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VACUUM TESTING OF A MICROPROPULSION SYSTEM BASED ON SOLID PROPELLANT COOL GAS GENERATORS

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The number of micro and nano satellite projects is expanding. Main focus is on providing these small satellites with the same capabilities as today's larger satellites. In the field of propulsion, efforts are on miniaturization of the on-board propulsion system. This though presents major challenges to the designers. TNO Defence, Security and Safety, Delft University of Technology and University of Twente have faced those challenges, developing a commercial off-the-shelf cold gas micro-propulsion system, the $T^3\mu PS$ capable of providing a pre-set thrust level in the range 1 to 10 mN. It is based on a highly integrated feeding and thruster system and cool gas generators, which contain nitrogen stored in solid form.

The Delfi-n3Xt triple unit cubesat, scheduled for launch in 2011/12, has been chosen as platform to test the capabilities of the $T^3\mu PS$. To satisfy the Delfi-n3Xt requirements the $T^3\mu PS$ is designed to provide a thrust of maximum 6 mN, minimum impulse bit less than 0.1 mNs and a total impulse of 0.7 Ns. To qualify the $T^3\mu PS$ and verify that it meets the requirements, an extensive test campaign has been devised by TNO. This paper describes the requirements generated, the performance qualification test campaign conducted at Delft University of Technology, the test setup, the used instrumentation and the results obtained. A comparison with theoretical results is also presented.

I. INTRODUCTION

With the advent of nano-sized spacecraft (with a wet mass between 1 and 10 kg), miniaturized propulsion systems or micropropulsion modules are needed to produce the low thrust levels and impulse bits required for stabilization, pointing, station-keeping, orbit insertion, orbit maintenance and end-of-mission de-orbit (1). Traditionally spacecraft on orbit propulsion is provided for by chemical rocket thrusters or cold gas systems. For nanospacecraft however, there exists no ready solution that fits within the design constraints of such spacecraft (1) (2). Hence, over the last decade, miniaturization of propulsion systems has been an active field of research. In the Netherlands efforts, amongst others, focussed on the development of a novel technology combining Micro-Electro-Mechanical System (MEMS) technology with nitrogen cool gas generator (CGG) technology (3). Like conventional cold gas systems it allows for using an inert gas as propellant, thereby reducing contamination problems, low complexity, and the possibility of providing very small impulse bits. In addition, by storing the propellant in solid form, it reduces the volume of the storage system as well as the storage system mass and limits the effects of leakage. The use of MEMS allows for a miniaturized thruster, which is integrated in the overall design. Design efforts by TNO (lead), UTwente and TUDelft lead to the development of the $T^3\mu PS$ (3). Its main characteristics are:

- Mass: < 140 grams
- Dimensions: 90 x 90 x 21 mm
- Thrust: thrust selectable by manufacturing micro machined nozzle up to 150 mN
- Propellant: cold nitrogen gas from 8 miniaturised CGGs; ignition is by a glow plug, thus bypassing the use of pyrotechnics.

In 2007 an Engineering Model (EM) of the micro propulsion system $T^3\mu PS$ has been tested successfully at TUDelft, demonstrating thrust levels up to about 250 mN (4).

In 2007/2008, the system was selected to fly on the Delfi-n3Xt triple CubeSat in 2012. For this application, the system had to be adapted as to allow for much lower thrust values. The major propulsive requirements for the Delfi-n3Xt $T^3\mu PS$ are summarized in the table I (5).

System requirements	
Thrust level	**≤ 6 mN**
Total impulse	**≥ 0.7 Ns**
Minimum impulse bit	**≤ 0.1 mNs**
MEOP	**6 bar**
Non-operating temperature range	**-40° to 75°C**

Table I Major propulsive requirement

In 2009/2010 a Qualification Model has been designed and built by TNO and UTwente. In this paper, we discuss the vacuum testing of the QM at TU-Delft.

II. DESCRIPTION OF TEST ARTICLE

The Qualification Model is shown in Fig. I and Fig. II. It centres about a Titanium buffer vessel (tank), which acts as the main structure of the T^{3}µPS, thus avoiding brackets and piping. It consists of a flat body with a top and bottom plate with the top plate holding the CGGs and the bottom plate holding the thruster. The internal volume of the tank is 28 cm^3.

