Aerodynamic Stabilization with a Drag-makeup Propulsion Unit for Very Low Earth Orbit

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Introduction

Power constraints, large RF free-space path losses, and system complexity prevent many researchers from fielding novel sensing hardware aboard nanosatellite missions. Access to lower orbits would decrease downlink losses, improve optical sensor performance, and ensure natural de-orbit for inoperable payloads. Conventional propulsion technologies are capable of providing thrust required to maintain a low orbit, but increase system complexity and draw power away from sensors. The United States Naval Academy has developed the Water Vapor Independent Satellite Propulsion system (WISP) to maintain orbits as low as 250km. This system utilizes an aqueous methyl alcohol propellant that passively evaporates across a phase separation boundary, requiring no electrical power during steady state operation. Theoretical calculations show that this system of 1U volume (10 x 10 x 10cm) is capable of providing sufficient thrust to maintain 250km orbit for 3U satellite for approximately 30 days.

System Architecture & CONOPS

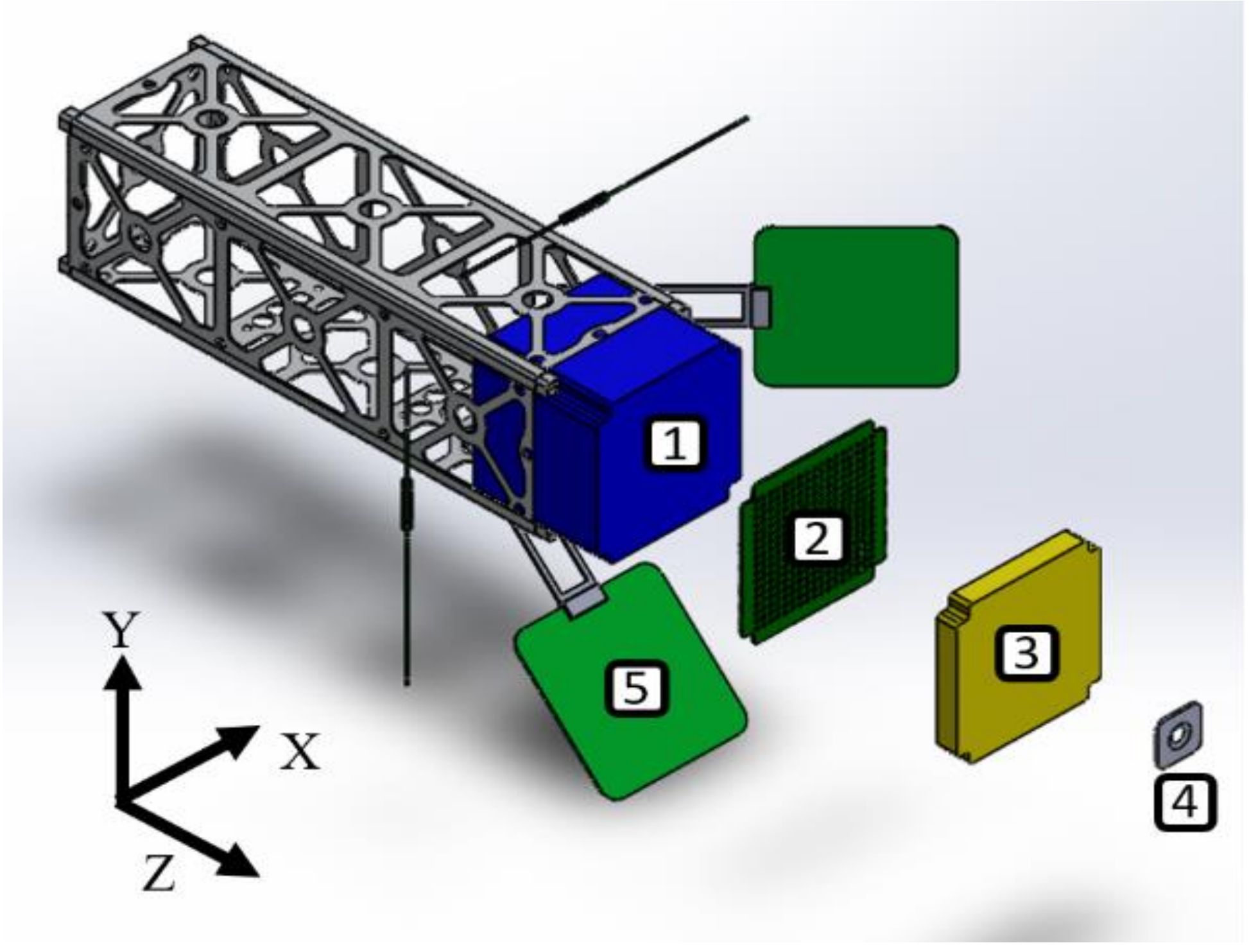

Figure 1. WISP system expanded view and CONOPS

WISP is composed of five main components: (1) a liquid propellant reservoir, a (2) passive phase separator, a (3) gas expansion chamber, a (4) converging-diverging micronozzle, and (5) four deployable attitude stabilization surfaces.

WISP's modular design and shelf-stable propellant allow for safe handling and storage followed by rapid integration to meet mission time constraints. After reaching the desired orbital altitude, attitude stabilizers deploy to detumble the spacecraft. Once a stable attitude is achieved, the thruster is activated, initiating propellant flow through passive phase separation. After propellant is exhausted, drag forces acting on the spacecraft cause natural deorbit.

