

De-Risking Space Debris Concerns of a Chemical Micropropulsion System using Metal Combustion

Masaya MUROHARA,^{1,2†} Marius C. BANICA,^{1†} and Matteo MADI²

¹ *Institute of Energy Systems and Fluid-Engineering, Zurich Univ. of Applied Sciences, Winterthur, Switzerland*

² *Sirin Orbital Systems AG, Zurich, Switzerland*

masaya.murohara@zhaw.ch, marius.banica@zhaw.ch,

[†] Corresponding Author

Abstract

This article addresses a hybrid chemical-micropropulsion using water and powdered-aluminum (Al) as propellants, by focusing on de-risking aspects. Propellants were selected for their safety, availability, multimode capability, and high performance. The use of powdered metal however raises concerns about exhausted condensed-combustion-products (CCPs) becoming space debris. High-speed imaging showed that CCPs remained below 0.1 mm for Al powders of around 4 μ m in diameter, compliant with space debris mitigation guidelines which requires solid or hybrid propellant rocket motors not to release particles larger than 1mm in their largest dimension into Earth orbit. Our results confirm system suitability for small satellite missions.

1. Introduction

The use of small spacecraft has been expanding, with a total of 2,956 satellites weighing less than 50 kg launched as of April 30, 2025 [1]. These small spacecraft are utilized not only for educational purposes and technology demonstrations, but also for practical missions such as communications and Earth observation [2]–[4]. The trend toward the use of small spacecraft is expected to accelerate further, with advanced missions such as constellations, formation flights, and deep space exploration being planned by leveraging their advantages in low-cost and short-term development [5].

A key component in enabling such advanced missions is the micropropulsion system. A variety of maneuvers are required to execute a mission, including orbit maintenance, orbital transfers, debris avoidance, and precise position and attitude control. In traditional large spacecraft, multiple propulsion systems optimized for each maneuver are employed to accomplish these tasks. However, small spacecraft often face severe constraints in volume, mass, and available power, making it difficult to accommodate even a single propulsion system.

Moreover, miniaturization introduces new challenges. For chemical propulsion systems, downsizing the combustion chamber can lead to increased pressure and thermal losses, and the reduced distance between components complicates thermal design. For electric propulsion systems, downsizing the discharge chamber can result in greater plasma losses and magnetic field leakage. Additionally, the limited physical space increases the risk of unintended short circuits and electrical discharge. These challenges specific to small propulsion systems have posed high barriers to entry.

Despite these difficulties, many startup companies have begun supplying small propulsion systems, particularly electric propulsion systems. Notable examples include Enpulsion, ThrustMe, and Pale Blue, and technologies such as FEEP, gridded-ion, Hall-effect, and resistojet thrusters are reaching practical levels of performance [6], [7]. On the other hand, companies handling small chemical propulsion systems tend to be traditional aerospace firms such as Aerojet Rocketdyne, MOOG, and VACCO. This is primarily due to the lower safety of chemical propulsion systems [6], [7].

The safety of a propulsion system is largely determined by the propellant used. There is a global trend toward replacing traditional hydrazine with alternative propellants [8]. However, major alternative propellants such as those based on ammonium dinitramide (ADN) and hydroxylammonium nitrate (HAN) have been predominantly developed by traditional aerospace companies, meaning that the barriers to entry remain high for newcomers [8].

Against this background, the present study reports on the initial development of a small chemical propulsion system that utilizes water and powdered metal, with a primary focus on lowering the barrier to entry while maintaining performance. Water offers high safety and has recently attracted attention for applications in multimode propulsion systems [9], [10]. Specifically, while water and powdered metal combustion can be used as a chemical propulsion mode, the same water can also be supplied to another propulsion system. This enables propellant tank unification, allowing volume savings and facilitating the realization of a multi-mode propulsion system.

