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Low-Cost Cold-Gas Reaction Control System for Sloshsat FLEVO Small Satellite

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A low-cost cold-gas reaction control system (RCS) has been designed and developed for liquid-slosh experiments in the ESA-sponsored Sloshsat FLEVO (Facility for Liquid Experimentation and Verification in Orbit) small satellite. Four spherical carbon/epoxy-wound stainless-steel tanks of a "leak before burst" design store 1.6 kg of the gaseous nitrogen propellant at 473 bars corresponding to 20°C. Each tank is equipped with an accessories assembly, which includes a pyrovalve of a self-seal design and a filter. The cold-gas propellant is supplied to 12 especially developed 0.8-N thrusters at a steady regulated pressure. Before reaching the thrusters, the gas passes through a surge damper, a two-stage pressure regulating assembly, and a latch valve. For safety and redundancy, two relief valves are mounted downstream of the regulators. A breadboard test system, which completely simulates the pneumatic nature of the Sloshsat RCS, was used for ground-test evaluation of the RCS performance in various modes of operation (continuous and pulses of various duty cycles) and for development experiments. Thruster opening and closing response times were less than 5 ms. Delivered specific impulse of 70 s in vacuum was demonstrated. The RCS successfully passed the required qualification and acceptance tests.

Introduction

COLD-GAS thrusters usually provide an inexpensive, highly reliable, low-power consuming, noncontaminating, and safe auxiliary propulsion means for small spacecraft.[1–3] They have been used extensively in various reaction control systems (RCS) providing multiple low-thrust pulses for actions, such as attitude control, stationkeeping, orbit adjustments, docking maneuvers, and trajectory control.[4] Other applications of cold-gas propulsion might include nutation control of sounding rockets, divert thrusting for control of missile and interceptor trajectories, and astronaut extravehicular activities.

Compressed nitrogen offers a very good combination of storage density and specific impulse, as compared with other available cold gaseous propellants. The use of hydrogen or helium, for instance, requires much larger system mass, because of their low gas density, which more than offsets favorable specific impulse values. Argon and krypton have levels of density and specific impulse, which are comparable to those of nitrogen, but are less available and more expensive. Reaction control systems, using cold nitrogen-fed thrusters, have been widely and successfully employed in operational space programs and spacecrafts, such as Pioneer, Vela III, Discovery, SCIT and Brilliant Pebbles experiments, COMET, and UoSat-12.[1,3,5] Recently, nitrogen cold-gas propulsion systems have been considered and designed for use in a communication constellation of small spacecraft,[6] and in a scientific constellation of numerous nanosatellites to study sun–Earth interactions.[7]

A low-cost cold-gas RCS has been recently designed and developed in RAFAEL to provide linear acceleration and rotation control of the Sloshsat FLEVO (Facility for Liquid Experimentation and Verification in Orbit) small satellite for liquid-slosh experiments in space.[8] This satellite is a free-flying minispacecraft sponsored by the ESA and the Netherlands Agency for Aerospace Programmes (NIVR) with the National Aerospace Laboratory (NLR) serving as the prime contractor. It was originally scheduled to be ejected into space from the Hitchhiker bridge of the space shuttle's cargo bay. ESA plans to launch the minispacecraft in 2004 by Ariane 5. A schematic view of Sloshsat FLEVO is shown in Fig. 1. The objectives of the Sloshsat FLEVO mission are to obtain experimental data for validation/verification of existing computational-fluid-dynamics models of liquid motion in space and spacecraft dynamics with liquid sloshing and to develop and qualify a low-cost small spacecraft bus complying with the space shuttle requirements.[8] For that purpose, the minispacecraft, weighing 129 kg, contains a cylindrical tank, partially filled with water (fill ratio of 0.39), and is subjected to various modes of linear and rotational motion using the cold-gas RCS. A comprehensive instrumentation system measures the location, velocity, and temperature of water in the tank and the satellite acceleration and rotation rate.

The purpose of this paper is to describe the propulsion requirements, design-to-cost approach and considerations for meeting the requirements, and the development of the cold-gas RCS for the Sloshsat FLEVO small satellite.

Sloshsat FLEVO RCS Design and Configuration

RCS Performance Requirements

The Sloshsat FLEVO reaction control system is required to excite the minisatellite with a known force or torque along or about each of the three orthogonal coordinate-system axis directions of the spacecraft (decoupled and simultaneously) and to realize initial payload fluid conditions. The maximum linear acceleration capability with two operating thrusters is 0.0122 m/s^2 for 692 s with a total ΔV of 8.4 m/s, corresponding to complete gaseous propellant utilization. The main RCS performance specifications were derived from the experimental program and defined by the minisatellite contractor as follows: 1) total amount of gaseous nitrogen, 1.6 kg at 473 bars and 20°C; 2) number of thrusters, 12 at defined locations; 3) nominal thrust per thruster at steady-state operation and 20°C, 0.8N; 4) specific impulse I_{SP} better than 65 s at ambient pressure of 10–12 mbar; 5) minimum pulse width, 33 ms; 6) minimum impulse bit, 0.025 Ns (by a single thruster); 7) maximum opening (90% thrust) and closing (10% thrust) response times for a thruster, 5 ms; 8) total RCS weight, less than 14 kg, including the propellant; 9) maximum operating temperature, +70°C; 10) minimum operating temperature, −40 to −20°C (depending on component); 11) specified