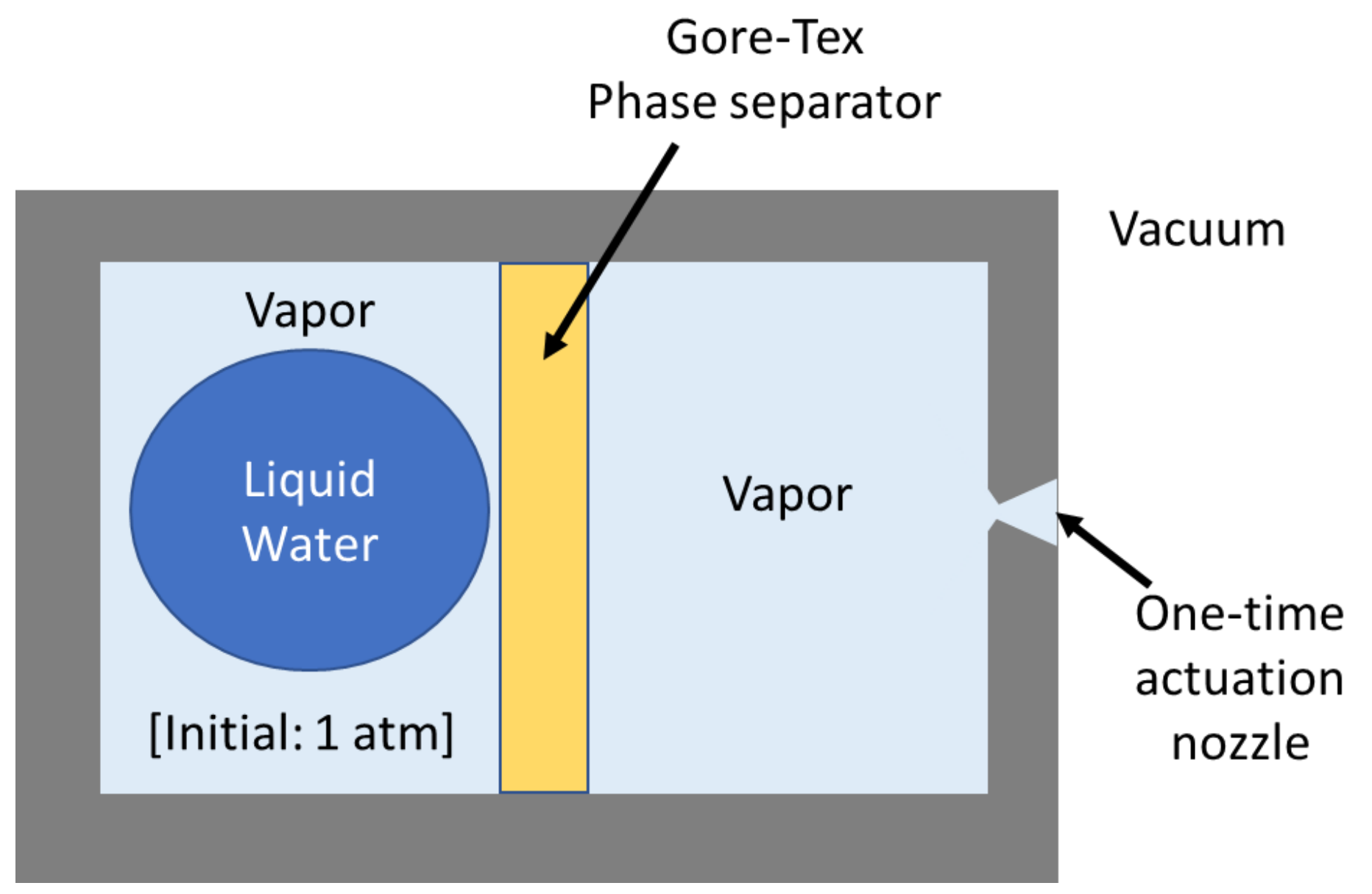

Figure 2. Propulsion unit depiction.

System Description

WISP is self-contained and designed for implementation in a 3U CubeSat form factor. The propellant reservoir ("1" in Figure 1) is capable of carrying up to 835 ml of propellant at 1 ATM. The 135 ml expansion chamber ("3" in Figure 1) allows evaporating propellant to expand and maintain inlet pressure for the nozzle assembly mounted on the outboard face of the chamber. The reservoir and expansion chamber interface only through means of a passive phase separation plane located along their adjoining surfaces. This phase separator exploits propellant surface tension properties to selectively retain liquid while allowing vapor to flow into the chamber. The phase separator ("2" in Figure 1) is mounted between the reservoir and chamber by bolting tabs located on the outside edge of the separator to the propellant reservoir body.

Once the exit plane of the nozzle is opened after reaching a stable on-orbit attitude, gas present in the expansion chamber will evacuate through the nozzle, as shown in Figure 2. As this gas evacuates, the pressure within the chamber will decrease, creating a pressure difference between reservoir and chamber and inducing flow of vapors generated at each separator pore.

Attitude stability is provided by atmospheric drag acting on attitude stabilizer surfaces. Since these surfaces deploy at a 135° angle relative to the surface of the satellite, any variation in attitude will alter the fraction of each