Water Vapor Integrated Satellite Propulsion System (WISP) for Nanosatellite Orbit Maintenance

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Introduction

Power constraints, large 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

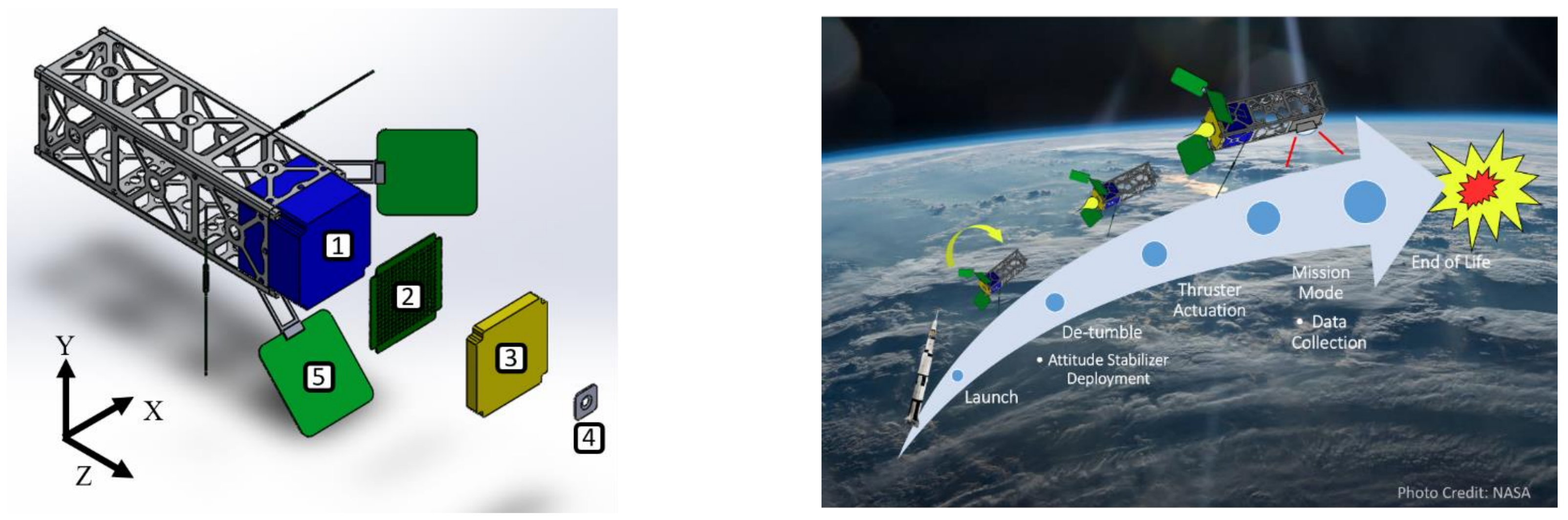

Figure 1. WISP system expanded view and CONOPS

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.

Performance Analysis

In order to achieve acceptable performance, stored propellant must be converted from liquid to gas phase prior to being expelled through the nozzle. Liquid propellant is allowed to evaporate from each separation pore according to gas reservoir pressure and temperature. Adiabatic, isentropic flow conditions were assumed.

Propellant properties (viscosity, density, vapor pressure) were projected by a combination of previously published data and weighted averages of constituents based on mole fraction.

Separation pore size was calculated for various operating temperature conditions according to the Laplace pressure and propellant surface tension strength. A minimum pore diameter of 70nm was calculated at the STP boiling point of pure methyl alcohol to ensure that no propellant constituent could escape the reservoir in liquid phase.

$$r = \frac{2\sigma(T)}{\Delta P}$$

Evaporation rates for each pore were calculated according to the Van den Bosch equation for pool evaporation, given propellant mass diffusivity, molar mass, and gas constant as functions of temperature.

$$E = k_C \frac{P_V(T)M}{RT}$$

Nozzle diameter was then selected such that mass flow through the nozzle would match mass evaporated through phase separation.