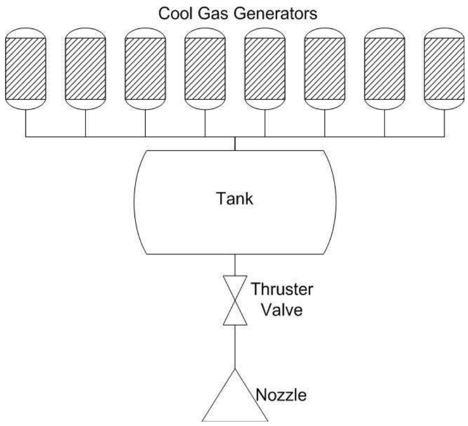

Fig. I: Schematic of T^{3}µPS (pressure and temperature sensor not included)

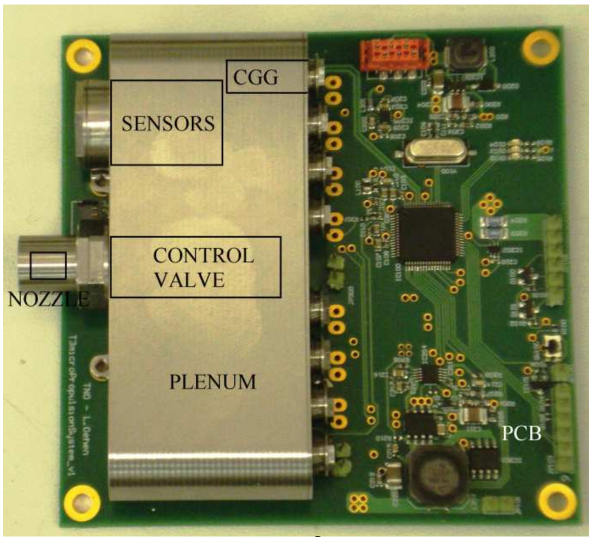

Fig. II: Photograph of T^{3}µPS QM

Each CGG has a propellant load of 0.3 grams, producing 0.1 normal liters of pure nitrogen gas. At start of operation, a CGG is ignited and the plenum is filled to capacity. The plenum then feeds nitrogen gas to a thruster valve and (micro) nozzle module for thrust delivery. When the buffer vessel is depleted a second CGG is ignited to re-pressurize the vessel and so on until all CGGs have been spent. To determine the gas temperature and pressure in the plenum, the bottom plate also holds a pressure and temperature sensor.

The whole system is mounted on a PCB, which also contains the control electronics for CGG ignition and for valve and pressure transducer operation. Total mass of the system, including mechanical and electrical interfaces, is below 140 grams and the volume below 100 ml.

To attain the proper thrust level, special care was given to the design of the micronozzle. To obtain the very small dimensions needed, various nozzles were produced using a method developed by the University of Twente. It consists of powder blasting the nozzle in pyrex glass followed by a high temperature anneal (6). A SEM photograph of the nozzle selected is shown in the Fig. III. Its main characteristics as established by UTwente are:

Mean throat diameter: 101 µm± 1.82 µm
Mean exit diameter: 310 µm± 10 µm
Throat area: 7979 µm^2 ± 2.55% (2σ)
Area ratio: 9.45 ± 5.23% (2σ)

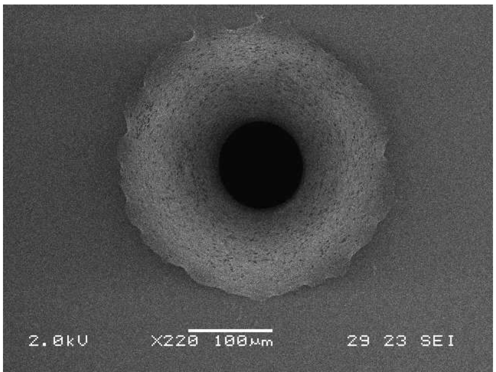

Fig. III: T^{3}µPS micronozzle (UTwente),

III THEORETICAL PERFORMANCE

A simple theoretical model has been developed to predict the performances of the system designed. Thruster performances are modelled on ideal rocket motor theory (7). Gas expansion in the plenum is modelled assuming that during expansion the gas temperature in the plenum remains constant (isothermal expansion). This is because it is expected that normal operation of the system is in pulsed mode with a fairly low duty cycle.

