Green Rocket Engine Test Site for High Performance Green Propulsion

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Abstract
The HPGP propulsion technology includes storable monopropellant blends based on Ammonium DiNitramide (ADN) and thrusters with a high temperature resistant thrust chamber and catalyst. After 3 years in space on the PRISMA mission, all planned firings with the High Performance Green Propulsion (HPGP) system using 1 N HPGP thrusters and the storable liquid monopropellant LMP-103S, have successfully been completed and all test objectives have been met and the mission is extended in order to accomplish new objectives [1]. In order to support the development efforts, the test stands (TS) designated TS-1 and TS-2, have been established for hot-firing under vacuum conditions. ECAPS' hot-firing test facility is conceived as a "Green Rocket Engine Test Site" with minimal impact on the environment and greatly simplified operations - as SCAPE suits are not required for fuelling or any other operations. The capacity of TS-1 is continuous firing of 1 N thrusters and the test stand is also used for the acceptance testing of the ECAPS 1 N HPGP Thrusters in production. The capacity of TS-2 is continuous firing of thrusters up to 22 N for 1 hour, and for pulse mode operation a 200 N thruster has successfully been tested. The test stand can be further upgraded for future testing of thrusters up to 500 N (100 lbf) at continuous firings (estimated to be up to 15 minutes at near vacuum conditions). The test facility and the aspects of operation will be presented in the paper.

1. Introduction

ECAPS have established two test stands for the hot-firing of HPGP thrusters required for the development work, acceptance testing and qualification testing under near vacuum conditions. Test stand 1, or TS-1, is used for 1N–5N thrusters, and test stand 2, or TS-2, is used for 5N–200N thrusters [2], [3]. The two test stands operate using different principles as described in this paper. The test facility is conceived as a "green" test site with minimal impact on the environment and greatly simplified operations.

2. ECAPS HPGP thruster test facility

The facility is located at Swedish Defence Research Agency – FOI, in Grindsjön, 50 km south of Stockholm. ECAPS lease the building (including the compressors and large 26 m^3 pressure vessels for compressed air). The test equipment is developed, owned and operated by ECAPS. The test facility consists of two test stands with associated support systems as shown in figure 1 and 2.

