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Contamination assessment of a freely expanding green propellant thruster plume

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Abstract. A number of propellant/thruster combinations are under development in recent years that aim to replace the prevailing hydrazine-driven reaction control thrusters with less hazardous substances ("green propellants"). With some of these systems already in orbit, characterizing their contamination potential in a space environment becomes relevant. In this paper we discuss experiments on plume induced contamination from a novel propene/nitrous oxide bipropellant thruster, including high-speed imaging, SEM-EDS analysis, QCM measurements and in-situ mass spectrometry. Additional measurements of combustion chamber pressure complement the overall characterization of the thruster performance in a high vacuum environment. The main findings of this exploratory study are strong indications of solid and liquid phase particles being ejected from the nozzle, which will be investigated in a subsequent phase of the activity.

1. Introduction

Spacecraft contamination due to reaction control thruster plume impingement is a subject of concern since the early days of space exploration, especially for long-term and manned missions, but also for spacecraft bearing sensitive instrumentation. Exhaust plume constituents of chemical propulsion systems are known to affect the properties and performance of functional spacecraft materials. In particular, they may alter the thermo-optical properties of thermal control surfaces, and mechanically or chemically erode protective or functional coatings. While the pertinent data gathered in space and on ground is sparse and hardly generalizable for the common hydrazine-based mono- and bipropellant propulsion systems [1], it is practically non-existent for either of the many alternative propellant/thruster combinations developed since about the mid-1990s in response to the imminent threat of a hydrazine ban under the European Regulation No 1907/2006 ("REACH"). This absence of data makes reliable plume contamination predictions during the design phase impossible, and potentially hinders the adoption of the novel propellant/thruster combinations for contamination sensitive missions. ESA has thus initiated a research activity with a particular green propellant/thruster combination, in which the composition of the freely expanding plume and its impact on properties of impinged representative spacecraft materials is evaluated in order to derive applicable input parameters for industry-standard numerical prediction software.

This paper presents the results of preliminary experiments with a green bipropellant propene/nitrous oxide reaction control thruster, dedicated to determining its contamination potential and general behaviour. Insights gained from these experiments will be used to optimize the aforementioned experiments regarding plume impingement and composition analysis.

2. Theory

Throughout this study we concern ourselves with the construction and operation of the particular thruster only insofar as it affects the plume gas expansion and production and distribution of potential non-gaseous contaminants. The main features of a thruster plume expanding into high vacuum ("free expansion") from a gas dynamic perspective are the following: Emerging from the combustion chamber, the propellant gas reaches sonic speed at the nozzle throat and continues to expand supersonically. Friction and heat transfer near the nozzle walls lead to the formation of a non-isentropic zone, the boundary layer. Boundary layer gas is much slower than the flow near the nozzle axis and thus tends to extend well upstream the nozzle exit plane ("backflow") once it reaches the nozzle lip, forming a potential source of spacecraft self-contamination. The supersonic core expands at an even greater rate after leaving the exit plane, associated with a decrease in thermal energy, which may promote condensation. A narrow zone around the nozzle axis, extending a few exit diameters downstream, is dense enough to be treated with the methods of continuum gas dynamics. Far away from the nozzle the plume gas is so rarefied that molecules practically do not interact with each other ("free molecular flow") and travel on straight paths unhindered.

Studying free plume expansion experimentally in a vacuum chamber is not trivial, as the chamber walls and the pumping system must be designed so as to prevent a build-up of background gas during thruster operation. The only way to achieve this in practice is to use large-surface cryopumps. The high-vacuum plume test facility for chemical thrusters at DLR Göttingen (STG-CT) [3] makes use of a liquid-helium cooled cryopump to enable plume analysis of actual mono- and bipropellant reaction control thrusters. Refrigeration to below 4.7 K becomes mandatory when hydrogen gas is a plume constituent and background pressure must be maintained below 10-5 hPa. While STG-CT provides this space-like vacuum for the thruster plume that will be required for QCM (quartz crystal microbalance) measurements, in-situ mass spectrometer species characterization, as well as material exposition in a later phase of the project, it is comparatively costly to run, and optical access is limited due to the cryopump necessarily enclosing the test section. However, much can be learned about the contamination potential of the thruster by conducting exploratory tests in a sufficiently large conventional, mechanically pumped vacuum chamber with better optical access, such as the DLR Contamination Chamber Göttingen (CCG). In such a chamber, background pressure will quickly rise during firing, providing a hindrance for the plume gas to expand. It is well known that in such a case a barrel-shock system will form, that will separate the supersonic dense gas ultimately downstream of the nozzle exit from the background gas. The axial extent of the barrel shock system is proportional to the square-root of the ratio of stagnation- to background pressure [4, 5]. Information from the background cannot propagate upstream past the shock system and thus all measurements and observations inside the domain enclosed by the barrel shock are perfectly representative of the free plume expansion.