The Table II shows theoretical values for mass flow rate and (vacuum) thrust versus plenum pressure.

Plenum pressure (Bar)	**Mass flow rate (mg/s)**	**Vacuum thrust (mN)**
1.00	1.84	1.25
2.00	3.68	2.50
3.00	5.52	3.75
4.00	7.36	5.00
5.00	9.20	6.26
6.00	11.04	7.50

Table II: Theoretical values of thrust and mass flow rate for various plenum pressures

The figure IV shows a typical thrust, pressure and mass flow rate history obtained for a simulated blow down from a starting pressure of 6 down to 0 bar (vacuum pressure). Nitrogen gas temperature is 297 K.

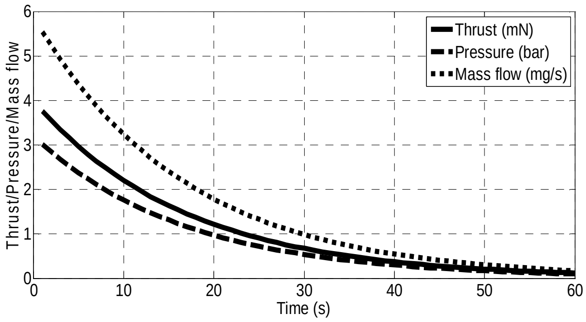

Fig. IV Predicted thrust, pressure and mass flow rate during blow-down (with a starting pressure of 3.01 Bar).

The results show that pressure, mass flow rate and thrust decrease with time. The results also indicate that the time for the pressure to decrease to 0.1 Bar is 59 s. This is considered to be the operation time of the thruster. The pressure of 0.1 Bar is the lowest pressure limit set for refilling the pressure vessel. At present, it is foreseen that the plenum will be refilled when the pressure decreases below 1 bar. Total impulse delivered is 0.061 Ns. Based on the minimum impulse bit, it is found that the maximum number of impulse bits is $1.96 \cdot 10^3$ (duty cycle 50%).

Actual performance usually is less due to friction effects especially at low Reynolds number conditions. For the $T^3\mu$PS the throat Reynolds number is in the range of 3500 to 4500. At these conditions, nozzle discharge factors in the range 0.96 to 0.93 are not uncommon (8) (9). Another factor not taken into account is that the nozzle surface has some imperfections, which could further lower performance. In an earlier theoretical study, it was found that under certain conditions, this could lead to a decrease in thrust of more than 20% (8). Finally, we note that the theoretically expected thrust, mass flow rate and pressure levels also depend on the uncertainty in the nozzle dimensions. For instance, at a given pressure, the mass flow rate that results is predicted with an accuracy of 2.55% due to the uncertainty in the throat area (Fig. V).

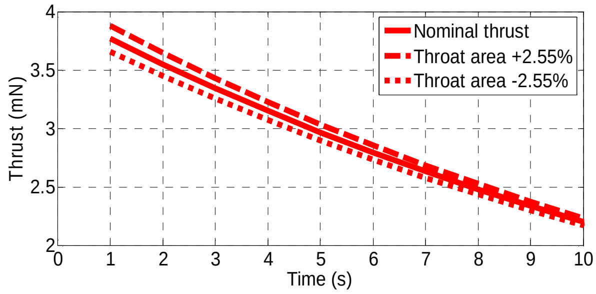

Fig. V: Effect of uncertainty in throat area on thrust.

IV. TEST PLAN

To qualify the $T^3\mu$PS for the Delfi-n3Xt mission a test campaign has been devised by TNO. Part of this campaign is to performance test the microthruster at TU-Delft. Aim of these tests is to verify the capability of the system to deliver the required thrust, total impulse and minimum impulse bit under specified conditions, see the Table I. All tests are to be performed in near vacuum conditions at a pressure ≤ 50mBar. No active control of the gas temperature is included. Instead gas temperature is measured throughout the test. No heating or cooling of the gas is foreseen as to test the system over the full operating temperature regime.

To obtain the necessary experimental results and since the thruster itself does not provide for a means of measuring and controlling the mass flow rate three types of tests were agreed upon with TNO:

a) **steady state** tests with as aim to accurately determine mass flow rate and thrust in relation to plenum pressure.
b) **blow-down** tests to determine the total impulse available from the system at different starting pressures in the plenum;
c) **impulse bit** tests to determine the impulse bit capability of the system.