surface that is normal to the direction of motion. This arrangement minimizes drag forces when WISP's z-axis is aligned with the direction of motion, providing a natural method of stabilizing satellite attitude. Previous design studies indicate that these attitude stabilizers would provide enough restoring moment to limit off-axis deviation between the Z-axis and direction of motion to roughly 20°.

Phase Separator Performance

Due to its ability to repel liquid water while allowing water vapor to pass through its membrane, expanded polytetrafluoroethylene (ePTFE) was chosen as the prime material to be tested as a potential phase separation boundary for the WISP system. ePTFE is unique in that each pore in its membrane is 20,000 times smaller than a water droplet, but 700 times larger than a water vapor molecule. This microporous structure thus repels liquid water while remaining breathable to water vapor. These unique characteristics allow ePTFE material to seamlessly operate as a water phase separator.

Figure 3. ePTFE material as phase separator being tested in vacuum chamber (left), and also in ambient condition (right).

Performance Analysis

Expansion Ratio

Maximum expansion ratio was determined by the stagnation temperature relation, applied to prevent an exit temperature lower than the propellant freezing point, as shown in Figure 4. In addition, the aerodynamic surfaces ("5" in Figure 1) will also be acting as a heater for the propellant, transferring heat into the system with max absorptivity and min emissivity.