Figure 1. ECAPS Thruster Test Stand 1, TS-1

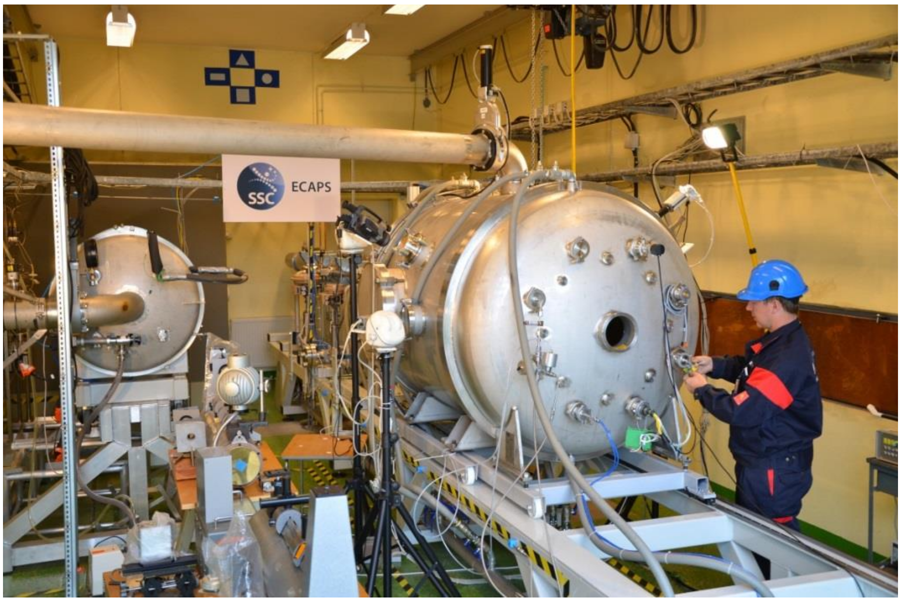

Figure 2. ECAPS Thruster Test Stand 2, TS-2

For simulation of the working condition in space the thrusters are hot fire tested at low pressure in vacuum tanks that form the main part of the test stands. In TS-1 vacuum is created by a rotary vane vacuum pump-roots pump combination. When testing thrusters at 1 N, vacuum levels of less than 1 mbar are sustained continuously. In TS-2 a two stage ejector system is used together with the rotary vane vacuum pump-roots pump combination used for TS-1. In TS-2 the capacity is to keep the vacuum level $\leq$ 5 mbar at 22N thrust level for up to 1 hour.

This paper describes the systems and their components that are used to create and maintain vacuum in TS-1 and TS-2 during testing of HPGP thrusters.

3. Vacuum pump systems for ECAPS test stands

The main function of the test stand is to provide a proper ambient environment for testing thrusters to be used in space applications. This is achieved by creating an appropriate vacuum level during testing. TS-1 uses a combination of a rotary vane pump and a roots pump that are running continuously during testing. Test Stand 2 uses two different systems to create vacuum. The first system is the same combination of rotary vane pump and roots pump used by TS-1 (connected through a gate valve). The second system is a two stage ejector system which is used intermittently during hot fire sequences.

When starting a hot fire test in TS-1, after all preparations has been made, vacuum is created by running the rotary vane pump-roots pump combination until the pressure is stabilized at about 0.3 mbar. The pumps then run continuously during testing.

For TS-2 initial vacuum is first created by running the rotary vane pump- roots pump combination until the pressure is stabilized at about 0.3 mbar. The pumps then run continuously. A short moment before a hot fire sequence is started the two stage ejector system is started. During the hot fire sequence the thruster itself augments the ejector system and acts as a third ejector stage (with the exit nozzle of the thruster carefully matched with the inlet to the thruster diffusor pipe of the ejector stage). After the hot fire sequence is finished the ejector system is turned off but the vacuum pumps continue to run.

In both test stands the vacuum pumps are kept running for the whole duration of the test and are turned off when the testing is finished for the day or the test is completed. If the test is stopped for the day a maintenance vacuum pump is connected and left running over night.

3.1 Vacuum pumps

The vacuum pump combination consists of a Sogevac SV 630 rotary vane pump as pre-vacuum pump and a RUVAC SW 2001 roots pump as fine vacuum pump. Both pumps are manufactured by Oerlikon Leybold Vacuum GmbH.
The vacuum pumps are controlled from a wall mounted panel in the control room.

The vacuum pump combination is located in the pressure storage room next to the testing room (figure 3) in the building that houses ECAPS test facilities at FOI Grindsjön. The pumps are placed behind the two $13m^3$ pressure vessels (which are used for the high pressure system to be described later). From the intake of the roots pump a system of pipes connects the vacuum pumps with the two test stands as shown in figure 4.

A gate vale is located close to the vacuum outlet of the two test stands in order to seal off the test stand not in use. For venting the vacuum system a vent valve is placed close to the gate valve of TS-1. It is also possible to vent the vacuum tank of TS-1 separately with the gate valve closed through a vent valve placed on the tank close to the vacuum outlet. All valves are operated from one control panel in the control room except the gate valve for TS-2 which is operated from the computerised ejector control system.

The vacuum pumps are mounted in a steel frame with the Roots pump placed above the rotary vane pump. The inlet of the rotary vane pump is connected to the outlet of the Roots pump with a DN 100 pipe with a flexible compensation element, figure 4.