For the steady state tests a mass flow controller will be used installed in front of the plenum to measure and control the mass flow rate of nitrogen to the plenum and hence to the microthruster nozzle. In total 6 different mass flow rates are planned to be tested, see the Table III.

For the blow-down tests, the system will be used as under normal operations. The plenum is filled with nitrogen until some pressure level is reached, thereby simulating the filling of the plenum upon CGG ignition. The nozzle control valve is then opened and all the nitrogen exits the plenum. From the thrust history, then the total impulse is calculated. In total six different starting pressures, referred to as design points (DP), were selected. The Table II gives the selected design points as well as the expected (theoretical) results.

Design point no.	Mass flow rate (mg/s)	Plenum pressure (Bar)	Thrust (mN)
1	5.0	2.70	3.51
2	6.0	3.25	4.10
3	7.0	3.79	4.81
4	8.0	4.33	5.52
5	9.0	4.87	6.23
6	10.0	5.41	6.94

Table III: Steady state test series design points, vacuum chamber temperature 13 mBar, plenum temperature 297.28 K.

Impulse bit testing is performed with by controlled opening/closing cycles of the valve to allow for different pulse times or bit durations to be tested. The test is normally performed in blow-down mode: at every new bit the gas stored into the plenum decreases as well as the pressure. The duration of the bits ranges from 1 second to 15 milliseconds.

V. $T^3\mu$PS TEST SETUP

To allow for testing, the QM was modified by TNO in that the CGGs were removed and caps were placed to ensure the plenum is leak tight. To allow for filling the plenum with nitrogen gas the plenum was connected to the test facility gas supply. For this TNO added a solenoid valve with the associated tubing on the $T^3\mu$PS, see the Fig. VIII.
The QM is mounted on the TU-Delft developed TB-50m test bench, see also Fig. VI. This bench allows for measuring thrusts up to 50 mN (10). Other parameters measured during the tests are specified in Table IV.
Mass flow rate is only measured when performing steady state measurements.

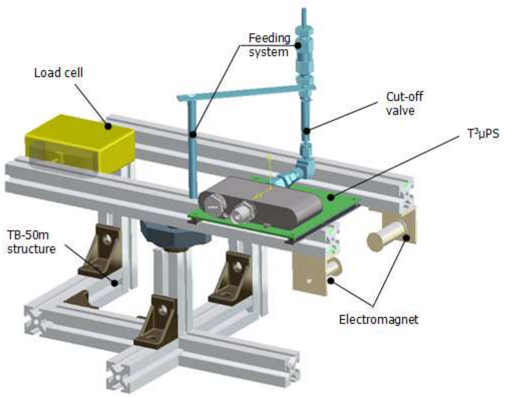

Fig. VI: 3D model of the test setup with indication of the main features.

Parameter	Sensor
Plenum pressure, ambient pressure	Kulite pressure transducers
Plenum gas temperature, ambient temperature	K-type thermocouples
Thrust	TB-50m test bench equipped with Futek load cell
Mass flow rate	Brooks mass flow meter and controller

Table IV: Overview of parameters measured.

For vacuum testing the TB-50m thrust bench is placed inside a modified Heraus vacuutherm vacuum chamber providing a test volume of size 50x50x50 cm.

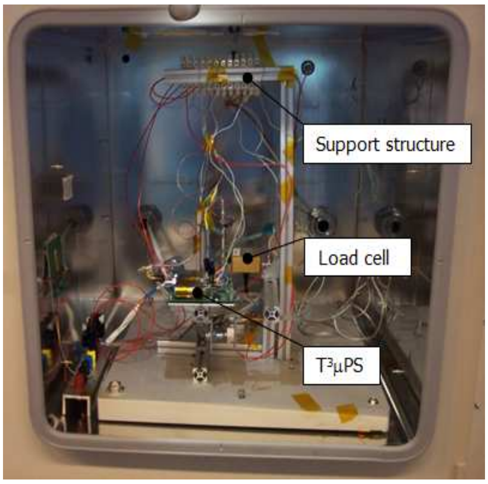

Fig. VII: TB-50m in vacuum chamber. A support structure for electrical wires and gas feed tubing can be seen on the right and on top. Calibration over the range of interest (1-6 mN) showed an accuracy of the thrust measurement of ± 15%.