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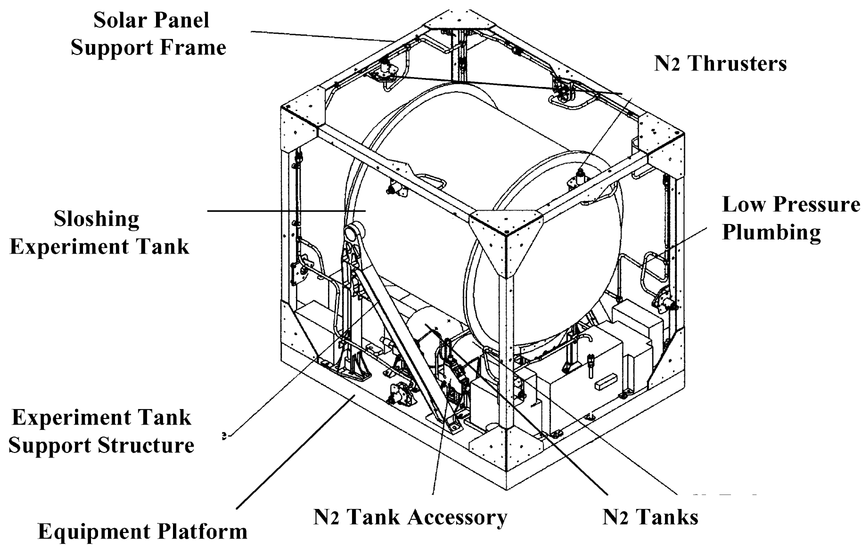

Fig. 1 RCS assembly in the Sloshsat FLEVO satellite.

space, limited, as defined in the interface drawings; and 12) internal and external leakage at each thruster shall not exceed 10^{-4} and 10^{-6} std l/min of gaseous nitrogen, respectively, at 20^{+5} bars and $20^{\pm 5}$°C.

General Description of RCS Design Architecture

A schematic block diagram of the Sloshsat FLEVO cold-gas RCS is shown in Fig. 2. It consists of the following subsystems: compressed-gas storage subsystem, gaseous-propellant management subsystem, cold-gas thrusters subsystem, and tubing and mounting brackets.

The compressed gaseous nitrogen (GN_2) is stored in four identical spherical tanks at a nominal pressure of 473 bars, corresponding to temperature of 20°C. Each tank has an internal volume of 0.97 l and contains 0.4 kg of high-purity nitrogen at the preceding conditions. The relatively high pressure enables economic utilization of the limited space available in small satellites. Each tank accessories assembly (TAA) includes a pyrovalve (PV) and a filter (F), attached to the tank, as shown in Fig. 2. One of the assemblies includes, in addition, a high-pressure transducer (HPT) and a test port valve (TPV). The PVs are activated in sequence to allow gas flow to the propellant management subsystem and the thrusters. The first pyrovalve can be activated only when Sloshsat FLEVO is at safe operational distance from the shuttle (10 to 50 n miles). The second pyrovalve will be activated when the gas contained in the first tank has been depleted, and so on. The test port valve is provided to conduct ground testing and leak tests. All RCS components and tubing downstream of the pyrovalves can be tested by applying test-level proof pressure from an external source. A surge damper (SD) is applied to the gas-feed pipeline, significantly reducing the pressure surge at the activation of each pyrovalve.

The supply gas pressure is reduced to 15.5 bars (nominal) in two stages by a pressure-regulating assembly, before entering the latch valve and the thrusters. For safety reasons and redundancy, two relief valves (RV) are mounted downstream of the two regulators (Fig. 2). The two RV outlets are connected to one discharge opening that will release the gas on the satellite platform and distribute it uniformly in such a way that the developed thrust is nullified.

A low-pressure latch valve (LV) is installed in the propellant management subsystem upstream of the thrusters as an additional means against unintentional thruster firing in ground testing or in orbit, and to prevent unnecessary wasteful thrusting in space in case of gas leakage in one or more thrusters. A low-pressure transducer (LPT) monitors the actual working pressure of the thrusters.

The cold-gas propellant is supplied to 12 0.8-N nominal-thrust thrusters, which were especially developed to meet the specific program requirements. The thrusters are located on the spacecraft external frame, as shown in Fig. 1. They will normally be operated in pairs to provide the required linear acceleration or rotational motion. The RCS is designed to actuate two pairs of thrusters at a time.

High-pressure $\frac{1}{8}$-in.-diam stainless-steel tubing links the gas tanks upstream of the pressure regulators. The low-pressure plumbing (all-welded $\frac{1}{4}$-in.-diam titanium tubing) provides the regulated-pressure gas to the thrusters.

RCS Component Design and Selection

General Design Approach

The principal approach to the RCS design, development, and qualification was to use, wherever possible, off-the-shelf items from other projects. Those components were adapted for space application and qualified to meet stringent NASA/ESA man-rated space-mission requirements. This approach made it possible to attain a man-rated, space-qualified cold-gas propulsion system with low-cost, safety, and high-reliability attributes.

