr>
</tbody>
</table>
**FRAME FEA RESULTS**

Max: 0.00269mm
Min: 0.00081mm

Total Deformation (mm)

Frame Assembly
**FRAME FEA RESULTS**

Maximum Principal Stresses on struts (MPa)
- Max: 2.350 MPa
- Min: 0.389 MPa

Total Deformation of Strut (corner impact 35N) (mm)
- Max: 0.008 mm
- Min: 0.002 mm
 COMPONENT MASS CONTRIBUTION

• Overall mass of system – 1.79 kg, design goal of 2.26 kg

- Frame/Piping: 29.41%
- Tank: 23.98%
- Nozzles: 10.77%
- Valves/Filters/Regulators: 1.73%
- Remainder for Sensors/Cameras/Equipment/GPS/Radiosonde: 34.10%
DESIGN RESULTS & RECOMMENDATIONS

- Total design mass is 79% of target mass
- Nozzle, frame and pressure vessel component design valid for application
- Testing/prototyping of propulsion system
- Remote control system design
- Simulate/analyze system within vacuum chamber to measure thrust characteristics
ACKNOWLEDGEMENTS

Our sincere gratitude to the following WMU Department of Mechanical & Aerospace Engineering Professors:

- Dr. Kristina Lemmer
- Dr. Jennifer Hudson
- Dr. Javier Montefort-Sanchez
- Dr. Bade Shresta

This thesis was funded through the Research Excellence Award though the Western Michigan University Office of the Vice President for Research.

Western Michigan University Aerospace Laboratory for Plasma Experiments for usage of laboratory space.

QUESTIONS & COMMENTS

Western Michigan University