Electric solar wind sail

# ESAIL D45.1
# Final Report of Remote Unit Gas Thruster

Work Package: **WP 45**

Version: **Version 1.2**

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# 1. Introduction

This is the ESAIL Remote Unit (RU) cold gas thruster system final report. It shortly describes the objectives, key requirements and system design and configuration before presenting the manufacturing, integration and testing.

Because of the close resemblance to the NanoSpace CubeSat propulsion module (AD3), the actual manufactured and tested thruster system is somewhat more advanced than the one intended for the RU, but the key functionality is the same.

# 2. Applicable documents

AD1 ESAIL D41 Requirements specification of the Remote Unit
AD2 ESAIL D41.2 Design description of Remote Unit
AD3 CubeSat MEMS Propulsion Module (www.sscspace.com/nanospace)

# 3. Objectives and Requirements

The overall objective for Nanospace is to design, manufacture and test a prototype of a cold gas thruster system for the RU. The thruster system should be used to provide angular momentum to the RU when deploying the tethers and to modify their spin rate if needed. The system delta v should be 40 m/s. (AD1)

The complete cold gas thruster system requirements are listed in AD2. Some key requirements are listen in table 1.

| Requirement ID | Title | Value |
|---|---|---|
| ES1-RU-GTH-101 | Mass (Dry) | <150 g |
| ES1-RU-GTH-203 | Number of thrusters | 2 on each RU |
| ES1-RU-GTH-603 | Temperature Range – Operating | 15 to 50ºC |
| ES1-RU-GTH-105 | Power, flow control valve | < 3 W (pull in for 50 ms), <0.6 W (hold) |
| ES1-RU-GTH-106 | Power, heater | <1 W |
| ES1-RU-GTH-204 | Thrust @ nominal pressure | 1 mN |
| ES1-RU-GTH-201 | Total impulse | 40 Ns |

Table 1: Selected key requirements on the RU cold gas thruster system.

Because of the number of thrusters needed, the thrusters should preferably be compatible with batch fabrication.

# 4. System design and configuration

Given the requirements, different systems configurations, designs and working principles were studied and through trade-offs, a suitable system was selected (AD2).

## 4.1 Propellant trade-off and selection

In the propellant trade-off, a number of possible propellants were included in the study and through their properties combined with the requirements, the most suitable propellant was selected.

The two most attractive selections were nitrogen and butane. The former due to the heritage from the PRISMA mission and laboratory tests and the latter because it can be stored as liquid and has a suitable vapor pressure in the operating temperature range of 15 to 50 ºC, which would correspond to feed pressures of about 1.8 to 5 bar. Nitrogen would have to be stored under high pressure, about 250 bar, which would require both a larger and heavier tank. In the trade-off, it was estimated that the tank mass would be about 50 g with butane and 200 g for nitrogen. Based on this, butane was selected as propellant in the RU cold gas thruster system.

## 4.2 Propulsion system configuration trade-off and selection

The ESAIL micropropulsion system basically consists of a propellant tank with a temperature sensor, a propellant fill/drain tank and two thruster modules. Two different configurations of the thruster module were considered in a trade-off study. The simpler version would consist of a thruster chip with a nozzle and integrated heater, a temperature sensor and a normally closed valve. With this configuration, the thruster would run in an on/off mode where the feed pressure determines the thrust. The more advanced configuration would, in addition to all above, include an integrated, normally open valve and integrated mass flow and pressure sensors. In this configuration, where the integrated valve is controlled through a feedback loop from the integrated sensors, the thrust can be controlled proportionally. The second alternative would require more power and be heavier, and based on this it was decided to use the simpler configuration, Fig 1, since it would fulfil the requirements, despite offering less control of the thrust.