3. Methods

Measurements are conducted at the CCG as well as the STG-CT test facility of DLR Göttingen. The bipropellant thruster under investigation is the Dawn Aerospace B20 model (6.6 N to 19.3 N), additively manufactured from Inconel 718. Propene (C_3H_6) as the fuel and nitrous oxide (N_2O, “laughing gas”) as the oxidizer are the two self-pressurizing propellants, each actuated by two solenoid valves (isolation and firing). Control electronics are built inhouse at DLR to trigger valves, igniter and measurement equipment in the required sequence. The thruster features a built-in ratiometric combustion chamber pressure sensor, along with a type-K (NiCr-Ni) thermocouple installed on the outside of the combustion chamber.

CCG is a 12 m^3 stainless steel vacuum chamber. The pumping system consists of two strands designed for high throughput, each of which is identically equipped with three pumps in series (Leybold SOGEVAC SV300B, RUVAC WH2500 and RUVAC WH7000), with a total effective pumping speed in excess of 12000 m^3/h. A background pressure in the low 10^{-3} hPa range is ultimately achieved, which rises to less than 0.2 hPa when firing a typical 250 ms pulse with the thruster described here, but returns to its original value within 30 s. The B20 thruster is shown in figure 1(a) mounted inside CCG, together with the Pitot probe used to characterize the expanding beam profile. A high-speed camera, seen in the background, is employed to detect potential liquid or solid contaminants ejected from the nozzle, provided they are sufficiently large. Possible solid contaminants are captured with double-sided adhesive carbon tape attached to both the Pitot probe support and the chamber wall facing the thruster. Samples are analysed using a SU3900 scanning electron microscope (SEM) from Hitachi High Technologies. The latter is equipped with an energy-dispersive x-ray (EDS) detector (Oxford Instruments Ultim Max).

Figure 1. Dawn Aerospace B20 thruster inside CCG vacuum chamber, together with a Pitot probe and a high-speed camera (a). B20 thruster installed in STG-CT with LED beneath the nozzle for shadowgraphy imaging (b).

As described above in section 2, STG-CT is a cryo-cooled high-vacuum plume test facility which allows to maintain a vacuum level below 10^{-5} hPa while firing small chemical thrusters (mass flow rates at the order of g/s) with hydrogen as a plume constituent. The cylindrical test section with a volume of 10 m^3 allows for a plume expansion well into the highly rarefied flow regime including the backflow region. Figure 1(b) shows the thruster mounted at STG-CT with a LED sitting right below the nozzle which is used for shadowgraphy high-speed imaging. A quadrupole mass spectrometer (MS, Hiden Analytical Ltd., model “HAL PIC 101”) faces the nozzle exit 3 m downstream on the plume axis for in-situ measurements. A spectral scan of integer increments of mass-to-charge ratio (m/z from 3 to 50) is used, so that both spectral and temporal information about the gaseous plume species can be obtained at reduced resolution compared to the attainable step size of 0.01. Additionally, a cryogenic QCM (CQCM, QCM Research, Type MARK 18) is mounted to the cryopump, facing the thruster under an angle of 30° to the plume axis at a distance of about 1,6 m in order to monitor condensable plume constituents just below 80 K. A built-in heater is used at the end of the thruster activity to conduct a thermogravimetric analysis (TGA) by heating the crystal surface at a rate of 2 K/min.

3.1. Thruster operation

To achieve nominal operation pressure in the feed lines (fuel and oxidizer are driven by their vapor pressure), the gas bottles are kept at room temperature. At CCG the latter varied between 21°C and 22.5°C from day to day. The resulting feed line pressure is documented for the length of each firing and varies between 9.25 and 9.58 bar (fuel) and 51 to 51.9 bar (oxidizer). An oxidizer-rich off-design operational point targeted for some firings is obtained by raising the N_2O gas bottle by 5 K, resulting in a pressure increase of 6.6 to 6.8 bar. In addition, operation at CCG allowed for the testing of

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varying pulse length as well as pulse trains. While testing at STG-CT, the maximum room temperature was 25°C with a resulting maximum feedline pressure of 11 bar (fuel) and 53.5 bar (oxidizer). In each case, a single pulse length of 250 ms was chosen.