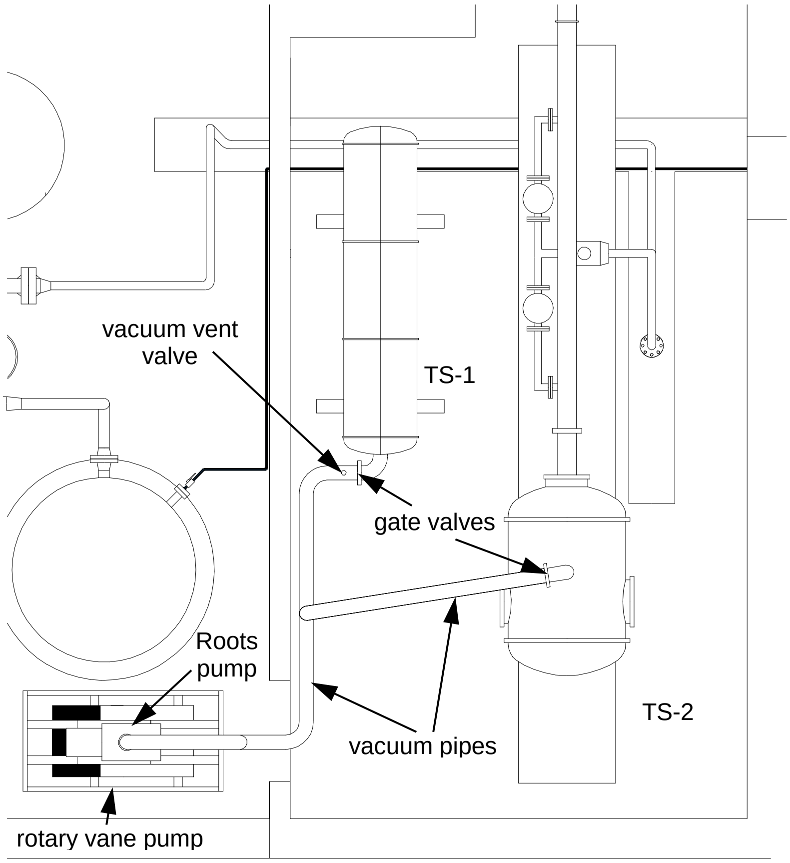

Figure 3. Schematic of the vacuum system

Figure 4. Pump and rotary vane pump with the connection pipe

3.2 Ejector system

The ejector system for TS-2, shown in figure 5, is a two stage high pressure air ejector. High pressure air to drive the ejectors is supplied from two 13 m^3 pressure vessels certified for a maximum pressure of 200 bar. The ejector system is controlled by a dedicated PC connected to a real time controller programmed in LabVIEW RT.