A detailed schematic of the test set up is shown in the Fig. VIII In the upstream direction it consists of:

1. Nitrogen gas storage tank
2. Pressure gauge
3. Manual valve 1
4. Manual valve 2
5. Pressure regulator 200-20 bar
6. Pressure regulator 20-0 bar
7. Relief valve
8. Manual valve 3
9. Filter
10. Mass flow controller 1-40 mg/s
11. Check valve
12. TNO added inlet tube with cut-off valve
    Series of Swagelok fittings to connect the plenum to the gas supply system; it includes a (cut-off) valve

used to close-off the inlet tubing during the blow-down tests

13. $T^3\mu$PS QM: Control valve
14. $T^3\mu$PS QM : Nozzle

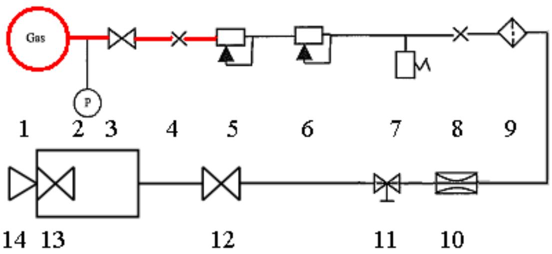

Fig. VIII: Feeding system schematic (elements 12 to 14 are placed inside the vacuum chamber)

VI PRELIMINARY RESULTS

Due to delays in preparing the test set-up and some leakage in the thruster system and the associated feed system only a few tests have been run. Especially the steady state tests were found to be influenced by leakage, and by not properly evacuating the thruster in between tests. Hence in this section, only some first test results are presented, with focus on the blow down test results and the impulse bit test results.

VI.I Steady state

Steady state tests are conducted at a constant mass flow rate. Testing commences upon opening of the thruster control valve. Steady state conditions are considered to be reached when the variation in thrust and pressure over time is less than 1%.

Fig IX shows the pressure and thrust history as obtained during steady state testing at a controlled mass flow rate of 10 mg/s.

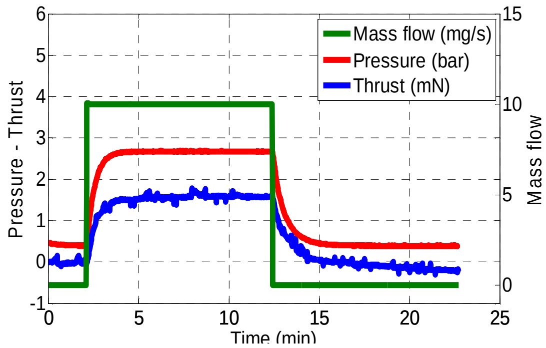

Fig. IX: Pressure and thrust history during a steady state test at 10 mg/s; data are averaged every 10 ms (vacuum pressure 14 mBar, plenum temperature 297.4 K).

The figure also shows that mass flow rate reaches steady state almost immediately. Both thrust and pressure take some time to rise to the steady state value, here about 2 minutes. This is because of the filling of the plenum and the feed tube connecting the nitrogen storage with the plenum. When stopping the mass flow rate also pressure and thrust decrease. Again it takes some time for thrust and pressure to return to zero as of emptying of the plenum and the feed tube. The results show a steady state thrust of 1.57 mN (± 15%) at a chamber pressure of 2.67 bar.

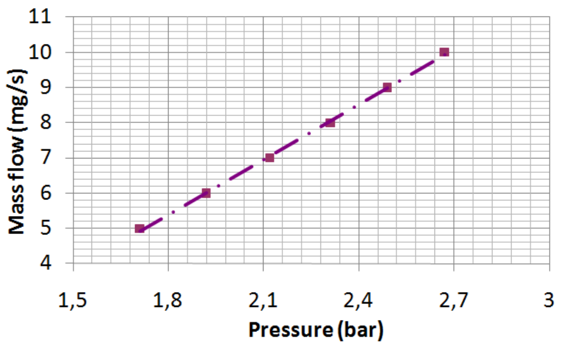

Fig. X Mass flow versus plenum pressure from steady state testing.