3.2. High-speed imaging
A high-speed camera (Phantom UHS Series, Model v1210) equipped with a tele-lens (AF-S DX NIKKOR 55–200 mm) is set up outside an angled view port of CCG to observe the thruster and a downstream region of about 30 cm during firing, figure 1. Images are taken at a resolution of 1280 by 800 (approx. 400 µm per pixel) with frame rates ranging from 100 frames per second (fps) to 4000 fps. At STG-CT, a high-speed camera (ix Cameras, i-speed 726, resolution 2048x1536) observes the thruster nozzle with the same tele-lens from a top-view under an angle of 55°. In addition to indirect lighting, a LED with a diffuser plate serves as background light underneath the nozzle for shadowgraphy imaging. Images were taken at 200 to 1000 fps.

4. Measurements and results
4.1. Thruster performance
At CGG a variation of single thruster pulses and pulse trains were fired in the course of this investigation, with a focus on a nominal on-time per pulse of 250 ms. The overall behaviour of the thruster is very reproducible, as deduced from the high pulse-to-pulse repeatability of the combustion chamber pressure. Figure 2 shows a plot of the median combustion chamber pressure ($p$cc, in dark blue) for 30 representative 250 ms pulses. The pulse-to-pulse variation in the measurements is indicated by the 5th percentile range shown in light blue. A delay of about 15 ms from command to actuation is discernible for both, start-up and shut-down, with the combustion chamber pressure increasing only slightly during the duration of the pulse. Shown on the same time scale is the chamber background pressure, pb, recorded by a capacitance gauge mounted to the chamber wall. The background pressure repeatably remains below 0.2 hPa for duration of the pulse.

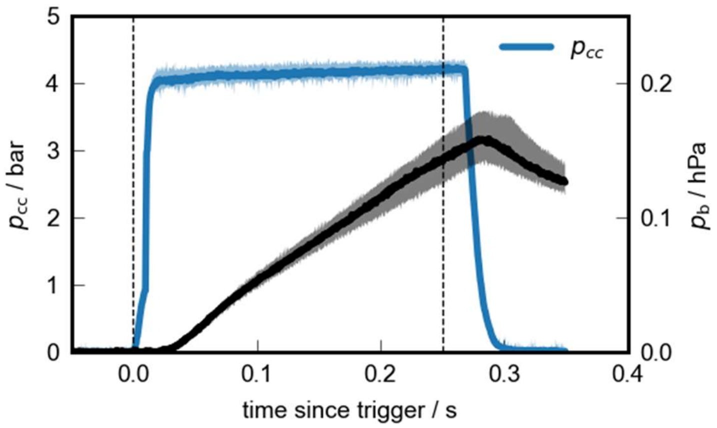

Figure 2. Combustion chamber pressure (box profile) and background chamber pressure for 30 pulses of 250 ms duration. Vertical dashed lines mark pulse start and end trigger.

At STG-CT about 30 pulses were triggered in order to familiarize with the thruster behaviour at the cryo-cooled facility. The thruster was first operated at a starting temperature slightly below the specified operational temperature and the first 15 pulses of 250 ms length were fired to raise the combustion chamber temperature to about 90°C. Before firing five nominal pulses (compare behaviour at CCG, figure 2) at the end of the test day, the temperature of the propellants had to be lowered as an increase of the feedline pressure greater than the specified operational pressure had presumptively led to a misfunctioning of the oxidizer valve.