Powdered metal, on the other hand, has a high energy density, enabling high thrust and specific impulse. While safety precautions such as wearing a dust mask and ensuring adequate ventilation are necessary during handling, specialized equipment such as SCAPE suits, as well as facility certifications or regulatory approvals, are generally not required. However, since condensed-phase particles will be emitted from the nozzle, it is necessary to demonstrate that these particles are sufficiently small so as not to violate space debris mitigation guidelines.

A manual issued by Japan Aerospace Exploration Agency (JAXA) reports on the damages of submillimeter debris on spacecraft [31]. It experimentally confirmed that if the debris size is smaller than 0.1 mm, they do not give catastrophically damage to solar array panels or power harnesses. Thus, the exhaust particles smaller than 0.1 mm are preferable, when it concerns the released particles from solid or hybrid propellant rocket motors into the Earth orbit.

2. Concept

2.1 Propellant selection

In selecting a propellant, four key factors must be considered: safety, availability, multimode capability, and performance. Although hydrazine has long been used as a conventional propellant due to its high performance, it poses significant challenges in the others [11]. Consequently, a variety of alternative propellants have been studied from the perspective of them. Representative candidates include ADN-based propellant, HAN-based propellant, nitrous oxide, hydrogen peroxide, water, and powdered aluminum.

The first two alternatives, ADN and HAN, are typically used in the form of ionic solutions such as LMP-103S and AF-M315E [12]. However, the raw materials themselves are considered hazardous substances and are subject to regulations similar to those for explosives, making them difficult to manufacture, handle, or obtain. Thus, despite their promise, they cannot be regarded as highly safe or readily accessible [12], [13].

Nitrous oxide, while relatively safe from a combustion standpoint, is a high-pressure gas and requires special handling licenses. It also acts as an anesthetic, necessitating strict monitoring of its concentration in enclosed facilities. Hydrogen peroxide exhibits safety levels highly dependent on its concentration. High-concentration hydrogen peroxide (>60%) is corrosive and self-decomposing, thus classified as hazardous. In contrast, low-concentration hydrogen peroxide (<60%) is much safer but suffers from poor combustion performance, with flame temperatures and specific impulse comparable to cold gas thrusters [14].

Powdered aluminum presents a trade-off between safety and performance depending on particle size. Larger particles offer higher safety but suffer from poor combustion efficiency. A powder size of around 10 micrometers is considered optimal, offering a favorable balance between ignition resistance and combustion performance [15]. Being a solid, powdered aluminum does not require high-pressure handling, and the necessary protective gear, such as dust masks, is relatively low-cost and less restrictive compared to other alternatives.

When powdered aluminum is used as a fuel, water emerges as a promising oxidizer. The application of aluminum and water as a propellant combination in space propulsion has been studied by A. Ingenito et al. [16] based on analyses using NASA's Chemical Equilibrium with Applications (CEA) software, this combination has been shown to be a promising alternative to conventional propellants from the point of safety and performance. In addition to its high safety, this combination offers excellent availability. Both water and powdered aluminum are available in many countries, reducing the burden of export/import and enabling straightforward loading at launch sites. In this regard, it clearly outperforms ADN and HAN, which have limited production and distribution. Furthermore, water can potentially be extracted on the Moon as well as aluminum, making this technology well-suited for future lunar exploration and long-term in-situ resource utilization.

Water also offers exceptional multimode capability and can be usable as a propellant for chemical and electrical propulsion. Most chemical propellants, due to their strong oxidizing properties, are incompatible with electric propulsion systems. However, water has already been demonstrated in resistojet and electrolysis-based thrusters, and its application in gridded-ion and Hall-effect thrusters has reached technology readiness level 6, awaiting only in-orbit demonstration [17]–[20]. This multimode capability provides many maneuvering options to achieve complex missions. For all these reasons—safety, availability, multimode capability, and performance—the combination of powdered aluminum and water can be regarded as a highly promising and future-proof propulsion solution.