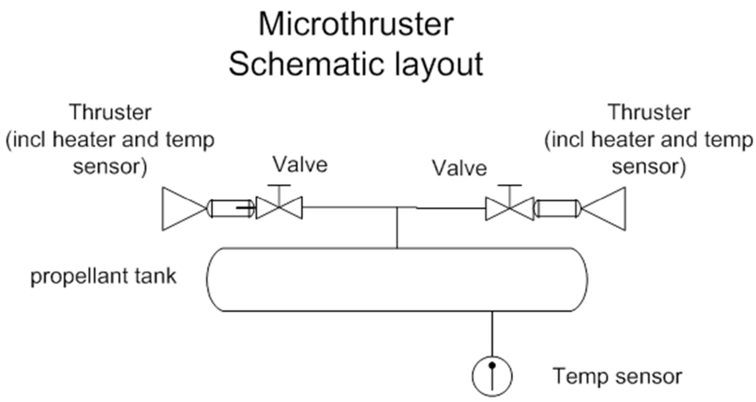


Fig. 1: Schematic of cold gas micropropulsion system.

## 4.3 System design

On the RU, the two thrusters are positioned with an angle 15º outward from the tangential spin plane of the ESAIL, one in the spin direction, and one in the opposite direction, Fig 2.

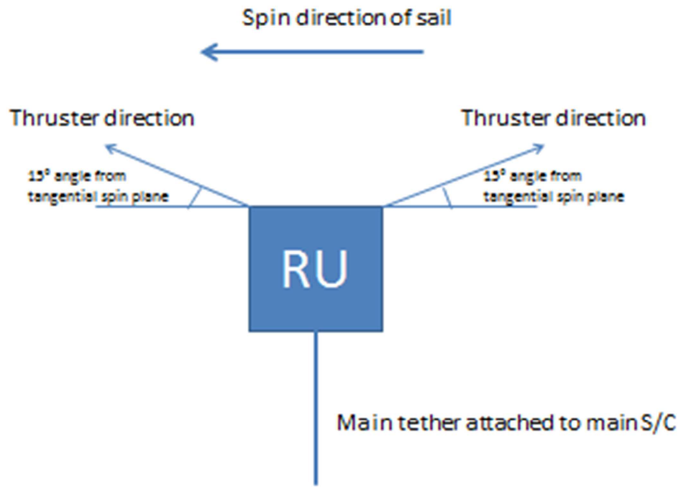


Fig. 2: Cold gas thruster positions and orientation on the RU.

With the system in Fig 1, the temperature of the propellant tank (and the propellant within it) determines the feed pressure, and hence the thrust because of the vapor pressure of the propellant. The integrated heaters in the thruster chips, which consist of two bonded silicon wafers, are used to increase the temperature of the gas to avoid condensation inside the chip. As on/off, normally closed valves, solenoid valves (INKX0508450AA) from the Lee Company are used.

The 100 $cm^3$ propellant tank consists of 1.5 mm thick aluminium and has been optimized to provide mechanical strength with low mass. The MEOP is 5 bar, the proof pressure 7.5, and burst pressure 12 bar. Mechanical analysis has been performed in Pro/ENGINEER Wildfire 4.0, Fig 3.