Compressed-Gas Storage Subsystem

A spherical, off-the-shelf carbon/epoxy-wound stainless-steel tank was selected and adapted for the compressed-gas storage. Four tanks were required to provide the RCS propellant demand. The use of four small tanks, rather than a single big one, enabled a very efficient RCS architecture that satisfies the limited-volume constraint. The tanks have a "leak before burst" design, developed and tested in accordance with MIL-STD-1522A (U.S. Air Force). That design is very advantageous from the safety point of view. The design was subjected to a comprehensive finite element stress analysis.[9] The burst pressure was found to be higher than 1700 bars. The tank materials were found suitable for space applications. The gas tanks are supplied prepressurized and mechanically sealed to 473 bars (at 20°C). The maximum expected operating pressure (MEOP) is 600 bars at 70°C. They will be depleted upon demand by activating the pyrovalves, described in the following. The unique approach eliminates leakage and pressurization activities before launch and provides safety and flexibility to the system.

Each pyrovalve uses a RAFAEL- developed pyrotechnic cartridge that complies with MIL-STD-1576 (U.S. Air Force). It passed all required testing, including ESD tests with the resistor removed, as demanded by NASA for approval. The pyrovalve is of a self-seal design, which includes a sealing mechanism that prevents contamination of the system during pyrovalve actuation. The filter, installed as a redundant measure, comprises a 10-mm-diam disk made of a woven stainless-steel wire with a nominal filtration rating of 10 μ.

As already mentioned, the test port valve allows proof pressure and leakage testing of the assembled system. After test completion the pressure is released by actuating a thruster. The TPV comprises

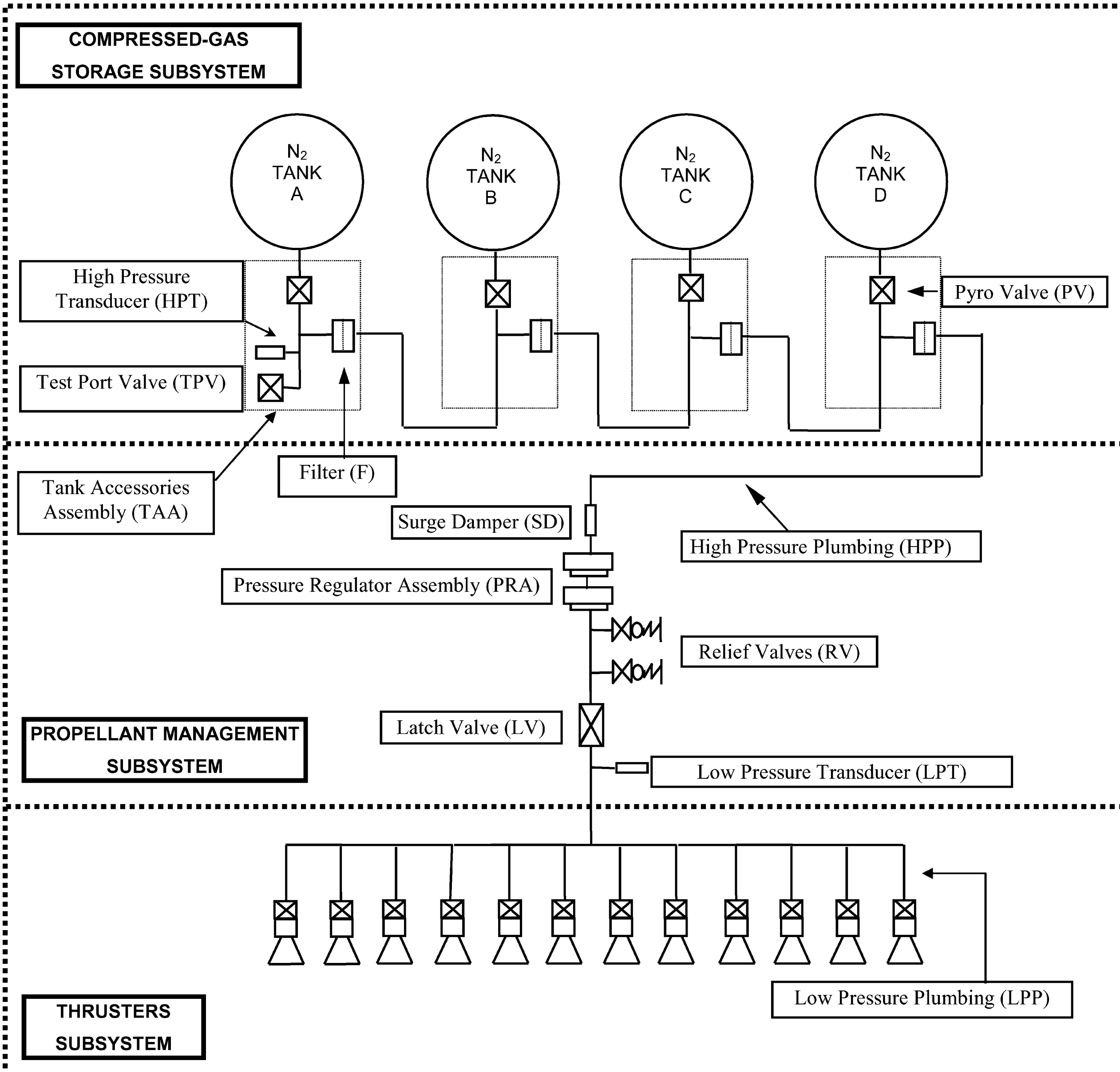

Fig. 2 Schematic of the Sloshsat RCS.

a commercial zero-leak-check insertion plug and was qualified by extensive high-pressure testing.