2.2 System concept

While section 2.1 discussed the selection of propellants, this section outlines the conceptual design of a chemical micropropulsion system. For such a system, the following characteristics are considered desirable:

- Minimal volume, mass, and power consumption
- Absence of high-pressure gas components

- Propellants stored separately to prevent unintended ignition, enhancing safety
- Multimode capability
- Propulsive performance typical of chemical thrusters, i.e., thrust in the order of 0.1 N.

Based on the propellant combination of water and powdered aluminum discussed in section 2.1, possible implementations include ALICE, a solid propellant formed by mixing aluminum powder with water, and resistojet thrusters that utilize the steam generated by the exothermic reaction [21], [22]. ALICE has demonstrated thrust exceeding 100 N, but its solid-state nature raises concerns regarding handling safety. On the other hand, resistojet thrusters currently exhibit insufficient performance for practical application.

To address these issues, a hybrid thruster system is proposed [23]. This hybrid propulsion system consists of a water supply system, a powdered metal supply system, a combustion chamber, and a nozzle. The water supply system stores water in the liquid phase and vaporizes it in a vaporizer. The generated steam is supplied to the combustion chamber. To reduce power consumption, the system utilizes waste heat from the combustion chamber to supply the latent heat of vaporization. Water is transferred from the tank to the vaporizer using a blowdown system with a pushing gas. A portion of this gas is also used as the carrier gas for the powdered metal supply system, allowing for structural volume reduction. An inert gas is used for pressurization to ensure safety. Since the water tank will be the highest-pressure component at launch, it is desirable for the tank pressure to remain below the regulatory threshold defining a high-pressure vessel, thus avoiding handling restrictions.

The powdered metal supply system delivers the metal powder into the combustion chamber via a carrier gas method. A portion of the pushing gas from the water tank is supplied to the powder tank, fluidizing the powdered metal and forming a gas-solid two-phase flow directed to the combustion chamber [24]. A check mechanism is required between the powder tank and the combustion chamber to prevent backflow of steam or combustion gases when not feeding powder. The water vapor and powdered metal supplied to the combustion chamber are ignited using an igniter. To allow for multiple ignition cycles, a discharge-type igniter is adopted.

While combustion increases the chamber pressure, maintaining a low propellant supply pressure for safety and handling reasons would normally constrain the maximum combustion pressure. To resolve this, a pulsed operation mode is introduced to decouple propellant supply pressure from combustion pressure [25]. In this mode, as illustrated in Figure 1, propellant is first injected into the chamber in a short time, both propellant valves are closed to prevent backflow, then ignited to generate high-pressure combustion gas. After combustion, the system waits until the chamber pressure drops below the supply pressure before initiating the next cycle. This pulsed operation allows for independent design of the supply and combustion pressures. Additionally, by adjusting the number of pulses, it becomes possible to fine-tune total impulse, thereby minimizing the need for corrective maneuvers.

