A "Green Cold-Gas" Propulsion System for Cubesats

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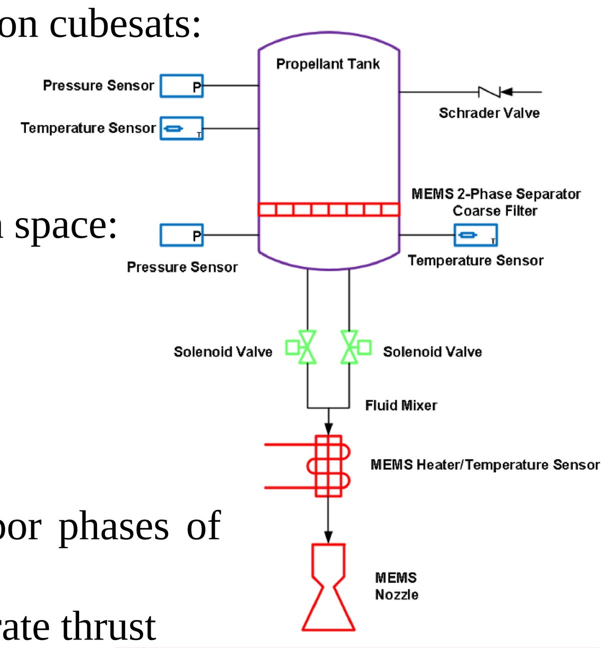
Background – Cubesat Maneuvering

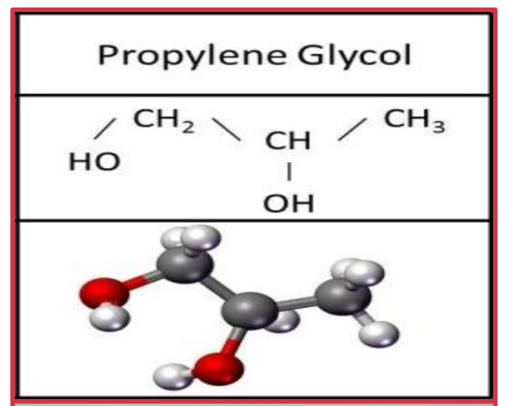
- Current Cubesat maneuvering techniques are mainly passive, with little to no ability to change orbits.
  - Basic attitude control primarily using Earth's magnetic field or gravity.
  - Very low torque, long time-constant stability (hours), and low accuracy.
  - Near-term flights with momentum wheels. Need momentum dumping.
- Available technologies
  - Magnets, Magnetorquers, Momentum wheels (needs dump), *Conventional thrusters (solid, fluid thrusters)*, Gravity gradient, Drag, Electric Thrusters (ion, plasma,…)
- A push in research to determine a high efficiency, green propellant that it is less harmful to the environment
- **This work is developing a "green" cold gas thruster system capable of producing thrust in the uN to mN range to be used for small satellites**

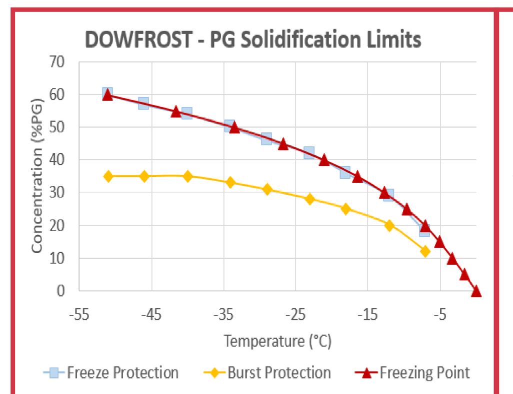
Cold Gas Thruster and Propellant

- **Cold Gas thruster:** commonly used in satellites since the 1960's due to their relatively low complexity, efficiency, and low cost/power consumption.
- Litany of limitations for cold gas thrusters used on cubesats:
  - Scaling down to the pico/nanosatellite size
  - Secondary payload status restrictions)
  - Regulations for non-toxic emissions
- Signficant benefits of using cold-gas thrusters in space:
  - Dynamic orbital maneuvers
  - Low budget, mass, volume
  - Minimal moving parts
  - Relatively inexpensive fabrication costs
- System Design
  - Nanochannel array separates liquid and vapor phases of propellant
  - Relies on vapor pressure of the fluid to generate thrust