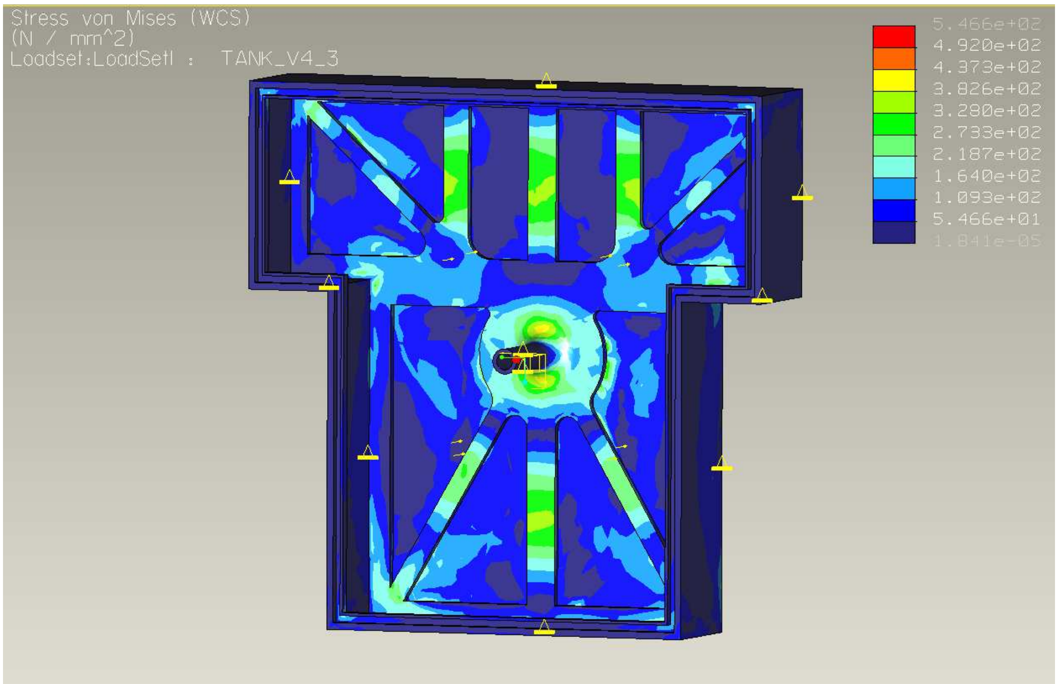


Fig. 3. Proof pressure case from the mechanical analysis.

A 3D-cad drawing of the propulsion system is shown in Fig 4.
The main performance and physical specification of the micropropulsion subsystem is:

- Two 1mN thrusters (Nominal: 1mN @ 25°C and 2.45bar)
- Thrust directions 15° outwards from the tangential direction of the ESAIL spin rotation
- Butane as propellant
- Operating pressure: 1.8-5bar
- Total impulse: 40Ns
- Size: 98*98*17mm
- Weight: 157g (107g dry weight)

The main electrical and thermal specification of the micropropulsion subsystem is:

- Peak power: 3W
- Continuous thrust power: 0.6W
- Thermal management power: 1W
- Voltage supply: 12V/2.5V (Pull in /hold solenoid valve), 12 V (int heater)
- Operational temperature: 15°C - 50°C
- Non-operational temp: -30°C – 60°C

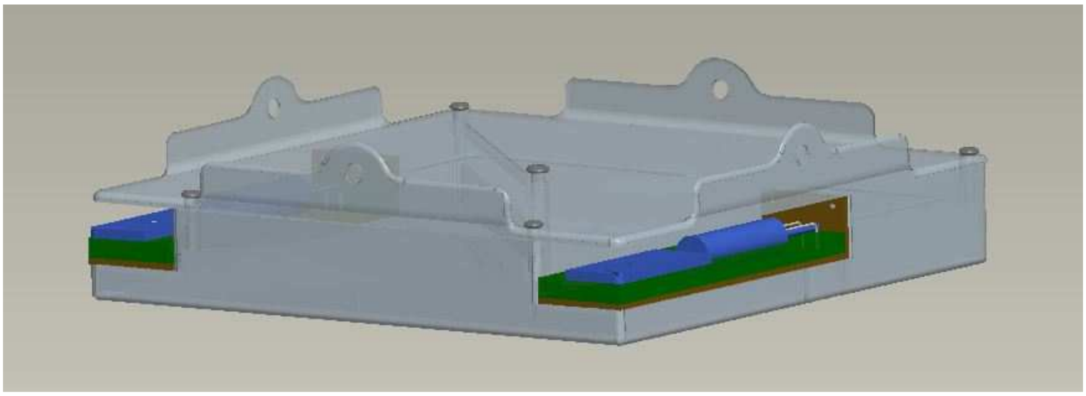

Fig. 4. CAD drawing of the micropropulsion system design.

The mass breakdown of the system is shown in table 2.

| Part | Mass (g) |
|---|---|
| Propellant | 50,0 |
| Tank_bottom (0.5/1.5mm Al) | 41,5 |
| Tank_top (0.5/1.5mm Al) | 29,0 |
| Adaptor bracket (integrated in tank top) | 0,0 |
| Support_bracket | 5,6 |
| Board | 4,9 |
| Thruster_chip | 1,6 |
| solenoid_valves | 8,0 |
| Electric_wires | 5,0 |
| Feeding_tube | 6,0 |
| Screws and others | 5,0 |
| TOTAL MASS (dry mass) | 106,6 |
| TOTAL MASS (wet mass) | 156,6 |

Table 2. Mass breakdown of the ESAIL cold gas micropropulsion module.