4.2. Imaging
Examination of the thruster exit plane and near field using a high-speed camera at CCG, exposed a number of phenomena potentially relevant to contamination. Figure 3 displays what will be referred to as streaks of apparently glowing or reflecting solid particles which follow straight trajectories (a) and elastically bounce off of the Pitot probe structure (b). The number of streaks appears to change inconsistently between few and numerous from pulse to pulse, and typically no or very few streaks are observed during the second half of a nominal pulse (250 ms on-time). The same applies for pulse trains of several 250 ms pulses, where the sequence of observed events does not follow a discernible order. When evaluating a series of twelve oxidizer rich pulses, a slight decrease of streaks is observed on average only. No change compared to initial standard operational points can be observed when returning to these settings after the oxidizer rich runs. Overall, solid particles were detected leaving the thruster under angles no greater than 17° to the nozzle axis, with velocities ranging from approximately 175 m/s to 850 m/s (estimated from the streak lengths) and particle sizes in the range of 200 to 800 µm (estimated from the streak width). Smaller particles or droplets may well be present but not detectable with this technique. Further observations reveal that light is scattered in distinct areas which indicates the presence of small droplets.

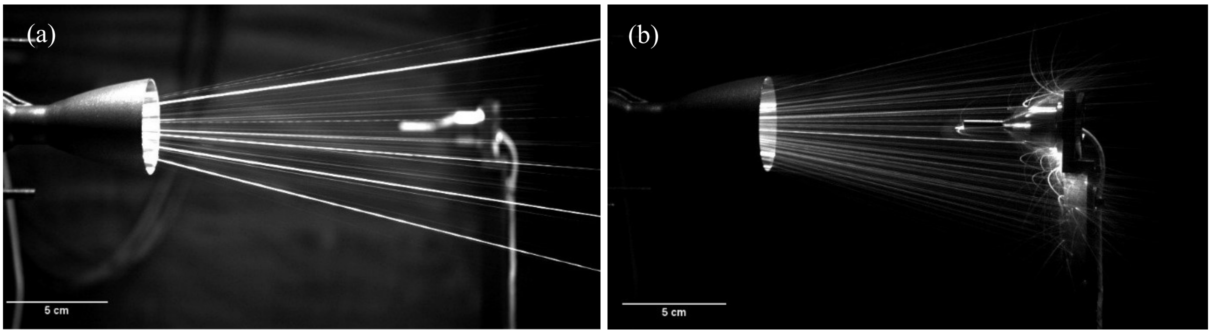

Figure 3. High-speed camera images of near field with bright streaks observed at 400 fps (a) and 1000 fps (b).

At STG-CT, the high-speed camera did not reveal as many details as in the CCG chamber, as the optical access is highly limited but a bright, striped cone emitted from the nozzle was visible at the beginning of most pulses as well.

4.2.1. Particle analysis. SEM inspection of adhesive carbon tape, which had been installed at CCG to capture ejected particles, revealed several beads with sizes on the order of 100 µm (figure 4(a)). An EDS analysis at 15 keV incident electron energy (table 1(a)) points to the composition of soda-lime-glass [6, 7]. The carbon signal, as well as about 14% of the oxygen signal, are due to the carbon tape itself. The beads appear transparent under the stereomicroscope and charge up lightly under the high-energy electron beam during EDS analysis, supporting the assumption of them being glass beads. Several even smaller spheres (figure 4(b)), with sizes ranging from 5 to 10 µm, yield EDS signals that strongly suggest Inconel 718 [8] (table 1(b)), the material the thruster nozzle is made of. Particles were captured in a pouch of adhesive carbon tape, and here too the oxygen signal as well as part of the carbon signal originate from the background. Both kinds of particles (glass and metal alloy) are so sparsely present, that no average population per surface area can be inferred from the findings.

4.3. Mass spectra
The mass spectrometry analysis conducted at STG-CT revealed the signature of both unburnt propellants and signals of exhaust gases nitrogen and water when the thruster was cold started below its operational temperature. With each following pulse the thruster warmed up and the amount of unburnt propellant decreased in comparison to the expected exhaust gases. The analysis yielded rather clean MS spectra at an initial combustion chamber temperature of 90°C with hydrogen as the main

constituent, a fraction of water below 20% and an unknown peak of over 40% intensity at a mass-to-charge ratio of 29. The temporary misbehaviour of the oxidizer valve due to an out of range increase in propellant temperature was verified by a distinct spectrum of unburnt propene.

Table 1. EDS elemental analysis results of glass beads (a) and smaller spheres (b).