$$\dot{m} = p_1 A_t \gamma \frac{\sqrt{\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}}{\sqrt{\gamma RT}}$$

Using mass flow along with characteristic velocity and thrust coefficients determined from propellant properties, system thrust can then be projected.

$$c^* = \frac{\sqrt{\gamma RT}}{\gamma\sqrt{\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}}$$

$$C_F = \sqrt{\frac{2\gamma^2}{\gamma-1}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}$$

$$F = \dot{m}c^* C_F$$

Results

Expansion Ratio

Maximum expansion ratio was determined by the stagnation temperature relation, applied to prevent an exit temperature lower than the propellant freezing point.

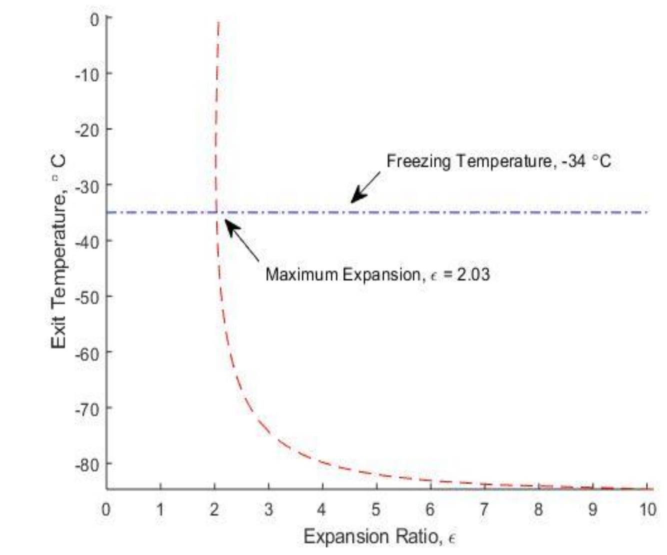

Figure 2. Maximum expansion ratio to prevent freezing

Thrust & Runtime

To maintain orbit, a thrust equal to atmospheric drag must be generated. According to mean atmospheric density at 250km 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 516m/s, and mass flow of 0.213mg/s through a 100μm diameter nozzle. According to these parameters, a steady state thrust of 158μN was determined. By dividing propellant reserve by steady state mass flow, a runtime of 42.1 days was calculated.

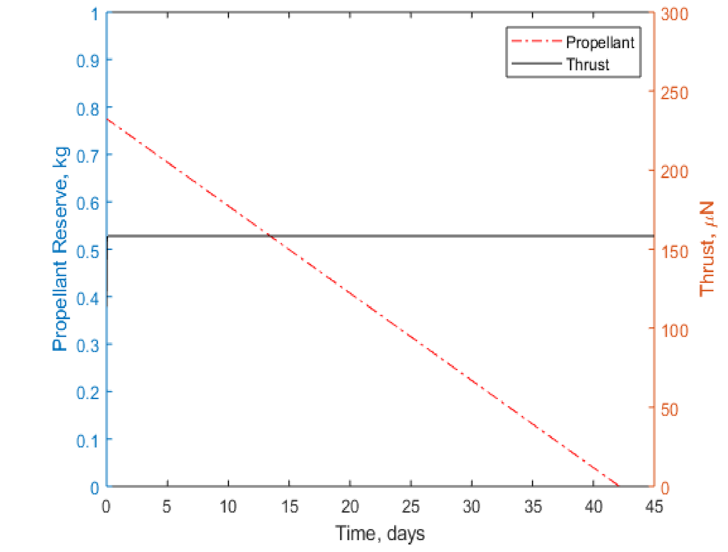

Figure 3. WISP operating runtime

Specific Impulse

Specific impulse was calculated as the quotient of the product of characteristic velocity and thrust coefficient, and acceleration due to gravity. This method yielded a theoretical specific impulse for the system of 51s.

References Printed in Paper SSC20-WP2-17