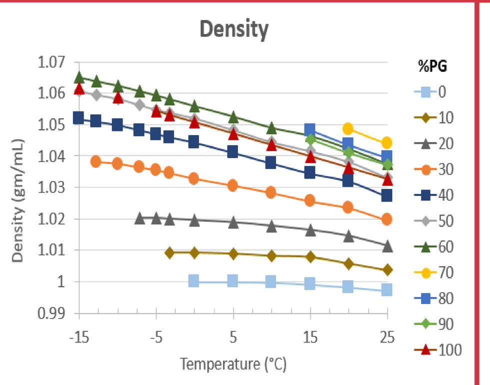


- **Propellant**: no pressurization and non-toxic exhaust.
- Based on the mission criteria, a water based solution with propylene glycol was developed.
- Propylene glycol is commonly known as modern day anti-freeze but has a multitude of applications
  - Humectant food additive
  - Bio-fuels
  - Pharmaceutical solvent
- Minimizes freezing in two ways:
  - Freezing point depression – hydrogen bond disruption minimizing chance for nucleation
  - Less solid ice means less overall expansion at higher concentrations of PG

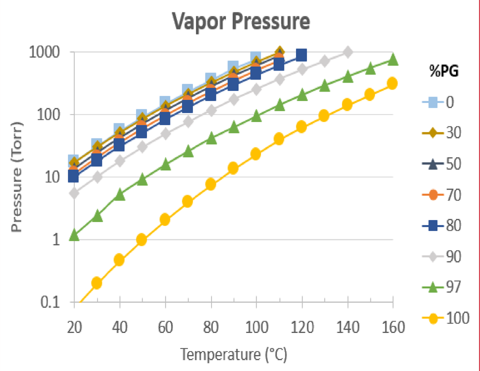




Aqueous Propylene Glycol has strict guidelines regarding working temperature to prevent expansion of water during freezing.



Density is known for liquid phase but not documented for solids. On a volume limited cubesat, any expansion could be catastrophic.



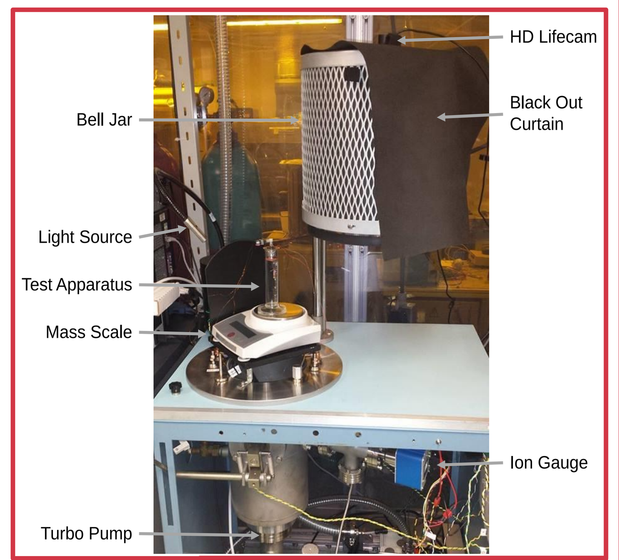
Water has a vapor pressure that is orders of magnitude larger than propylene glycol, but the relationship of the solution is nonlinear.