(a) Element	A / wt%	B / wt%
O	49.2	47.4
C	22.8	23.9
Si	17.6	15.1
Na	6.1	7.6
Ca	2.9	3.7
Mg	0.6	1.8
Al	0.5	0.4

(b) Element	A / wt%	B / wt%	C / wt%
Ni	34	34.9	47.3
Cr	28.5	14.8	17.6
Fe	14.2	14.9	19.7
C	18.2	26.2	10.8
Nb	5.7	3.6	1.8
O	3.8	3.9	0.6
Ti	2.9	1.4	0.7
Mo	1.6	-	1.3
Al	1.1	0.4	0.1

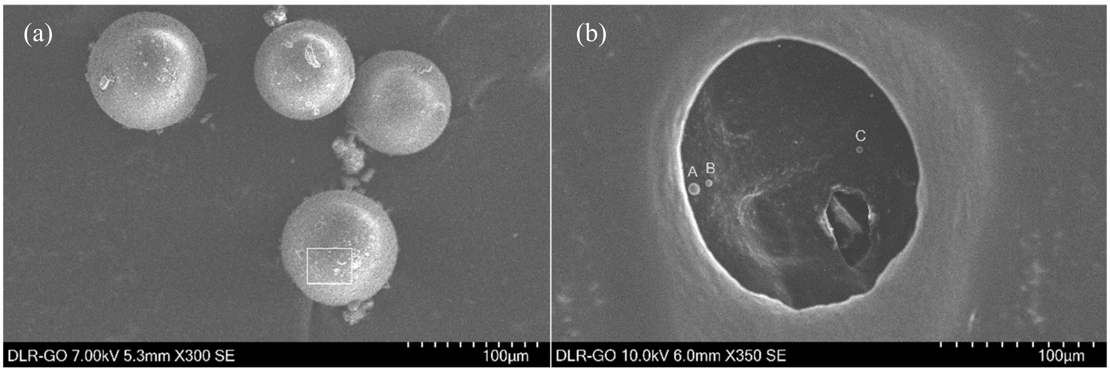

Figure 4. SEM images of beads (a) and spheres (b) captured on adhesive carbon tape during thruster testing.

4.4. QCM analysis

The QCM-TGA measurement conducted at the end of the test day at STG-CT exhibited three major desorption events (figure 5) of which the first one started just above 80 K exhibiting distinct rippling features. It is most likely caused by CO_2, one of the three main exhaust gases, while the unburnt oxidizer N2O could also be a source as a result of cold starting the thruster [9]. The second desorption peak occurs at about 150 K which may be related to the unburnt propellant propene. This correlation is based on the chemical species available from propellants and exhaust gases after ruling out all non-condensable species at the given QCM temperature. Propene impacted the QCM due to both the cold start of the thruster and one misfiring without the oxidizer. The 0^{th} order desorption peak starting above 160 K is most likely due to evaporating water. The desorption temperature matches the corresponding vapour pressure at an ambient pressure of 10^{-6} mbar according to the low temperature Arden Buck equation [10].

5. Discussion and outlook

Actual contamination prediction for spacecraft is inherently complex, as it depends not only on the source of contamination (here a reaction control thruster), but also on the properties of the impinged surface and the environment it is subjected to. In this first part of the activity, we studied the plume of a 20 N bipropellant propene/nitrous oxide reaction control thruster supplied by Dawn Aerospace.

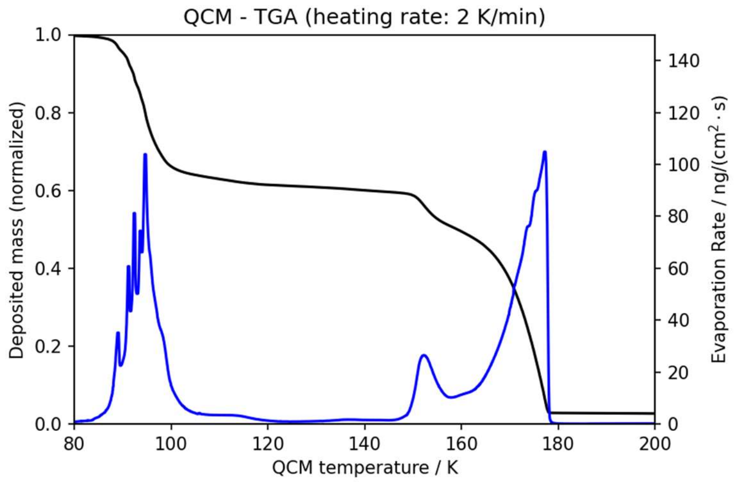

Figure 5. QCM-TGA plot of decreasing deposited mass and three major desorption events (evaporation rate).