The figure indicates a linear relation between mass flow rate and pressure as predicted from theory. However, the results also show that the curve does not intersect the x-axis at zero. Leak testing showed that the system was not completely leak free, which could explain for this discrepancy. Once repairs have been made, further testing should provide us with better data.

Thrust data obtained showed to be unrealistically low. This in part is attributed to the leakage, but also to insufficient evacuation of the thruster in between tests. This led to an offset in the thrust signal as well as a high degree of signal drift, for which it was difficult to correct. Again future testing shall allow for improved test data.

The rise in vacuum chamber pressure during the tests is $7.6 \cdot 10^{-4}$ Bar/min. However it is neglected in the analysis since it produces only 0.02% overall thrust decrease.

VI.II Blow down

Prior to a blow-down test the plenum is filled from the nitrogen feed system. Next the feed system is disconnected by closing a valve. At this point the amount of gas in the system is fixed except for some small leakage (less than 1% of the initial mass flow rate at start of thruster operation). At the start of the test the control valve (inside the plenum) is opened and the nitrogen is exhausted via the micronozzle.

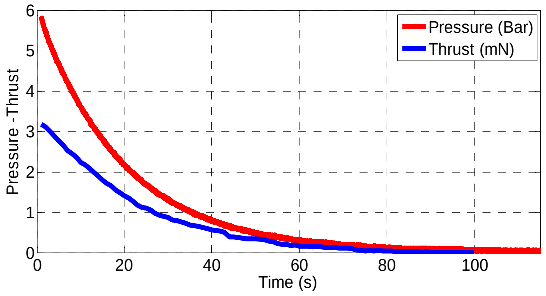

Fig. XI: Plenum pressure history during a blow-down tests (average chamber pressure 6.5 mBar, plenum temperature 297.4 K).

In total 6 different tests have been conducted, each starting at a different pressure to allow determining the total impulse delivered as a function of the starting pressure. The Fig. XI shows the pressure and thrust history for an initial pressure of ~6 Bar. It follows that it takes about 85 seconds for the pressure to reach a value of 0.1 Bar. Thrust varies from a little above 3 mN to zero at end of operation. Total impulse follows from integrating the thrust over the operation time and is equal to 120 mNs point.

All tests performed showed the same behaviour with comparable pressure and thrust curves, thereby illustrating good repeatability of performances.

VI.III Impulse bits

A number of impulse bit tests have been performed to determine the pulsed behaviour of the system. During these tests the thruster control valve was opened and closed in cycles from 1 second to 15 milliseconds.

In Fig. XII a typical result is shown for 3 impulse bits with each a pulse duration of 500 ms. The pressure before and after each bit remains constant because the system is directly connected to the nitrogen storage bottle (cut-off valve open). So during the impulse bit, the nitrogen that flows from the plenum is directly replenished from the storage tank.

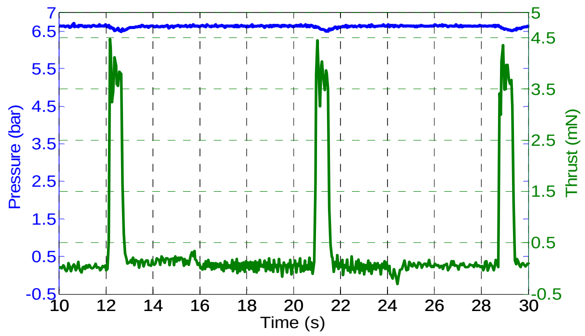

Fig. XII: Three 500 ms impulse bits. (vacuum pressure 18 mBar, plenum temperature 297.4 K).

The three pulses show good similarity, thereby demonstrating good repeatability of the performance of the thruster during pulsed operation. The average thrust measured during each bit is 3.79 mN at a pressure of 6.48 bar. Total impulse is shown in Table V.

Bit number	Valve opening time (ms)	Pressure (Bar)	Impulse (mNs)
1	560	6.48	2.54
2	560	6.5	2.42
3	560	6.5	2.64

Table V Impulse bits

VII ANALYSIS

In this paragraph an overview of some of the analysis performed so far is presented including a comparison with theoretical results.