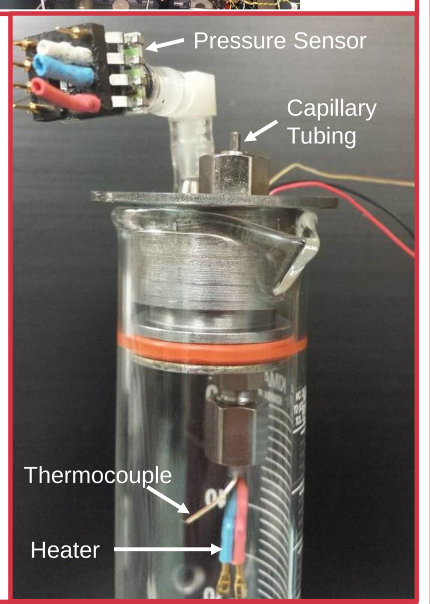
Propellant Characterization

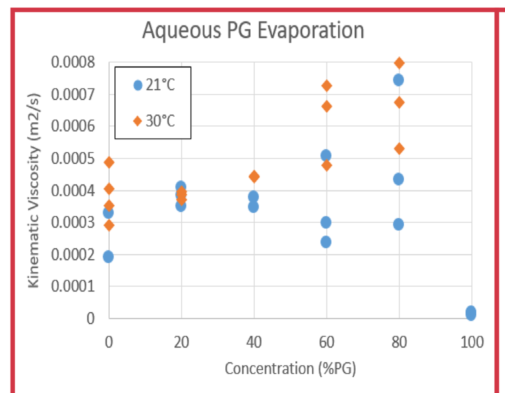
- Experiments were conducted in a vacuum chamber that maintained a milliTorr pressure to simulate space conditions
- Various trials were conducted to determine properties of vapor phase aqueous propylene glycol by varying:
  - Temperature – controlled with a bang-bang thermostat
  - Capillary tube diameter – order of hundreds of micrometers
  - Solution concentration – 0% PG (Water) up to 100% PG in intervals of 20% PG
- Flow in the regime tested is expected to follow Hagen-Poiseuille equation

$$\Delta P = \frac{8\mu L Q}{\pi R^4}$$

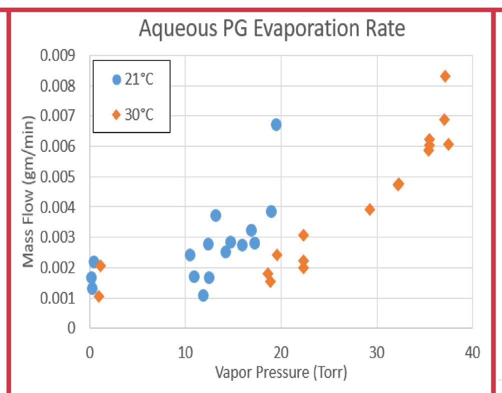
- Necessary data was gathered that will further the research for vapor flow through nanochannels
- For pure propylene glycol (100%PG) flow was higher than expected considering the low vapor pressure indicating potential slip



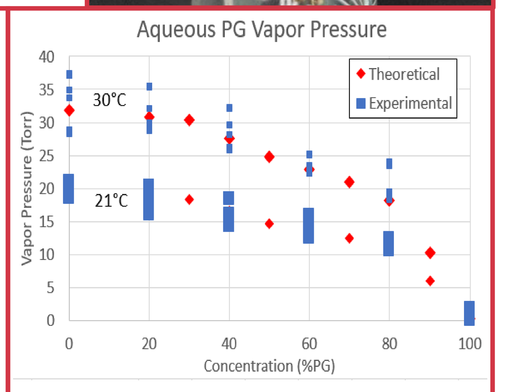




Viscosity of vapor phase aqueous propylene glycol is necessary to predict mass flow through a channel.



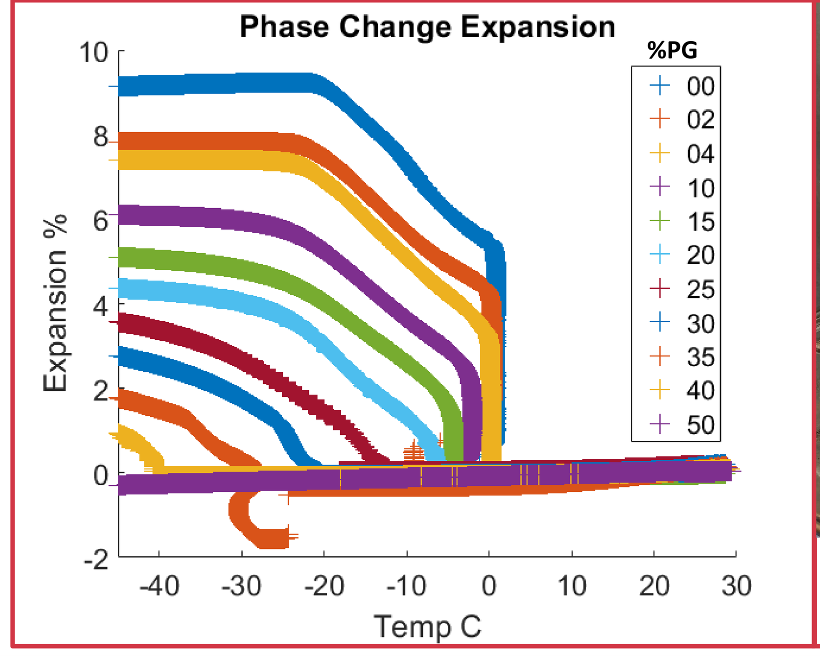
The relationship between mass flow and pressure indicates that there is a significant reduction in flow as %PG increases.