Gaseous-Propellant Management Subsystem

The pressure surge phenomenon that follows a pyrovalve actuation was precisely analyzed and extensively tested at worst-case simulated conditions.[10] The surge damper consists of several circular turns of the high-pressure $\frac{1}{8}$-in.-diam stainless-steel tubing, which connects the tanks outlet to the pressure regulators. The surge peak value defines the MEOP in the high-pressure part of the system, which is 650 bars.

The pressure of the stored gaseous nitrogen is reduced in a two-stage pressure-regulating assembly to the nominal static working pressure of 15.5 bars at the entrance to the thrusters. Two pressure regulators, qualified for 620 bars (9000 psi) inlet pressure for space use, are being used in the system. The lockup pressure (pressure after more than 8 h with no flow) is 17.4 bars. It was found in the simulated testing that the regulated pressure is unaffected by the surge phenomenon. The sensitivity of the regulated pressure to the pulse modulation of the thrusters was investigated. A theoretical model that predicts the working pressure level as a function of the mass flow rate and pulse duty cycle was established.

The two identical relief valves act as safety devices in the system (see Fig. 2). Each valve can handle the total mass flow rate in case both pressure regulators are stuck open, with a minimum pressure rise, which defined the MEOP (35 bars) in the low-pressure part of the RCS system. A model for the calculation of that mass flow rate, taking into account the pressure drop between the tanks and the relief valves, has been formulated.

The latch valve is an off-the-shelf space-qualified component. Its response time is less than 20 ms at 28 V dc. It is an all-welded assembly with two dc solenoids and a position indicator. Its proof and burst pressure are 54 and 144 bars, respectively.

An LPT, installed downstream of the LV, measures the thrusters' working pressure. This measurement will be used for postflight thrust calculations, using calibration data.

Cold-Gas Thrusters Subsystem

Each thruster is an all-welded stainless-steel structure, consisting of a solenoid valve, a nozzle, and an inlet connection, as shown in Fig. 3. The nozzle has a throat diameter of 0.66 mm and an area expansion ratio of 50, the latter being a good compromise to satisfy both performance and maximum-weight requirements. The gas-passage areas in the valve are much larger than the nozzle throat

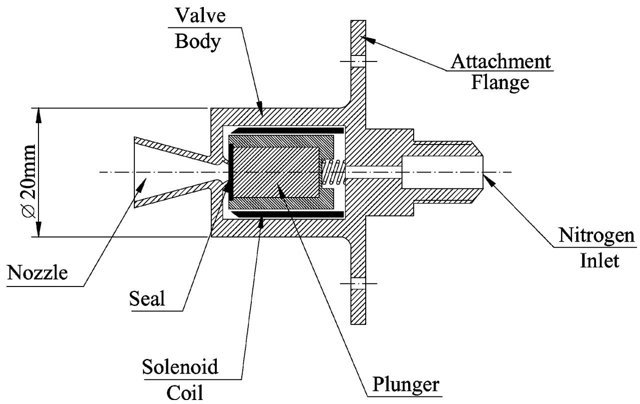

Fig. 3 Schematic cross section of a cold-gas thruster.

area. As a result, thruster opening and closing response times depend mainly on the solenoid valve response to ON/OFF commands. A power-saving valve driver was incorporated in the design for delivering peak current of 1 A to the solenoid for a short time at thruster activation to meet the transient time interval requirement. In addition, the valve design embodies a strong backspring to further decrease the thrust decay time on shut-off command. The thruster inlet pressure is regulated to provide a steady-state nominal thrust level of 0.8 N and meet the minimum impulse-bit requirement. Each thruster weighs 70 g.

Functional Analysis and Testing

Pressure Distribution During Operation

Gas pressure variations are expected within the RCS system during operation as a result of changes in the required mass flow rate and variations of the supply pressure. These variations might affect the total flow rate to the thrusters, which in turn will cause thrust level variation. An analysis of the quasi-steady pressure and mass flow variations was conducted to enable estimation of the pressure changes and proper selection of the flow-related components. The actual pressure distribution and mass flow rates were determined during the system development tests.

The highest pressure in the system will be developed at the opening of the first pressure tank. Nitrogen gas at pressure of 600 bars (corresponding to 70°C) will be released into the system by the fast opening of the associated pyrovalve. After the consumption of the gas in the first tank (to a specified pressure level), that tank will serve as an accumulator for the gas released on command from the second tank, and so on (see Fig. 2). Thus, the maximum peak pressure in the high-pressure part of the RCS system will prevail only for a short period of time at the opening of the first tank.

The gas pressure at the entrance to the pressure regulator will vary according to the supply pressure variation and the pressure drop from the tank outlet to the regulator. The latter was theoretically estimated as a function of the supply pressure in order to determine the minimum regulator inlet pressure at which the required thrust should be still obtained for the strict case of four thrusters operating simultaneously. It was found that the pressure drop becomes significant for supply pressure lower than 50 bars.

An analysis of the flow in the low-pressure part of the system revealed a pressure drop of 0.30 and 1.14 bars in the latch valve for simultaneous operation of two and four thrusters, respectively. This can cause a difference of about 4% in the thrust level. The pressure drop in the low-pressure tubing from the regulators to the thrusters was found to be negligible.