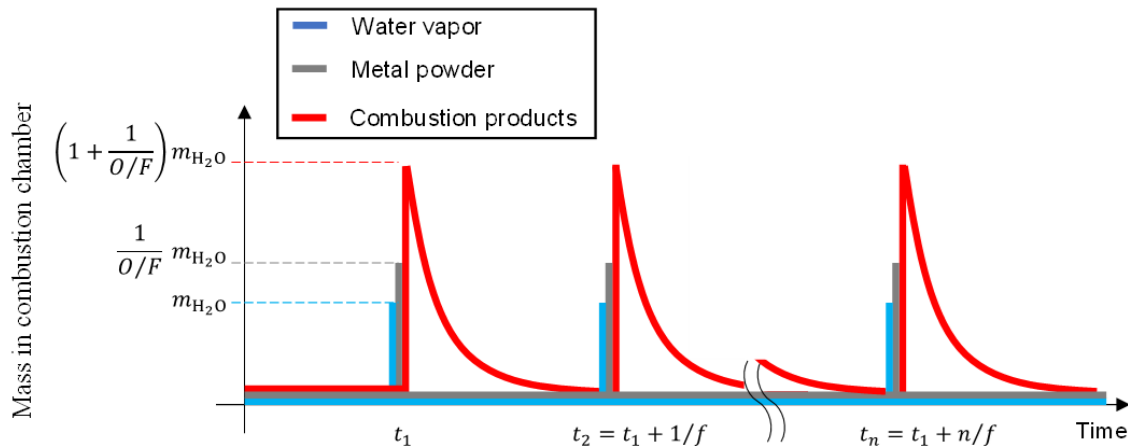


Figure 1 Schematic of mass time history in the combustion chamber of pulsed propulsion system in ideal situation. Where, m_{H_2O} is water vapor mass, O/F is oxidizer-fuel mass ratio, t_n is n th pulse, and f is frequency of pulse [26].

3. Size of exhausted condensed combustion products

A common issue with thrusters that use solid metal as propellant is the emission of solid particles into space [27]. This is an unavoidable problem due to the high boiling points of metal oxides generated during combustion. These solid particles can contaminate the orbital environment as debris, and depending on their kinetic energy, may render other spacecraft dam. For example, the debris mitigation guidelines specified in ISO 24113 regulate the release of solid particles larger than 1 mm into Earth orbit [27]. Similarly, the "ESA Space Debris Mitigation Requirements" (ESSB-ST-U-007 Issue 1, 30/10/2023) requires solid or hybrid propellant rocket motors to be designed and operated not to release space debris larger than 1 mm in their largest dimension into Earth orbit. In the case of this propulsion as well,

the emission of solid particles is unavoidable, and if the particle size is large, it falls under the regulations and cannot be operated in Earth orbit. Therefore, the size of CCPs emitted from the nozzle was measured, and the particle size distribution (PSD) was obtained. The purpose of these experiments was to make sure the CCPs under no circumstances are violating the space debris guidelines, i.e. the diameter of emitted particles from the nozzle are securely below 1 mm in diameter.

3.1 Method

For the measurement of PSDs, a particle image velocimetry (PIV) experimental setup was adapted. PIV is a technique used to measure velocity distributions by introducing tracer particles into the flow field and capturing their motion. Common tracer particles are plastics or aluminum oxide [28]. Since the solid particles emitted from this propulsion system are primarily composed of unburned aluminum and aluminum oxide, they can, in principle, be observed using a PIV setup. However, rather than using the PIV to calculate velocity distributions from observed positional information, we implemented post processing routines to obtain particle sizes from the captured images. The experimental setup is shown in Figure 2. As is typical for PIV, a planar laser sheet was generated that illuminated the plane of interest. A green laser (70JL, Ever Green) with wavelength 532 nm and energy 70 mJ was used for this purpose. The focal plane of the high-speed camera (pco1600, PCO) was adjusted by suspending a grid paper within the laser sheet. This also allowed calibration of the measurement length. The spatial resolution was limited by the size of the sensors in the high-speed camera, which was 20 μm . An initial attempt to directly measure PSDs from captured images without laser illumination failed. In parts, this is because the particles are engulfed by their flame, which may make them appear larger than they are. In addition, particles outside the focal plane must be rejected from the PSD calculations since they also appear larger than their true size. However, it is difficult to systematically identify particles outside the focal plane from the captured images in post processing operations. Laser illumination solved these challenges by only illuminating particles in the focal plane. In addition, the high-speed camera was equipped with a band-pass filter (FLH532-4, THORLAB) to ensure that only light reflected from particles illuminated by the laser sheet is captured. The captured image shows Mie scattered light since the laser wavelength was 532 nm and particle size is micrometre size.