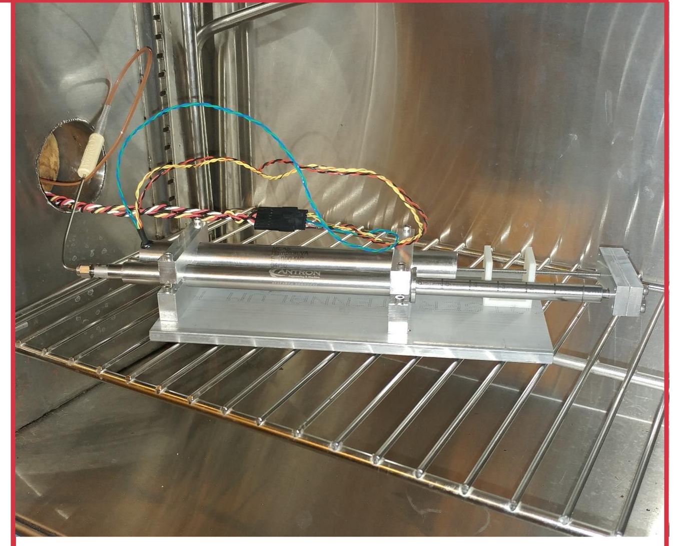


Vapor pressure data of the various concentrations matched the previously reported data.

Propylene Glycol Freezing

- Aqueous propylene glycol was tested in a thermally controlled chamber to measure the expansion that occurs upon transition from liquid to solid phase
- As temperature decreases the liquid compresses slightly, but sees a dramatic increase in volume once crystallization of the water occurs (~9% for water)
- Notably, the expansion during freezing decreased linearly with respect to increase in the concentration of propylene glycol in the aqueous solution





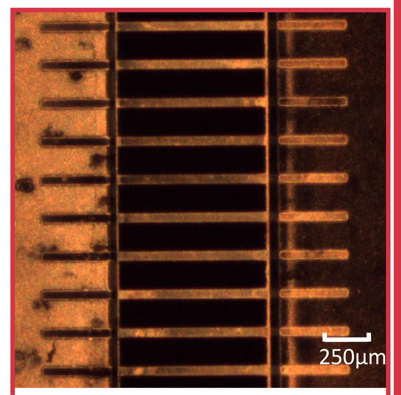
Temperature was controlled using a thermal chamber and the expansion of the fluid during phase change was recorded using a linear variable differential transformer.

Thrust Generated

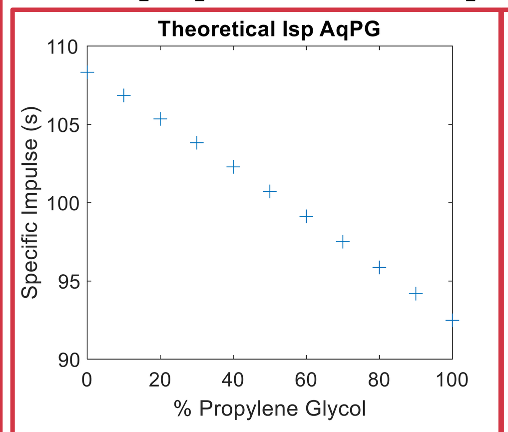
- Vaporizing a propellant via nanochannels to vacuum was studied as a means of propulsion for small satellites.
- Specific impulse (Isp) - measure of propellant efficiency

$$Isp = \frac{c^*\gamma}{g_0}\sqrt{\left(\frac{2}{\gamma-1}\right)\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \quad \text{where} \quad c^* = \frac{\sqrt{\gamma R T}}{\gamma\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2\gamma-1}}}$$