When the first pyrovalve is activated, the high-pressure gas stored in the corresponding tank is instantaneously released into the unpressurized system. This pressure surge phenomenon might overpressurize the gas feed system above the initial stored-gas pressure and cause a dynamic pressure oscillation. NASA specification requires the use of the maximum surge pressure as the maximum design pressure for the system. A simplified model was established to analyze the critical effects and estimate oscillation frequencies and

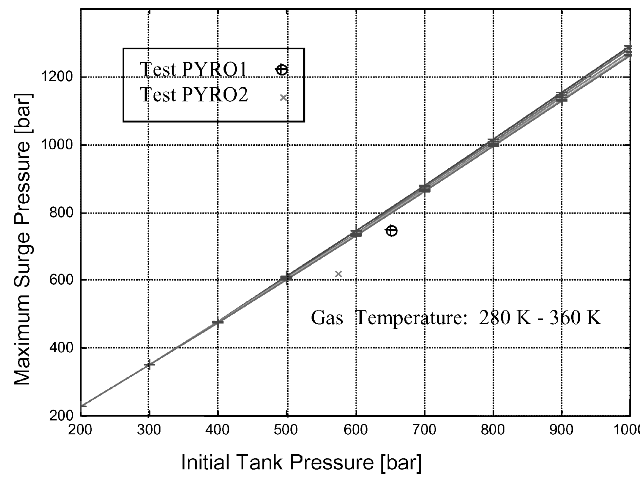

Fig. 4 Calculated maximum surge pressure as a function of initial stored-gas pressure. Test results are also noted.

worst-case maximum pressure surge amplitude.[10] Figure 4 shows the calculated maximum total surge pressure upstream of the regulators as a function of the initial stored-gas pressure at various initial temperatures.

Two tests with high frequency-response pressure measurements were conducted at simulated worst-case conditions to determine the actual pressure surge. In the first test, at a tank pressure of 635 bars and gas temperature of 25°C, the surge phenomenon had a frequency of 200 Hz, as theoretically predicted, and the pressure peak, measured upstream of the regulators, was 750 bars. Consequently, in order to decrease the surge-pressure amplitude and oscillation frequency, the length of the $\frac{1}{8}$-in.-diam tube between the tank outlet and the pressure regulators was doubled by adding three circular tube turns. Indeed, in the second test (with the modified design), at a tank pressure of 575 bars and temperature of 25°C, surge-pressure peak and frequency of 620 bars and 100 Hz, respectively, were measured. The two test results are also noted in Fig. 4. The measured surge-pressure peak at the tank outlet in the second test was 590 bars. It was found in the testing that the regulated pressure and the intermediate pressure between the two regulators were unaffected by the pressure surge phenomenon.

Thruster Development and Performance

The development and qualification of the thrusters was aimed at meeting the performance requirements, listed earlier, as well as a series of operational specifications, such as allowable leakage, power consumption, operating voltage, cleanliness, etc.

An experimental setup was constructed for thruster development and performance-measurement tests. It included a flexture-type thrust stand with a load cell, located in a vacuum chamber. In addition to thrust, pressure at the thruster inlet and nozzle entrance and gas mass flow rate were also measured.

During the development phase, an engineering-model thruster (EMT) was actuated in the continuous and pulse modes of operation at various pressure levels with ambient pressure kept between 10 and 12 mbars. Continuous-operation tests with a duration of up to 35 s were conducted in a regulated-pressure range of 5.5–25.2 bars. The corresponding measured thrust-level range was 0.3–1.4 N. The pressure drop in the valve/thruster (difference between pressure measured at the inlet to the thruster and that measured at the nozzle entrance) was about 1% throughout the range of testing. The EMT was also successfully test fired continuously for 20 s at low temperature conditions with the gas temperature at the thruster inlet varying between 150 and 200 K during the test. Pulse-mode test firings were conducted with pulse duration and impulse bits varying between 29 and 100 ms, and 0.032 and 0.122 Ns, respectively. Two pulse-train thrusting operations with pulse ON-time of 500 ms at different thruster inlet pressures were also conducted. Because of the dynamic response of the test stand to short ON-time pulsed thrusting, the thrust magnitude in that case was based on the pressure-thrust correlation determined from thrust measurements during continuous steady-state operation. This approach was justified by the findings that steady-state thrust varies linearly with inlet pressure and is reached in a very short time, as described in the following. The gas mass flow per pulse for the pulse-mode operation was determined by weighing the gas tank before and after the test, and dividing the amount of consumed gas by the number of pulses.

The use of a driver that applies an 1-A peak current to the solenoid valve for the first 10 ms of operation, and the incorporation of a strong backspring in addition to the reverse voltage, supplied by the driver, provided thruster startup and shutdown time periods of less than 5 ms over the specified temperature range, as required. It was also found that a current of 0.35 A is sufficient to hold the valve fully open during operation.

A well-fitted linear relationship between the thruster inlet pressure and thrust was found in the development testing throughout all modes of operation. Because the Sloshsat mission requires precise knowledge of thrust level during thrusting, that linear relationship allowed provision of coefficients for each supplied thruster, so that the thrust and impulse bit can be determined as function of the in-flight measurements of inlet pressure and pulse duration. These coefficients were stored in the satellite computer.