A total of 170 images were acquired per experimental run at a rate of 14 fps, which was constrained by the laser's recharge time. PSDs were analysed using a custom-developed image processing algorithm. The processing procedure comprised five steps: (1) adjusting the upper sensitivity threshold of the camera to suppress noise, (2) binarizing the images using Otsu's method, (3) applying morphological operations for noise removal, (4) identifying particle contours, and (5) calculating particle diameters. The properties of the powders used and the experimental conditions are summarized in Figure 4 and Table 1. As shown in Figure 4, two types of powders were used in the experiment. To ensure good ignitability, a particle size of approximately 4 μm was chosen. Larger sizes, for example 10 μm , may be used in future experiments. Aluminum powders are available in spherical and non-spherical shapes, where the former are typically associated with higher costs. Therefore, it is important to determine the influence of the powder shape on both the combustion process and PSDs. The former was studied in earlier work [24] The latter was studied here by using spherical and non-spherical particles from different suppliers, as shown in Figure 5.

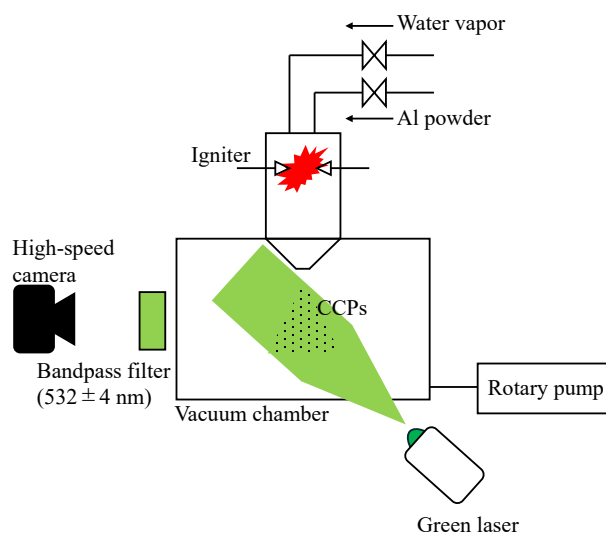


Figure 2 Schematic representation of the experimental setup for the measurement of CCP PSDs in the plume of the micropropulsion system.

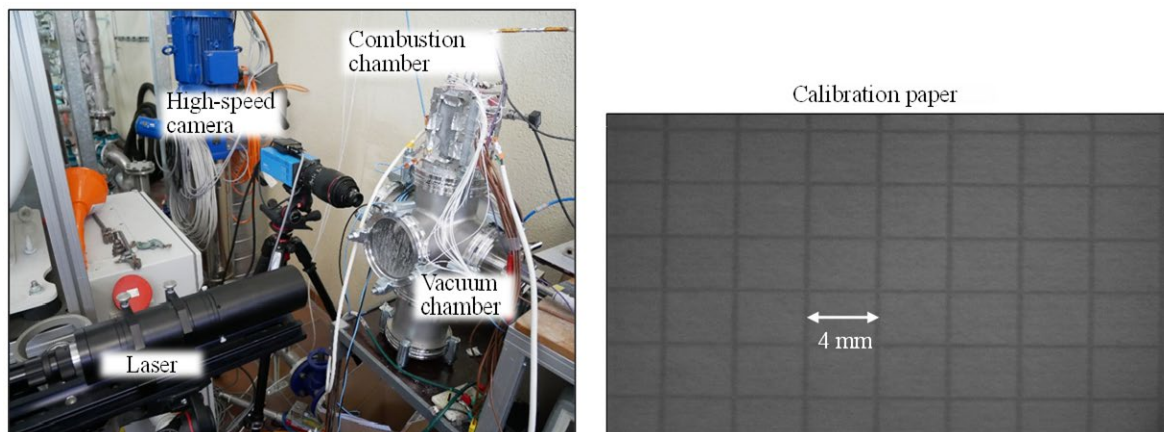


Figure 3 Experimental setup for the measurement of CCP PSDs in the plume (left) and the calibration paper (right).