The set of exploratory tests described in this paper provides the opportunity to familiarize with thruster operation, characterize its performance, as well as to verify and adapt plume diagnostics. The aforementioned findings help to design and improve subsequent sophisticated testing in the STG-CT facility. Operating the thruster inside the CCG test facility proved successful. With regard to the main objective of this study, the contamination behaviour of a green propellant thruster, potential solid and liquid particles ejected from the nozzle were captured with a high-speed camera and collected for chemical analysis. Operation of the thruster proved to be reliable and repeatable for the operating conditions foreseen for the subsequent in-depth STG-CT test campaign. A first test of the thruster at STG-CT pointed out which operational conditions must be followed for a reliable operation, while exploratory MS and QCM measurements proved successful. High-speed camera imaging was tested and will be optimized for future tests.

The observation of the thruster plume with a high-speed camera at CCG revealed particles being ejected from the nozzle, following linear trajectories with velocities of up to 850 m/s. As the combustion chamber emits light during a pulse, the particles could either scatter this light or could glow inherently. The original assumption of soot being the origin of the observed light streaks is contradicted by the ballistic behaviour of the particles as well as a rather ineffective shift to an oxidizer rich operational point of the thruster, aiming at reducing the tendency of soot formation. In order to identify expelled particles, surface samples positioned in the plume at CCG were inspected with SEM-EDS analysis. Generally, only very few noticeable objects were identified on the few sampled surfaces. Several of the identified spherical particles likely originate from the additive manufacturing process of the thruster body, as they exhibit EDS spectra resembling the composition of the material reportedly used. The analysis of another set of spheres is in good agreement with the elemental signature of soda-lime glass. The glass beads found by EDS analysis are likely the source of the bright streaks observable in the high-speed camera images, supported by their reflection of light and them elastically bouncing off of the metal structure of the Pitot probe. We suspect the glass beads to be remnants from the production process as they do not originate from the thruster body material itself. Both glass and metal spheres may have been trapped inside the combustion chamber, from where they gradually get expelled during firing. The 7 µm filters installed into the feedlines right in front of the valves preclude particles of this size or bigger to originate from upstream the thruster. Additionally, images taken with the high-speed camera indicate the presence of fine droplets, as light must be scattered off of particles condensed in the mentioned region. The phenomenon was observed multiple times during the ramp-up phase of a pulse and will be investigated further in the course of the project.

Exploratory testing at STG-CT provided first information about the freely expanding plume composition through mass spectrometry on the plume centreline and a QCM-TGA analysis at 30° off-axis. Both measurement techniques proved successful and will be repeated at a later in-depth experiment at the facility. Overall, MS data revealed a changing plume composition depending on the initial thruster temperature with dissipating unburnt propellant fractions after sufficient heating, but a general conclusion is not reasonable yet, as too many thruster pulses were fired outside of the applicable specification window. For the interpretation of mass spectra captured at low resolution as it is the case here due to thruster pulse length limitations, it is important to keep in mind that the mass-to-charge ratio of 44 might be misinterpreted as N_2O if the exhaust gas CO_2 is present, or vice versa. The QCM-TGA analysis delivered three distinct temperature ranges where desorption of one species or a mixture of soluble species took place, most probably caused by water, CO_2, propene and/or N_2O, as they were detected by the mass spectrometer and are condensable at the provided QCM temperature of 80 K. Generally, no definite attribution of chemical species can be made for a QCM-TGA when multiple unknown species are present, unless combined with a continuous MS scan during desorption. However, an analysis like the one conducted in this study, can provide information on how much mass is deposited on surfaces with at a certain temperature and how much heating is necessary to evaporate the deposited matter.

It is well known that the absence of an appreciable atmosphere in space allows for a wide expansion of the thruster plume, and it is necessary to replicate that high-vacuum environment in a ground test to obtain the distribution of the gaseous plume species that would be found in the vacuum of space. Additional measurements will thus be conducted in the DLR high-vacuum plume test facility Göttingen for chemical thrusters (STG-CT), using a mass spectrometer to record the gas phase composition at various angles from the plume axis. Non-gaseous effluents, i.e. droplets and particulates, will again be recorded with a high-speed camera during the STG-CT test campaign, providing information on size, velocity and trajectories if present and resolvable. The impact of plume contamination on the properties of relevant surface coatings and materials will be studied in a later phase of the activity.

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