The delivered specific impulse I_{sp}, calculated from thrust and mass flow rate measurements in tests at room temperature, was 70 s, well above the specification requirement. In the low-temperature test a delivered I_{sp} of 65 s was obtained. Overall, the specific impulse was found to be practically invariant with thruster inlet pressure, as expected for operation at that low ambient pressure.

RCS Performance Validation Testing

A breadboard system, schematically shown in Fig. 5, was constructed for ground-test performance evaluation of the entire Sloshsat propulsion system and for development experiments. For proper simulation of in-flight operation, the RCS components and connecting tubes were spatially located in that system as configured in the satellite. High frequency-response pressure transducers were installed in the TAA after the pyrovalve, and between the stages of the pressure regulator assembly (Fig. 5). Gas pressure was also measured upstream of the latch valve and at the entrance to the thruster. In addition, temperature at the TAA and at several places on the outside surface of the tubing and thrusters was measured by thermocouples. Gas mass flow rates to the thrusters were determined with the aid of Tylan hot-wire anemometers. A dedicated computer program was used for operation of the breadboard system, as well as data acquisition and analysis.

The breadboard system was tested, and performance was evaluated at continuous- mode operation of one or two, or four thrusters operating simultaneously at various tank pressure levels, and at pulse-mode firings of two or four thrusters within the same tank pressure range. Duration of all continuos-mode tests, except one which lasted for 90 s, was 30 s. In the pulse-mode testing, total firing duration was 30 s with the ON time being 30 or 300 ms, and the OFF time ranging between 30 and 600 ms. At the time of the described testing, the specified average regulated pressure (thruster feed pressure) was 19 bars (later changed to 15.5 bars). In all test firings, after a startup transient, the regulated pressure was stable at 19.3 ± 0.8 and 18 ± 0.8 bars for two and four thrusters operating, respectively, regardless of the operation mode. The minimum tank pressure, at which the thruster feed pressure (P4 in Fig. 5) is still regulated to the predetermined value, was found to be 45 bars. Overall, the feed pressure for operation of two or four thrusters was within the range of $18.7 \pm 8\%$ bars.

For high-frequency pulse-mode operation of the system (30 ms ON/30 ms OFF), the average regulated pressure history trace for a pulse is similar to that at continuous-mode operation, including the starting transient. Therefore, the individual impulse bit per pulse

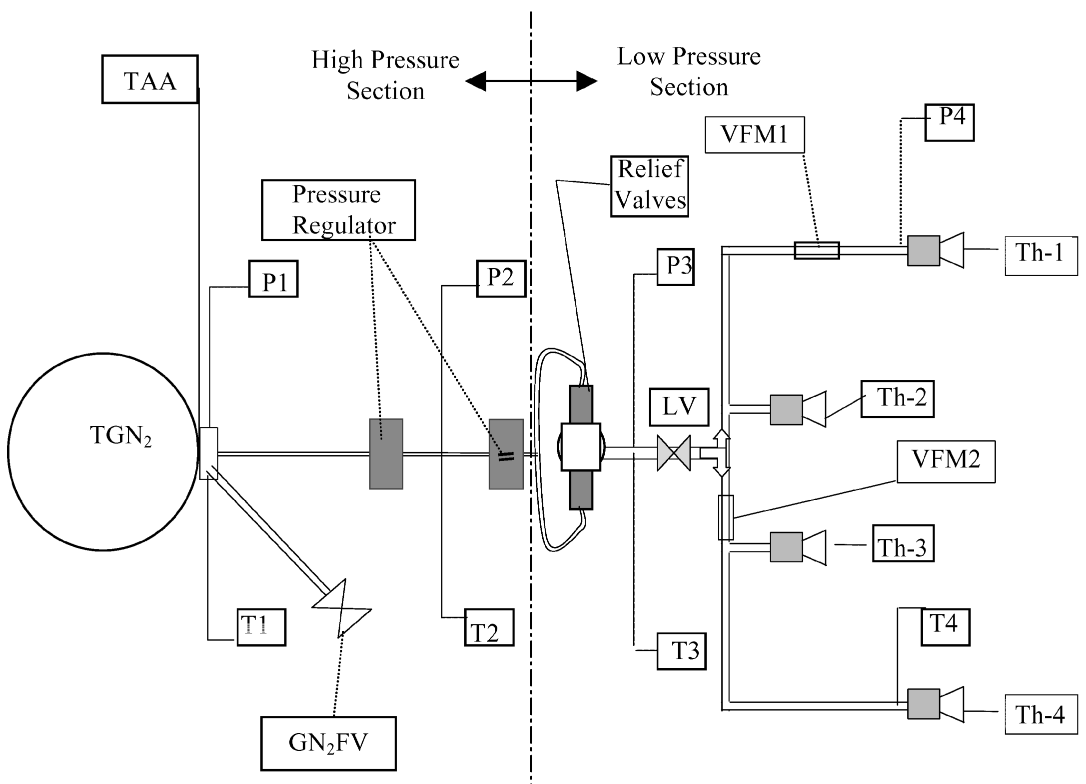

Fig. 5 Layout of the breadboard test system: TGN_2, pressurized nitrogen tank; TAA, tank accessory assembly; LV, latch valve; GN_2FV, nitrogen fill valve; Th 1, 2, 3, 4, thrusters (development level); P1, tank pressure; P2, pressure, between pressure regulator stages; P3, pressure, upstream of LV; P4, pressure, upstream of thruster; T1-T4, tubing surface temperature; VFM1, volumetric flowmeter for a single thruster operating; and VFM2, volumetric flowmeter for two thrusters operating.