Further details on the system design can be found in AD2.

## 5. Manufacturing and integration

A mass dummy model of the cold gas system based on the design in section 5 was supplied to the RU model which was used in WP 41.

The manufactured and tested system is somewhat different from that described in section 4.3, since it has been developed in parallel with the resembling NanoSpace CubeSat propulsion module. The main difference is that there are four thrusters modules positioned and oriented differently and that the more advanced configuration, described in section 4.2, is used. In principle this means that the thruster chips consist of more than two wafers and that there are integrated valves and sensors in them. The simpler design would be achieved by omitting some of these subcomponents.

The thruster chips have been batch fabricated on wafer scale and each wafer carries 20 chips. After fabrication and wafer dicing, the thruster chips are filled with the phase change actuating material for the integrated valve and the integrated sensors are mounted before the device is mounted and wire bonded to an electric interface card, to which also the tank temperature sensing thermistor is mounted. The solenoid valve is then glued to the thruster chip and to the tank. The electrical interface from the thruster module is a 21 pin nano D-sub on each thruster module. The integrated sensors output is digital SPI signals. The finalized CubeSat module is shown in Fig 5.

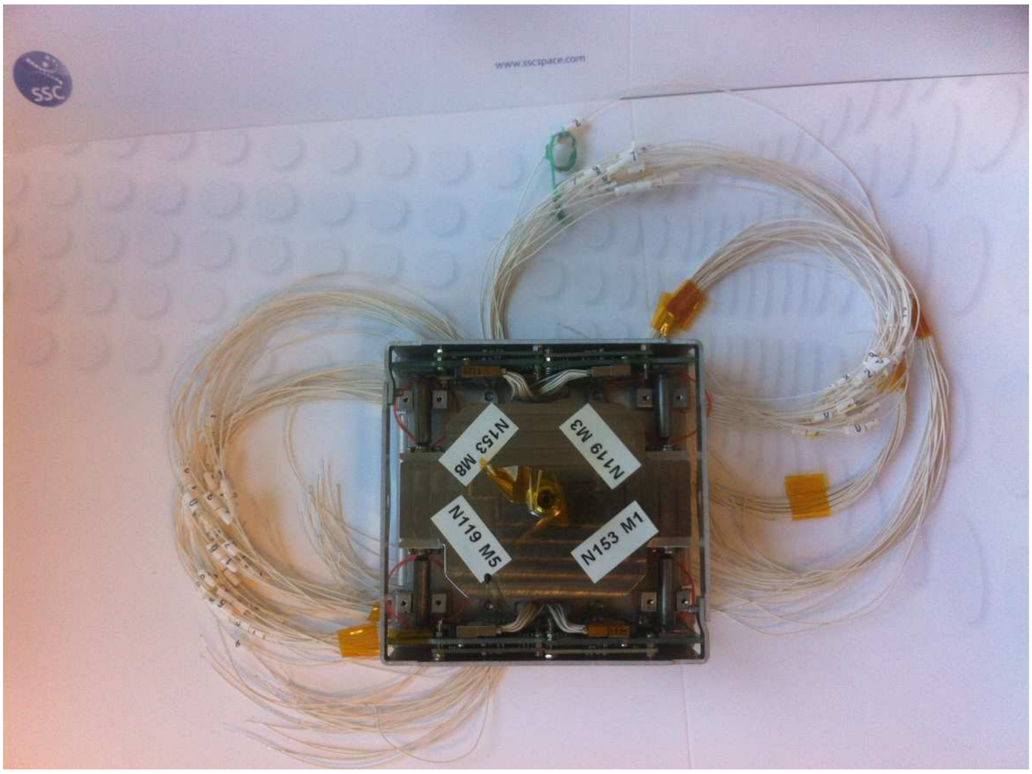


Fig. 5. NanoSpace CubeSat module with the tank in the center and four thruster modules with the thruster chips placed in the corners of the module.