VII.I Steady state

In Table VI measured versus theoretical pressure is given for the tests performed. Comparison shows that the pressure level reached inside the plenum is lower than anticipated (Table III). The thrust level measured also found to be lower than expected. The low quality of the nozzle (uncertainly on expansion ratio) affects the thrust as well as the nozzle discharge factor, that is different from one. This last factor will be explained m ore in detail in the next paragraph.

DP	Mass flow (mg/s)	Pressure measured (bar)	Pressure from theory (bar)	Discharge factor (%)
1	5	1.71	2.70	63.3
2	6	1.92	3.25	59.1
3	7	2.12	3.79	55.9
4	8	2.31	4.33	53.3
5	9	2.49	4.87	52.1
6	10	2.67	5.41	49.4

Table VI Measured versus theoretical pressure

The temperature measured inside the plenum during the test showed a significant increase, due for the most part of the heating of the control valve. The influence of the temperature rise on the thrust level is still to be investigated further.

VII.II Blow-down

In Fig. XIII the thrust is presented as function of pressure. The thrust levels are averaged over several measurements.

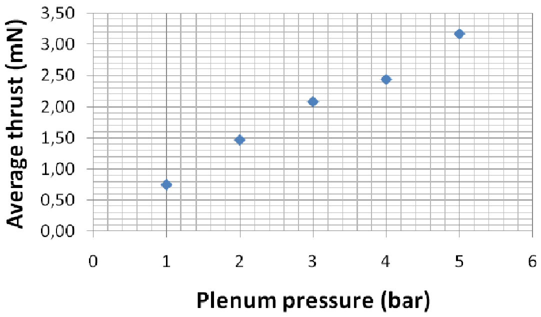

Fig. XIII Thrust measured as function of pressure during the six blow-down tests (accuracy 15%)

Fig. XIV shows the experimental pressure (in blue) during the blow-down test and the theoretical value (in red).

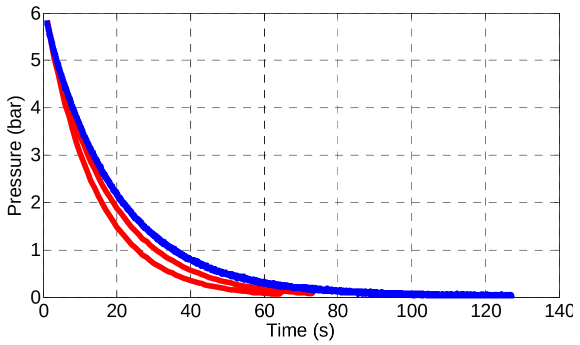

Fig. XIV: Experimental pressure (in blue) starting at 5.83 Bar and two theoretical curves (in red) , based on two different nozzle discharge factors.

The theoretical and experimental pressure profiles are very similar. They become identical if we assume a non ideal nozzle with a discharge coefficient (9) of 0.88 (k in Fig. XIV). This means that the real mass flow is 12% inferior to the one predicted by the theoretical model, based on ideal rocket theory. As the leakage is very small, this is mostly due to the existence of a boundary layer that blocks part of the nozzle (8).

The temperature measured inside the plenum shows no increase, this validates the initial assumption of isothermal expansion.

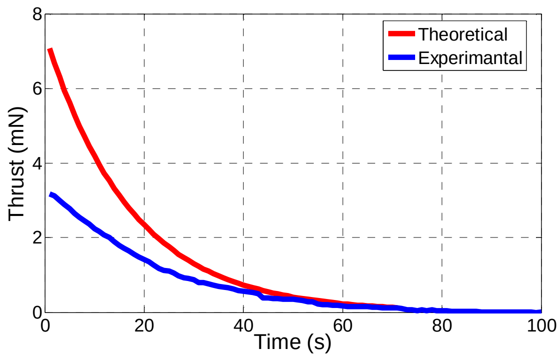

Fig. XV Theoretical versus experimental thrust level during a blow down test with a pressure at start of 5.83 Bar.

Fig. XV shows that experimental thrust is approximately half of the theoretical one. This is attributed to a reduced mass flow rate due to the flow blockage effect, and a low nozzle quality. The latter due to e.g. roughness of the nozzle walls (8). Another reason might be thrust misalignment, since it is not possible, with the current setup, to measure the direction of the thrust axis.