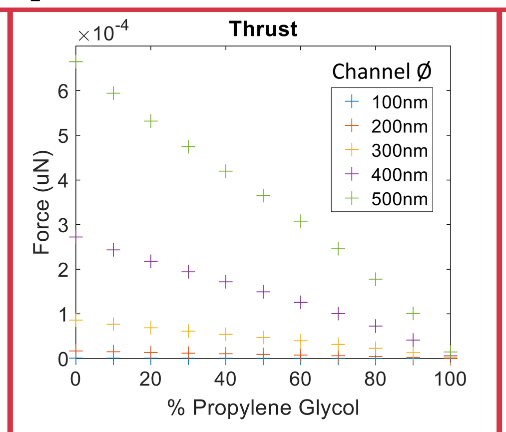
- Using Aqueous PG Isp and nanochannel array dimensions the theoretical thrust was calculated
- Thrust is tuned by adjusted the nanochannel dimensions or the propellant material properties



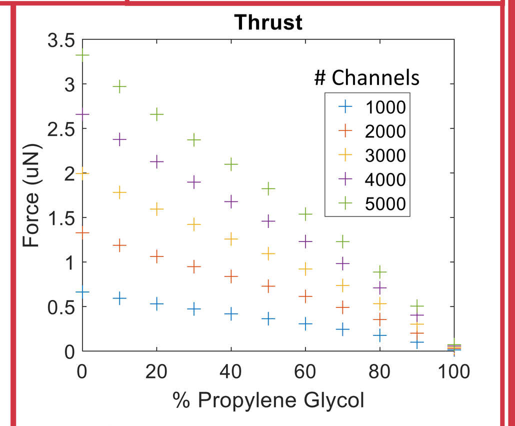
Channels 50μm wide x 500nm deep fabricated using KOH etching on silicon.



Theoretical Isp for water vapor is 108s while propylene glycol vapor was found to be 92.5s, comparable to other cold gas propellants.



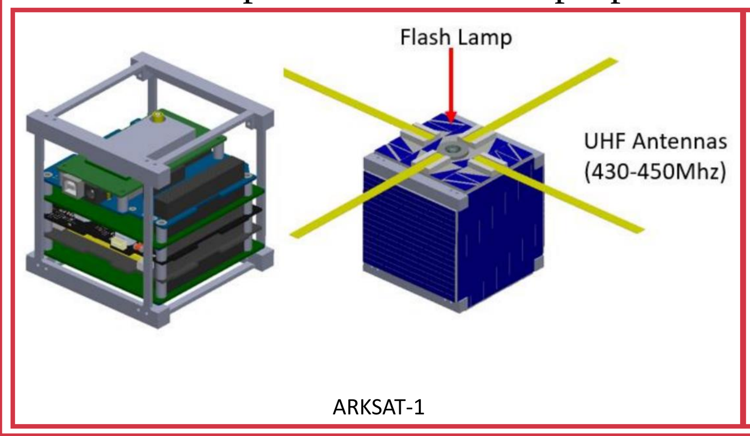
Thrust is proportional to diameter to the fourth power, a value that is scalable during fabrication.



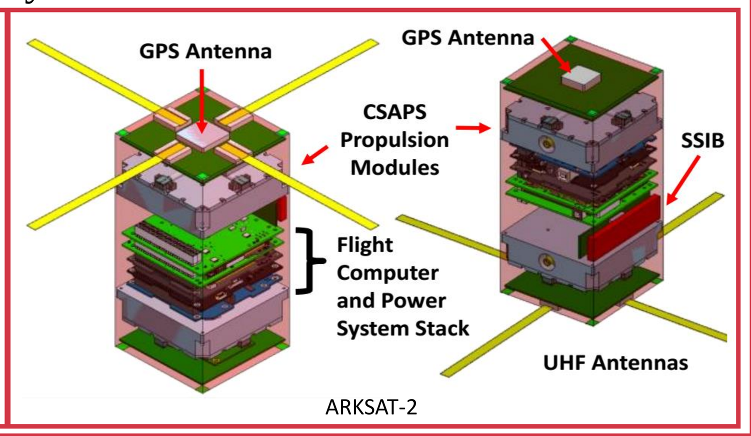
A nanochannel array is necessary to generate uN-mN level thrust. A 500nm diameter was used for reference.

ARKSAT-1 & ARKSAT-2

- **ARKSAT-1**
  - LEO-to-Earth atmospheric composition measurements
  - CubeSat deorbit using Solid State Inflation Balloon
- **ARKSAT-2**
  - In space demonstration of an agile, low-cost, non-toxic, biocompatible, and non-pressurized micro-propulsion system



ARKSAT-1



ARKSAT-2

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