CO₂ Cryofreezer Coldhead and Cycle Design Insights for Mars ISRU

Jared Berg (GRC LTT)
Malay Shah (KSC NE-XY)

Presented By
Jared Berg
jared.j.berg@nasa.gov

Thermal & Fluids Analysis Workshop
TFAWS 2018
August 20-24, 2018
NASA Johnson Space Center
Houston, TX
• In Situ Resource Utilization (ISRU) on Mars
  – Create propellant from Mars atmosphere
    • Must separate and compress CO$_2$ to utilize
      – Mars ~7 Torr (~0.1 psi), 95% CO$_2$, 3% N$_2$, 2% Ar
      – Approaches include direct compression, sorption pumps, freezer
  – Cryofreezer concept for ISRU discussed in 90s literature
    • Clark, Payne, and Trevathan experiment in 2001 (LM+JSC)
      – Describes basic configuration and tested simple coldheads
Atmospheric Processing Module

- Mars ISRU Pathfinder project APM (KSC)
  - CO₂ Freezer – Twin units
  - Sabatier reactor – Combine with H₂ to make CH₄
Cryofreezer Detail

• Sunpower CryoTel GT cryocooler
  – ~37 W lift @ 150 K
  – ~20% of Carnot efficiency @ 150K
  – 240 W input
  – External water cooling loop
  – Stirling cycle, helium working fluid

• Coldtip protrudes into freezing chamber

• Coldhead mounted on coldtip with thermal grease, securing nut

• External chiller loop maintains 15C rejection temperature
Why a coldhead?

- Initial sizing of cryocooler based on target production rate
  - How many Watts to cool gas and change phase?
  - Coldhead adds additional mass (launch and thermal) to increase collection performance

- Accretion insulates coldtip
  - Solid CO\textsubscript{2} \(\sim\) 0.1 W/m/K (Cook et al)

- Previous work explored some shapes
  - Muscatello and Zubrin SBIR used metal foams
  - Clark et al. tested bare coldtip and simple coldhead geometry
  - Muscatello et al. tried three other shapes with mixed results

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Similar Problems in Literature

• Heat sinks – well explored area, but phase change and accretion typically absent, mass-production design constraints
  – Dede et al study of 3D printed, flat plate, air-cooled heat sink, gradient-based optimizer
  – Iga et al study of 2D heat sink topology, continuous material distribution interpolated with finite element method
  – These and other approaches (genetic algorithms) yield “spikey,” “natural-looking” designs

• Phase change energy storage – liquid-solid transition, different density and convection regimes, cycling between states
  – Sparrow et al study with paraffin freezing on finned tubes
    • Fin area / temperature boundary condition / time correlation with collected mass
  – Pizzolato et al study of topology for phase change storage, acknowledges high physics complexity and design limitations of previous work
    • Density-based optimization, conduction dominated
    • Defined time minimization and steadiness maximization metrics
Initial Testing

- Based on previous experimental paradigm
  - Ferris wheel coldhead
  - Long freezing cycles (~8 hrs) going to “steady state” accretion levels
  - Temperature based cryocooler control (150K setpoint)
  - 1.2 SLPM CO$_2$ flow rate
- Steady state goal was attempt to correlate with CFD models
- Question assumptions
  - Why run so long?
  - Why use temperature control of cryocooler?
  - Why care about final collected mass?

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Computational Methods?

• CFD
  – STAR-CCM+ Melting and Solidification toolbox, volume of fluid method
  – Flow / no flow configurations
  – Single compound, solid / gas density change
    • Questionable accretion patterns, pseudotime

• Thermal Desktop
  – ACCRETE routine (basically reverse of ablation)
    • Stacked-layer technique not great for complex geometry
      – New feature, tricky to implement
    • Assumes energy is only limit on accretion rate

Reality?
Alternate Design

• Goals
  – Distribute metal more efficiently
    • “Biomimetic” branching shape
    • Curved top edge
  – Increase surface area
    • Increased diameter and length
    • Lattice-like surrounding belt
  – Flatten and extend collection performance curve
  – Demonstrate 3D printing with GRCop-84

• Results
  – Lower initial performance
    • Heat leaks
  – Superior late-cycle performance
  – 45 min to cool to 150K vs. 13 min for Ferris Wheel

• Success, but failure…
Cycle Insights

- Collection performance is a complicated function of surface area, conductive material distribution, etc.
- Because of temperature swing, any design must have sufficient performance to “pay off” time spent cooling 270K -> 150K
  - Minimize total mass of coldhead
  - Specific heat / conductivity
  - Scale up limit?
- Parasitic heat leaks from chamber
  - Radiation, convection to hot wall, bypass flow heating
- Early cycle performance is most critical
  - When has performance degraded sufficiently to stop and restart cycle?
    - Much shorter than we thought
  - How do the cycle and coldhead geometry interact?
- Simple optimization needed to determine ideal length of cycle and compare designs
Redesign

• Goals
  – Minimize mass to shorten cooling cycle
  – Increase surface area, but limit size to reduce heat leaks
  – Target early-cycle performance only

• Results
  – Max performance at beginning of cycle
  – Slow performance drop after peak
  – Poor late-cycle performance
More Testing

• Added data from legacy “Starburst” design
• Includes “Ideal” case meant to envelope possible designs
• Geometry can have measurable effect on collection performance
• Not a simple function of surface area

<table>
<thead>
<tr>
<th></th>
<th>Ferris Wheel</th>
<th>Branching</th>
<th>Tuning Fork</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume [in³]</td>
<td>1.74</td>
<td>6.67</td>
<td>2.37</td>
</tr>
<tr>
<td>Area [in²]</td>
<td>64.35</td>
<td>157.38 (with lattice)</td>
<td>128.4</td>
</tr>
</tbody>
</table>

Coldhead Performance Comparison

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Cycle Optimization

- Integrate collection performance curves
  - Assuming equal duration freezing / sublimation phases
    - Paired cryofreezer design
    - Sublimation rate determined by method
  - Starting offset determined by cool-down time
- Peak of curve indicates highest average collection rate
- Late cycle performance (Branching) never “pays back” initial time “debt”
- Best cycle times are much shorter than prior experiments
  - Given performance plateau, can trade collection rate vs. power efficiency, reduced on/off cycles, etc.
- Tuning Fork design superior
  - ~217 min cycle, ~100 min freezing
Non-condensable Gas Effects

- Ar and N\(_2\) remains after freezing, low temperatures and density limit diffusion rate
  - Previous work (Clark 2001) points this out and indicates importance of recirculation blower
- Differing impact on designs indicates geometry may be important
  - Tuning fork seemingly most affected
  - Ferris Wheel, Starburst most affected early in cycle
  - Branching least affected, likely due to lower overall rate
  - Additional cuts to open “pockets”? 
  - More open fin spacing, larger size?

![CO\(_2\) depleted region](image)
Conclusions

• Coldhead geometry does matter for performance
  – Tuning Fork ~11% improved cycle-averaged collection rate relative to Ferris Wheel / Starburst
    • But bounding “Ideal” case shows practical limitations
      – Only ~15% better than Ferris Wheel
      – Only 3% better than Tuning Fork
    • Worth trying harder?

• Cycle optimization is important
  – Impacts goals of coldhead geometry design
  – Allows trades with energy efficiency, system reliability, etc.

• Computational modeling is difficult
  – Multi-phase, multi-material, conduction and convection, 3D, transient, diffusion
  – Phase change energy storage analogy seems promising

• Novel concepts?
  – Self-cleaning / scraping coldhead
  – Other materials
References