Thrust & Runtime

To maintain orbit, a thrust equal to atmospheric drag must be generated. According to mean atmospheric density at 250 km for a circular orbit, a 3U spacecraft with drag coefficient of 2.2 would experience approximately 125μN of drag. Theoretical calculations yielded a thrust coefficient of 1.49, characteristic velocity of 516 m/s, and mass flow of 0.213 mg/s. By dividing propellant reserve by steady state mass flow, a runtime of 42.1 days was calculated (Figure 5)

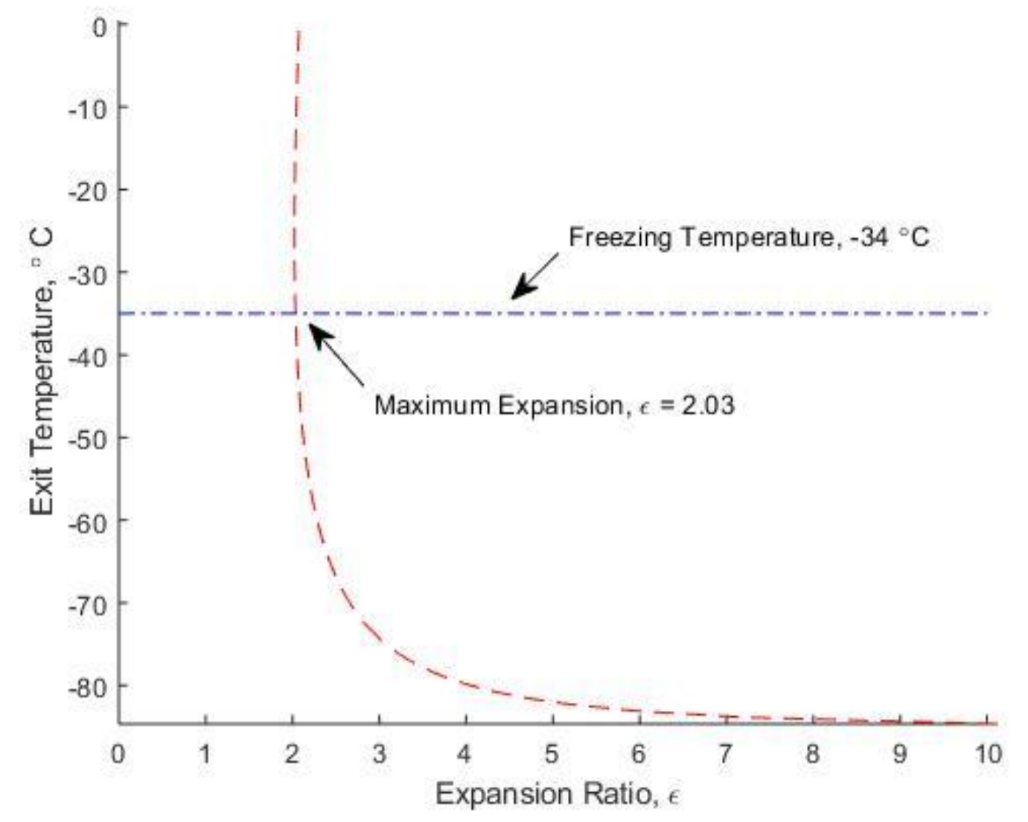

Figure 4. Maximum expansion ratio to prevent freezing

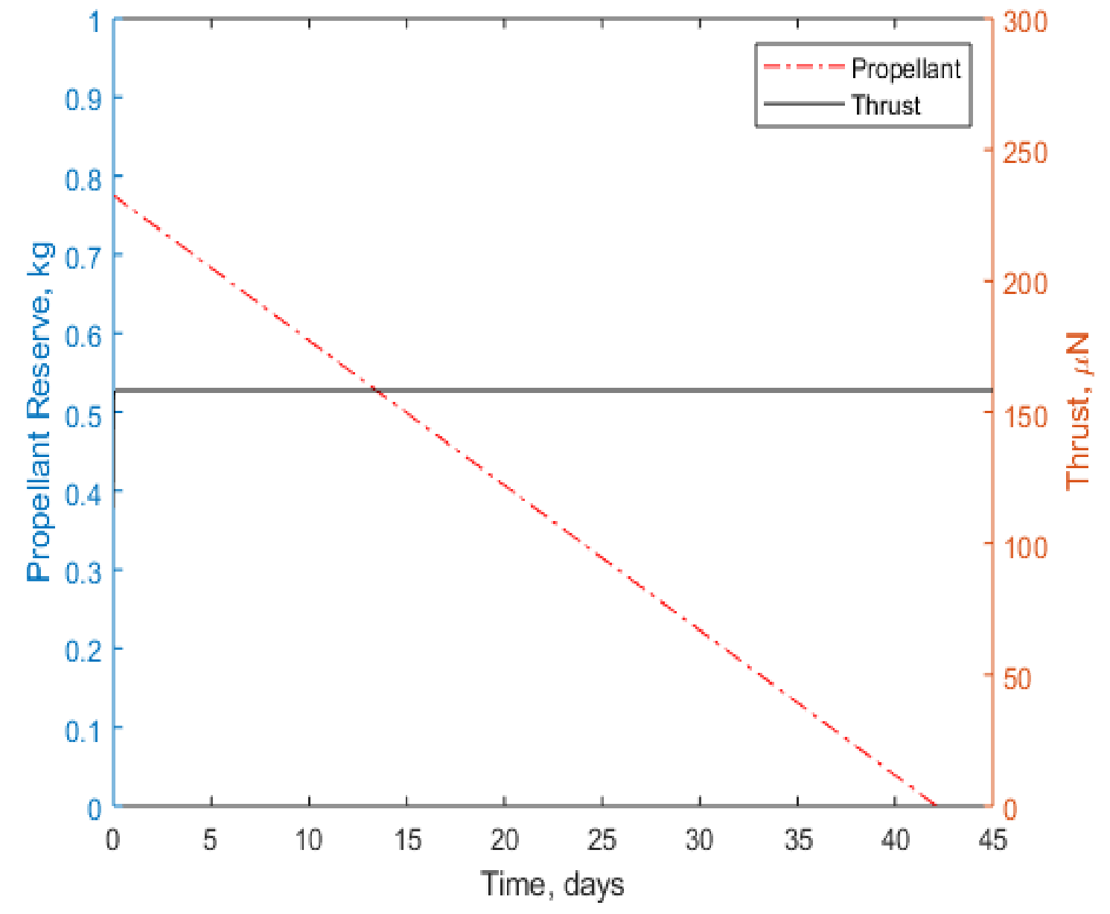

Figure 5. WISP operating runtime

Conclusion

Designed to provide thrust for nanosatellites meeting the CubeSat standard, WISP offers researchers the opportunity to collect data from the space environment without needing to design and integrate a custom bus, power management system, or communications hardware. Instead, scientific instruments can be installed directly into a universal bus system providing propulsion and attitude stabilization until natural deorbit at the end of the mission. This architecture would allow much greater numbers of researchers and institutions to contribute earth science data without adding to the volume of debris currently in orbit. This capability is contained within a 1U bolt-on architecture that allows for streamlined integration and use by members of the scientific community who lack dedicated satellite build capability. The thruster is scalable depending on the amount or propellant desired, and a system that fits within a 1U volume (10 x 10 x 10 cm) can extend the mission life of a 3U (30 x 10 x 10 cm) CubeSat to approximately 30 days.

One thing to note is that the nozzle performance was estimated using ideal rocket equations. At the scale of the nozzle throat area for the current design, the Reynolds number is low enough that the continuous flow assumption would start to introduce large errors. Previous researches by others have shown that the error is within 20% of the ideal values at this range of Reynolds number. Actual manufacturing and testing of the nozzle is planned to verify the theoretical performance.