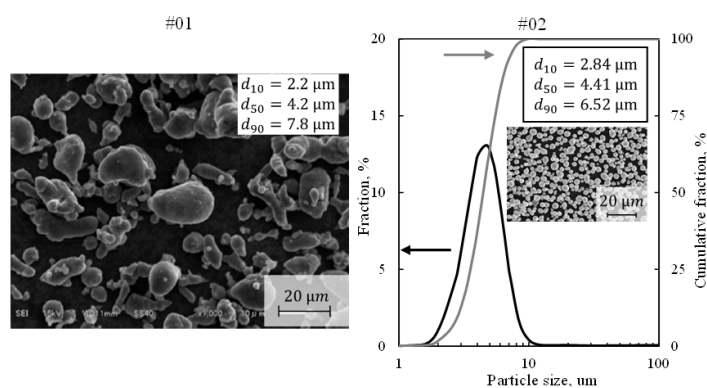


Figure 4 Aluminum powder used for the present investigations: 4 HPS from Toyal (#01) and AL4310 from Stanford Advanced Materials (#02). The pictures were taken by scanning electron microscope and provided by each supplier.

Table 1 Experimental conditions for CCPs size measurement. The H₂O mass and pressure are those in the combustion chamber just before the ignition.

Exp. No.	Powder No.	H ₂ O mass (pressure)	Injected powder mass	Ox./Fu. ratio
#01	#01	143.7 mg (80.4 kPa)	308.3±37.8 mg	0.47±0.06
#02	#02	129.1 mg (71.6 kPa)	201.7±75.6 mg	0.64±0.25

3.2 Result and Discussion

The measurement results are presented in Figure 5. Here, the particle sizes are divided into bins of size 11.9 μm, which are plotted on the horizontal axis. The bins size was the pixel size of the images. The vertical axis shows the probability of a particle of being in a particular size bin. The left and right figures show the results for the non-spherical and spherical powders, respectively. It can be observed that the resulting PSDs are nearly identical for both powder types, from which it may be concluded that the powder shape, at least for the size range studied here, has no significant influence on the PSDs of ejected CCPs. However, we point out that the shape is expected to affect various other variables, such as such as flowability, cohesiveness, and ignition delay [30], [31].

Although the original aluminum particles used in the experiments had diameters of 4.2 μm or 4.4 μm (nonspherical/spherical), the PSD mode of the exhausted CCPs fell within the range of 20–40 μm. This suggests that a particle agglomeration has occurred within the supply line, combustion chamber, or nozzle. We, therefore, suspect that a reduction in agglomeration will lead to a further reduction in ejected CCPs sizes.

While the use of larger aluminum particles has previously been noted primarily for issues such as delayed ignition and reduced performance [32], the present results suggest that agglomeration might also lead to the ejection of excessively large CCPs if larger powder particle sizes are used. If CCPs with diameters exceeding 1 mm are released, operation in Earth orbit becomes non-compliant with debris mitigation standards, effectively rendering the propulsion system unusable for its intended application. In contrast, with the ~4 μm particles used in this study, the maximum observed particle size remained below 0.1 mm (see Figure 5), confirming that the risk of space debris generation is sufficiently low, taking into account current space debris mitigation guidelines This is of course a subject of further works to

thoroughly study the impact of such tiny – micrometer size – particles on space environment and spacecraft operations in long term.