## 6. Testing

The CubeSat module has been tested in laboratory environment (1 atmosphere ambient pressure and room temperature). Fig. 6 shows a schematic of the test set up used. Here, a single thruster module was used and the gas was supplied from a standard gas bottle. The feed pressure and mass flow was monitored through commercial reference sensors.

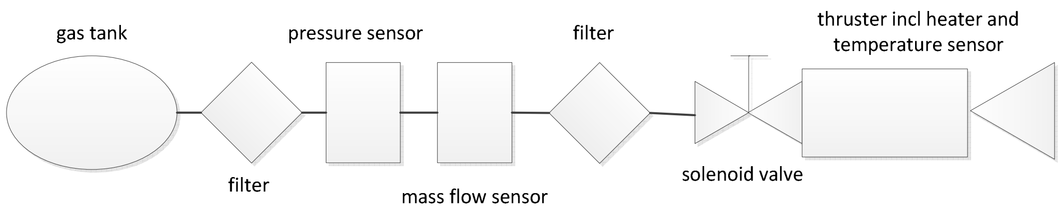


Fig. 6. Schematic of the test set up used in laboratory tests.

The integrated temperature sensor response was tested by increasing the power supplied to the integrated heater, Fig 7. The temperature sensor signal is not shown in temperature scale, but it is known that the internal temperature is at least 62°C at the highest heater power dissipation of about 1 W which should be sufficient to avoid internal condensation of butane.

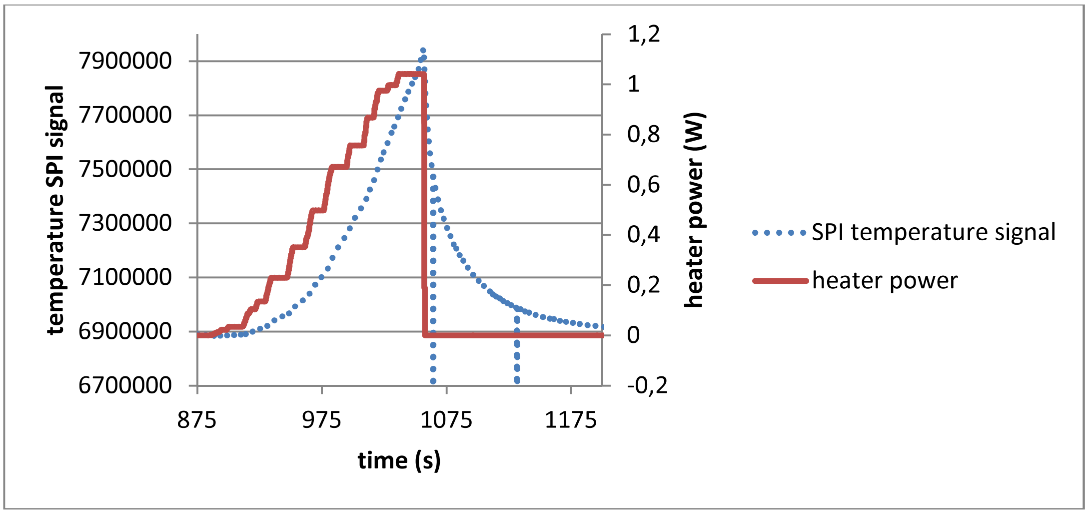


Fig. 7. On-chip integrated temperature sensor SPI signal response as the power supplied to the integrated heater is increased and switched off.

In Fig. 8, a five minute interval is shown where the solenoid valve is opened and quickly closed and opened. The mass flow and pressure signals are from the reference sensors located upstream from the solenoid valve. The (absolute) feed pressure is determined by the temperature of the gas bottle (about 21°C). The pressure and mass flow are stable during the on state which implies that the thrust is kept stable during long firings. The corresponding thrust, in vacuum, can from these values be calculated to be about 0.7 mN. In the operating temperature range it is about 0.5 to 1.5 mN. The solenoid valves have been tested to withstand pressures of 7.5 bar in both open and closed states in earlier projects, Fig. 9.

Shorter valve open/close cycles was tested, Fig. 10. Here, the digital SPI signal from the on-chip integrated mass flow sensor is included (though not part of the ESAIL configuration) in addition to the upstream reference sensor. It was found that the response from the integrated sensor is much quicker when opening and closing the solenoid valve. This is likely due to the large volume in-between the thruster chip and the external mass flow sensor, and possibly effects of working with butane, such as condensation in the tubing.