is calculated from the pulse duration and measured average-per-pulse pressure. The latter was found to depend on the pulse ON time, the duty cycle, and the pulse position in the pulse-train. It was also observed in the testing that for pulses with an ON time shorter than 300 ms the measured pulse-train average pressure was slightly higher than the pressure measured during continuous operation, because the pulse is developed in the transition between the lockup and regulated pressure levels. Plots for various pulse trains (according to the Sloshsat test plan requirements) were provided to the customer, as part of the RCS data package.

Pressure–time plots recorded for a test run of four thrusters, operating simultaneously with a pulse-train of 300 ms ON/300 ms OFF, are shown in Fig. 6. The pressure at the TAA, P1, drops from 195 to 100 bars during the test, which lasts 29 s. The average pressure levels upstream of the latch valve, P3, and at the thruster entrance, P4, are 19.5 and 19.0 bars, respectively.

Temperature measurements during breadboard system operation were conducted to evaluate the effect of pressure decrease in the compressed-gas tanks on the gas temperature at the entrance to the thruster. These measurements showed that despite a significant drop of gas temperature at the tank exit (down to −30°C for a long-duration test) the temperature at the thruster entrance, relative to the ambient, changed only by a few degrees, supposedly as a result of heat transfer in the gas-feed tubing. It must be made clear that the results of the temperature measurements do not represent the actual thermal behavior of the system in space because those measurements were made at ambient sea-level conditions of pressure and temperature. NLR had the responsibility for the thermal design of the RCS. The thermal analysis, performed by Fokker Space, showed that eight of the thrusters need to be heated. This heating demand is satisfied by utilizing thermostat-controlled heaters (1.5 W for each thruster).

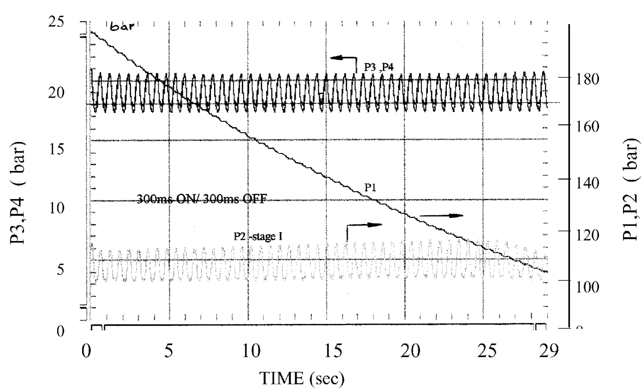

Fig. 6 Pulse-mode test—four thrusters operating.

Qualification Testing

RCS Qualification Concept

The RCS qualification program consisted of three stages: 1) component qualification; 2) qualification of the entire RCS on the assembly and testing system (ATS) structure, and 3) system qualification as part of the Sloshsat satellite protoflight model (PFM).

At the component level, each system component was checked and tested to ensure its qualification to the Sloshsat requirements and compliance with NASA safety requirements. There were three types of components with respect to their a priori qualification status:

a) *Manufacturer-qualified components*: previously fully qualified, and their qualification was found to comply with the Sloshsat requirements; therefore, no additional testing was needed (e.g., the tanks and the latch valve).

b) *Partially qualified components*: needed additional qualification tests to meet the Sloshsat and/or NASA safety requirements (e.g., the pyrovalve, relief valve, and pressure regulator assembly).

c) *Designed and developed components*: especially developed for the RCS, and their development program included qualification testing to meet the project requirements (e.g., the thrusters).

A detailed qualification testing program was prepared and performed for each component that needed qualification.

The ATS was built on a framework that completely simulates the final Sloshsat configuration. It was used to develop and practice the assembly and testing procedures, as well as for the qualification tests of structural elements and the entire RCS.

After system qualification, the RCS was assembled in the PFM of the Sloshsat satellite and subjected to the qualification tests at the third stage performed on the satellite by the main contractor (NLR). These tests included thermal-vacuum, metrology, end-to-end functional, electromagnetic compatibility, and vibration.[8]

Component Qualification

A summary of the major qualification-program tests conducted at the component qualification level is provided in Table 1.

Entire RCS Qualification on ATS

The ATS includes qualified flight components and tubes that were assembled on the framework according to the assembly procedure. Only one flight-weight tank and two operational thrusters were assembled, while all other tanks and thrusters were dummies. Table 2 presents a summary of the major tests conducted on ATS after the completion of the component qualification.

Acceptance Testing

The acceptance tests were conducted for each component (at the component level) and for the entire assembled RCS (at the system level).