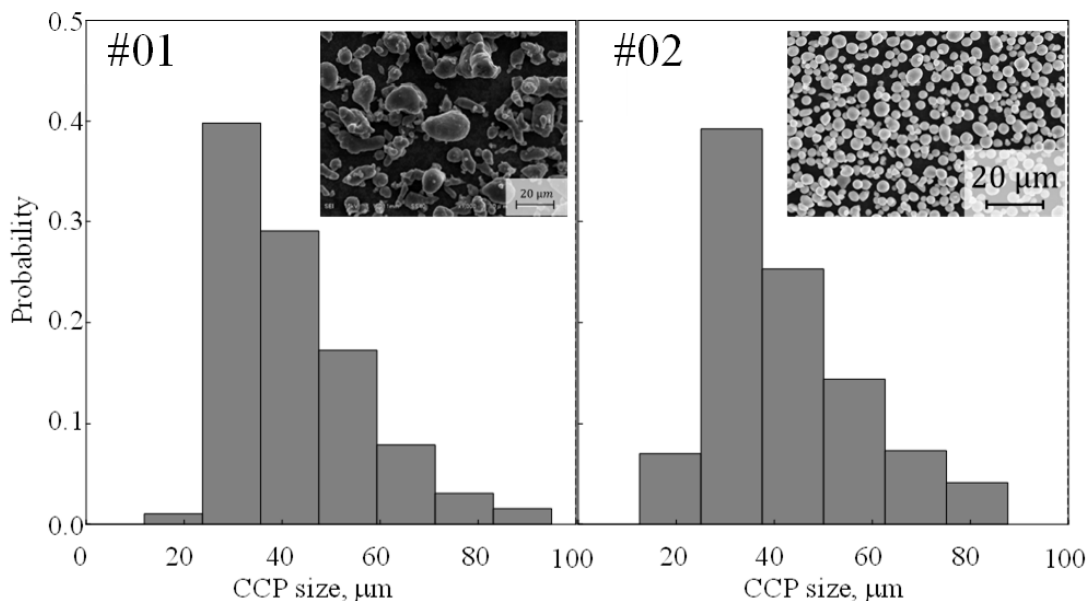


Figure 5 PSDs of CCPs size for a single experimental run. The pictures are same ones shown in Figure 4.

4. Conclusion

This study reviewed and evaluated the concept of a chemical micropropulsion system designed specifically for small satellite applications. The propulsion system utilizes water and powdered aluminum as propellants, selected based on four key criteria: safety, availability, multimode capability, and performance. Water offers high safety, widespread availability, and compatibility with multiple propulsion modes, including electric thrusters. Powdered aluminum, in turn, provides high energy density and solid-state storage advantages. This combination also shows promise for long-term sustainability, with potential applicability in lunar or deep-space environments due to the abundance of both materials.

The proposed hybrid system meets requirements placed on small satellites, including strict limitations on volume, mass, power, and operational safety. It features separate storage spaces for fuel and oxidizer for enhanced safety, and a pulsed-mode combustion chamber to avoid the use of high-pressure gas systems. Water is stored in its liquid phase and vaporized using waste heat from the combustion chamber, while powdered aluminum is delivered via a carrier gas flow, both contributing to compact system architecture. The pulsed operation not only allows independent control of propellant supply and combustion pressure but also enables fine adjustment of total impulse for precision maneuvers. One critical concern when using metal-based fuels is the formation of CCPs, which may contribute to space debris. ESA Space Debris Mitigation Requirements and ISO guidelines requires that solid or hybrid propellant rocket motors to be designed and operated not to release space debris larger than 1 mm in their largest dimension into Earth orbit.. Although the aluminum particles used in this study had a primary diameter of approximately 4 μm, there was concern that agglomeration or growing could increase CCP size. Therefore, experimental validation using high-speed imaging and laser-sheet illumination was conducted to characterize the size distribution of particles exhausted from the nozzle. Results in Figure 5 showed that the CCPs remained below 0.1 mm in diameter for aluminum particles of around 4 μm in diameter, well within the space debris guideline limits.. This confirms not only the safety of the proposed propellant combination but also the feasibility of implementing such a propulsion system in operational small satellites. Overall, the results demonstrate that the water–powdered aluminum hybrid thruster offers a viable and forward-looking solution for safe, efficient, and scalable propulsion in future space missions.

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