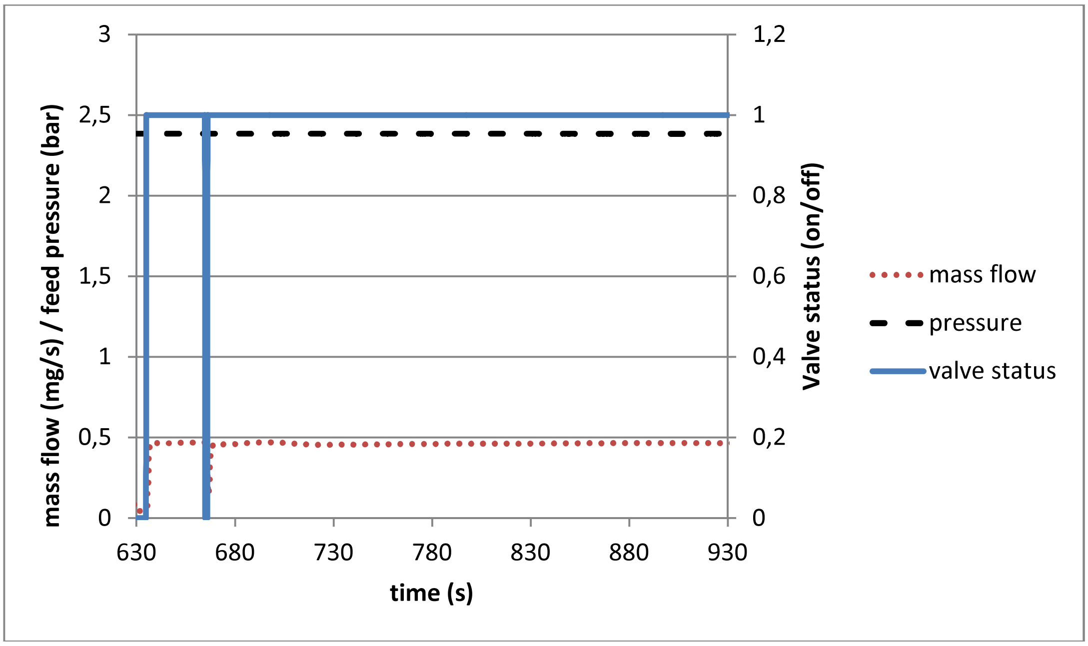


Fig. 8. Measured feed pressure, mass flow and valve status (equals zero when valve is closed and 1 when open) during a five minute interval.