The value of the total impulse, 120 mNs meets the requirement if the presence of eight cool gas generators is taken into account. Each one can pressurize the plenum producing eight times the thrust profile seen in Fig. XIV.

VII.III Impulse bits

Table VII shows the thrust and pressure levels obtained for three impulse bits of duration 500 ms.

The large deviation from the model was already explained earlier in the text.

Pressure (Bar)	Estimated mass flow (mg/s)	Thrust (mN)	Deviation from model (%)
3.10	3.60	1.66	51.32
2.93	3.42	1.53	52.48
2.80	3.20	1.37	55.52

Table VII Three impulse bits of equal duration (500 ms), thrust level and plenum pressure (cut-off valve closed).

An interesting feature of the impulse bit is the pulse rise time. The rise time can be easily seen when the duration of the bit is increased to 10 seconds, as shown in Fig. XVII. 460 ms are necessary to the thrust (as well as the pressure) to reach stabilization. This has a direct influence on the thruster capability of producing short impulse bits, since it was found that for impulse bits of duration inferior to 50 ms no stable operation is reached at all.

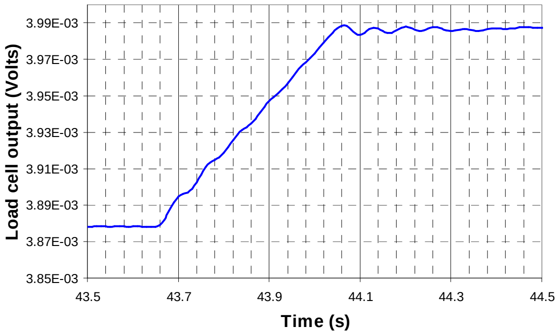

Fig. XVI Pulse rise phase (pulse duration: 10 seconds).

The long stabilization time is due to the presence of a volume between the valve and the nozzle throat (Fig. XVII). The amount of time necessary to fill this buffer volume decreases the stabilization time the system.

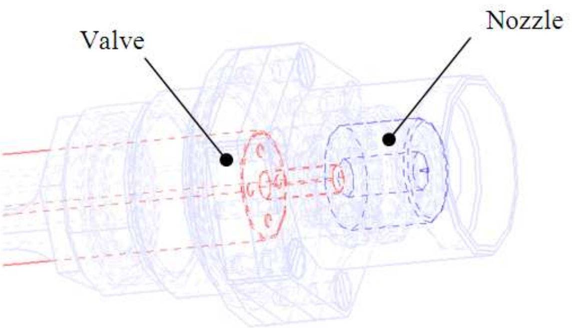

Fig. XVII Schematic of the nozzle-valve assembly

VIII CONCLUSIONS AND FURTHER DEVELOPMENT

A test campaign has been conducted to determine the thrust, impulse bit and total impulse performance of the Delfti-n3Xt $T^3\mu PS$ propulsion system. Since the test campaign is still in progress a final conclusion on the requirement fulfilment could not be reached. Nevertheless the preliminary results show:

- The $T^3\mu PS$ as well as the feed system showed some leakage. This in part explains for the difference between experimental and theoretical values of thrust and mass flow rate.
- Experimental results indicate a discharge factor of 0.88 for the blow down tests.
- The difference between experimental and theoretical thrust levels is in part is due to a low nozzle discharge factor. Other causes are a low nozzle quality, calibration inaccuracy, thrust misalignment.
- During all tests leakage was found. The theoretical model must be corrected to account the decrease in specific impulse of the thruster due to leakage.
- Thrust and pressure need a long time to stabilize; this is partly due to the volume between the valve and the nozzle.

Future work will include making repairs to the system as to allow carrying out the steady state tests, corrections for thrust misalignment and influence of the test setup.

IX ACKNOWLEDGMENT

This project is funded by Microned, one of the Dutch BSIK research programs.

X ACRONYMS

AOCS	Attitude and Orbit Control System
CGG	Cool/cold gas generator
MEMS	MicroElectroMechanical System
DP	Design Point
$T^3\mu PS$	**T**NO, **T**U-Delft, U**T**wente Micro-Propulsion System
TNO	Netherlands Organisation for Applied Scientific Research
TUDelft	Delft University of Technology
UTwente	University of Twente
MEOP	Maximum Expected Operating Pressure

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