Table 1 Component qualification program

Component	Qualification status	Test designation	Test program
Propellant tank	a	——	Acc. to MIL STD 1522A (USAF), Approach A
Pyrovalve cartridge	b	Thermal vacuum (TV)	8 cycles, 2 h @ 70°C, 2 h @ −40°C
		Lock shut test	Cartridge actuation while the valve piston is locked (NASA requirement)
Pressure regulator subassembly (PRA)	b	Functional endurance test (FET)	Total of 30,000 pulses of 2 thrusters with input pressure range of 70–600 bars
		TV	8 cycles, 2 h at 70°C, 2 h at −40°C
RV	b	FET	Total of 1000 cycles: In each cycle pressure level of 35–50 bars was applied to RV at various conditions
TPV	b	FET	20 cycles of 0–600 bars, 5 cycles of 0–975 bars
PRA, RV TPV	b	Strength test	Acceleration of 50g in all 6 orthogonal directions for 1 min
Tank bracket	c	Strength test	
TPV	b	Burst pressure	1550 bars
High-pressure tubing	c	Burst pressure	2600 bars
Low-pressure tubing	c	Burst pressure	140 bars
Latch valve	a	——	——
Pressure transducers	a	——	——
Thrusters	c	FET	16,000 pulses at various conditions
		Vibrations	12.9 GRMS at 20–2000 Hz on 3 axes
		TV	8 cycles, 2 h @ 70°C, 2 h @ −40°C
		Electrical tests	Electrical characteristic property measurements

Table 2 System qualification program

Test	Test program	Criteria for success
Proof pressure	Pressurization of RCS low-pressure section at 52.5 bars	No change in performance No leakage
Proof pressure	Pressurization of RCS high-pressure section at 975 bars	No change in performance No leakage
Vibration	3-axis random GRMS	No change in resonance frequency and performance No leakage
External leakage	Leakage test with helium leak detector	Less than 10^{-5} scc he/s
Performance	Two thrusters operating simultaneously	No change in regulated pressure

Table 3 Acceptance tests sequence at the system level

Sequence	Test	Timing
1	Visual and documentation inspection of Sloshsat PFM	At Sloshsat PFM arrival
2	Sloshsat PFM dimensional checks	At Sloshsat PFM arrival
3	Sloshsat PFM weighing	At Sloshsat PFM arrival
4	Low-pressure section proof-pressure test, including LPT calibration check	After low-pressure section assembly
5	Leakage test of low-pressure section	After completion of low-pressure section integration
6	High-pressure section proof pressure test, including HPT calibration check	After integration completion of the high-pressure section
7	System leakage test	After system integration
8	Flow impedance check[a]	After system integration
9	System performance tests[b]	After system integration
10	Electrical checkout[c]	After system integration
11	Sloshsat PFM weighing	After system integration
12	Visual examination	After system integration
13	Packaging and delivery	After system integration

[a]The actual gas flow through the thrusters was measured.
[b]The performance tests included actuation of the thrusters on the system according to the typical operation sequence given by the main contractor.
[c]All of the electrical components were tested using an electronic tester developed for the project. The tests included thruster and latch valve actuation and response time measurements.

The acceptance tests at the component level were based on those conducted by the component manufacturer and additional testing, performed to meet the Sloshsat and/or NASA requirements. Passing the tests approved the component for installation in the system. Each nitrogen tank passed acceptance tests in accordance with the tank specifications. Additionally, one tank from each production lot was burst tested. The pressure regulator subassembly, which includes two connected regulators, passed performance tests in a dedicated breadboard system, which resembled the actual RCS, to validate the outlet pressure level stability at various operational conditions throughout the entire relevant inlet-pressure range. Part of the tests were conducted in vacuum conditions. The relief valves were tested, in addition to the standard performance tests, for checking the pressure level developed at the extreme situation when all of the tank pressure is released through one of the valves, as described earlier. The pyrovalve cartridge was tested and accepted in accordance with MIL-STD 1576 (U.S. Air Force).

The acceptance tests at the system level were carried out during and after assembly on the actual Sloshsat satellite structure (PFM). The proof-pressure test of the low-pressure part of RCS was conducted before the installation of the pressure regulators, due to the requirement to rise the pressure above the regulated level. The sequence of the acceptance tests is presented in Table 3.

The system passed successfully all acceptance tests. They are summarized in Ref. 11. After their completion, the satellite was subjected to qualification tests at NLR, as described earlier.

Summary

A low-cost and safe cold-gas reaction control system (RCS) has been successfully developed and qualified for liquid-slosh experiments on board the Sloshsat small satellite. The RCS uses mostly off-the-shelf qualified components, adapted for space application. The design, architecture, and development satisfied limited space constraints and met stringent NASA/ESA man-rated mission requirements. The development was accompanied by a theoretical analysis of the pressure and mass flow variations throughout the system during operation. The pressure surge performance was appropriately treated.

The specially developed thrusters were successfully test fired in the continuous and pulse modes of operation in vacuum at various pressure levels. Thruster opening and closing response times of less than 5 ms and delivered specific impulse of 70 s (at room temperature) were demonstrated. Ground-test performance evaluation of the entire RCS was conducted on a dedicated instrumented breadboard system that simulates in-flight configuration and operation. For a specific mode of operation and number of thrusters actuated, the thruster inlet pressure level was stable throughout a test. A linear correlation between specific-thruster inlet pressure and thrust, revealed in the testing, will be used for in-flight performance evaluation.

The RCS was qualified at the component and entire-system levels, according to the requirements. A system, composed of qualified and accepted components successfully passed acceptance tests at the system level during and after assembly in an actual satellite structure, and was delivered to the prime contractor.

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