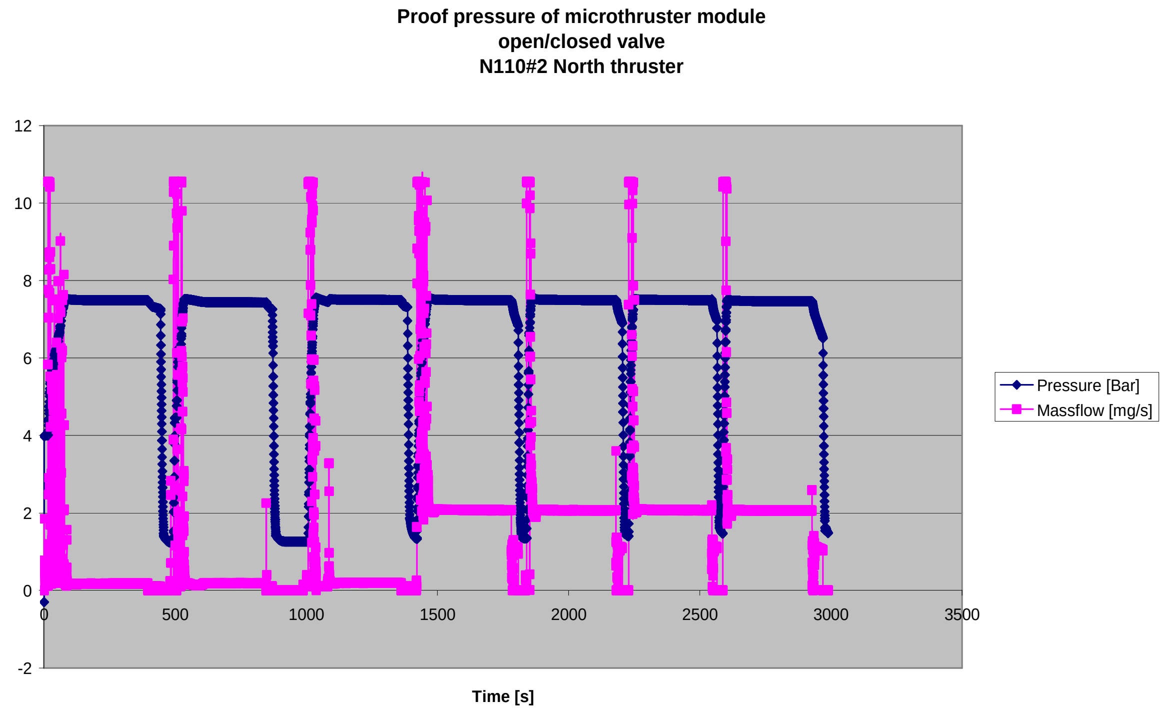


Fig. 9. Testing of solenoid valve at 7.5 bar feed pressure. The proof pressure was applied for 5 min and 3 cycles with the solenoid valve closed and then the same procedure with the solenoid valve opened.

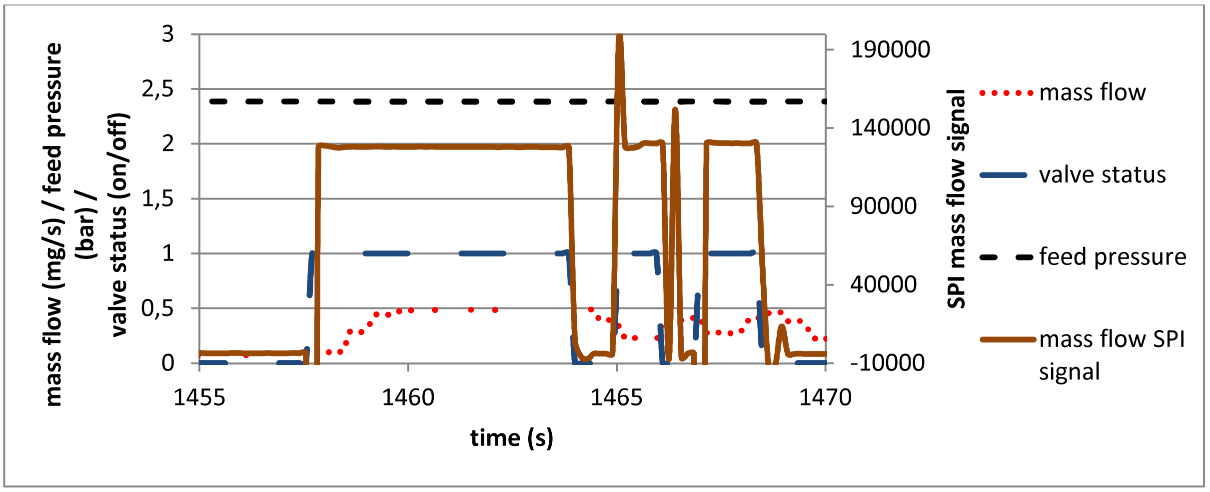


Fig. 10. Measured feed pressure, mass flow (from integrated and external sensors) and valve status during short on/off cycles of the solenoid valves.

## 6. Conclusions

A prototype of the ESAIL cold gas propulsion system has been designed, manufactured and tested with butane as propellant. It should however be noted that the prototype system is slightly different and more advanced, but all key functionalities required by this project have been demonstrated in laboratory environment.

The results achieved in this project demonstrate that a cold gas propulsion system capable of meeting the requirements for an E-sail mission is indeed feasible. Furthermore, the experimental results achieved with the prototype model of the cold gas propulsion system, justifies the statement that TRL-4 has been reached.