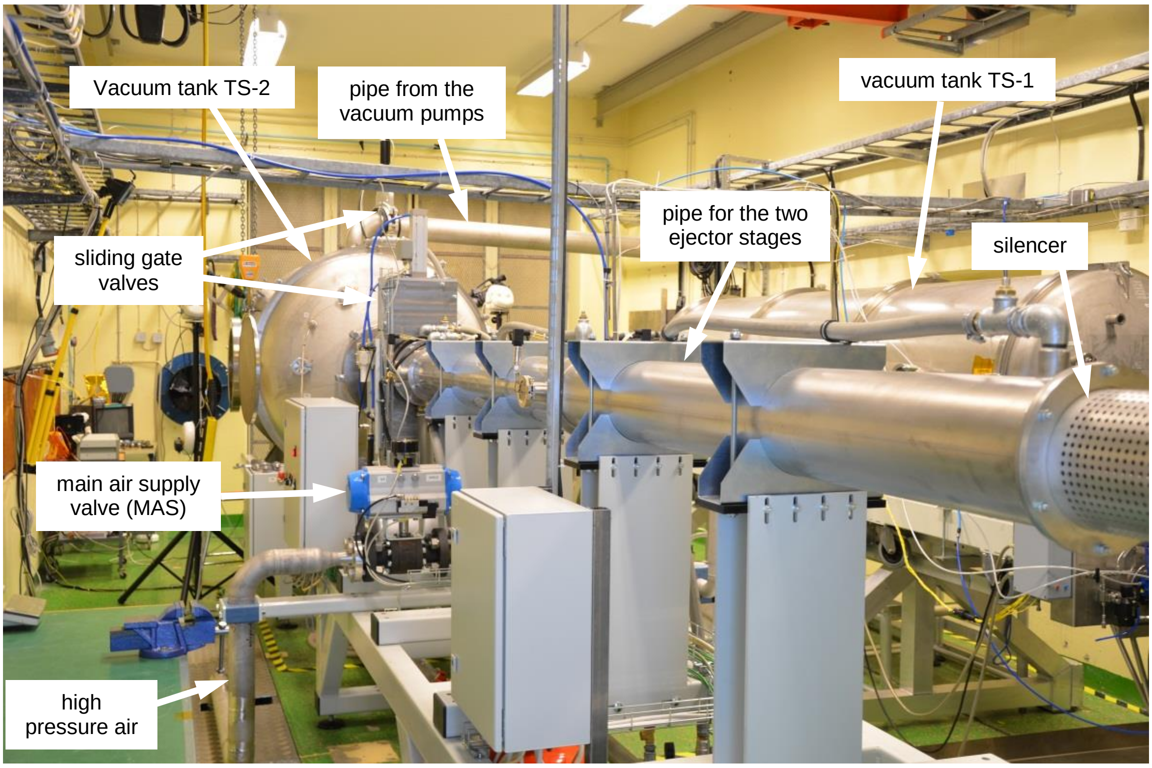

Figure 5. The ejector part of TS-2

3.2.1 Ejector principle

In ejector systems, pumping action is achieved through the controlled interaction and mixing of a high velocity and high-energy stream with a lower-velocity and lower-energy stream within a duct, figure 6. The high energy stream, the primary flow, in TS-2 is achieved by expanding high pressure air through a de Laval nozzle. This produces a high velocity jet directed away from the lower energy stream. In TS-2 the low energy stream is the content of the vacuum chamber which is mainly made up of the exhaust gases from the thruster tested. The high-velocity high-energy stream entrains the lower-velocity stream by viscous interaction and thus creating a lower pressure upstream of the de Laval nozzle.

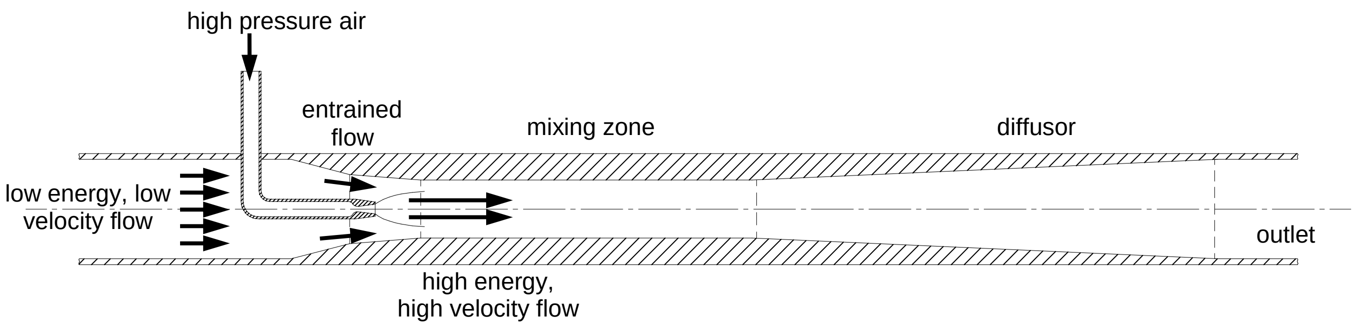

Figure 6. Schematic of an air ejector

3.2.2 TS-2 ejector

Figure 7 shows a schematic view of the ejector system for TS-2. The ejector system is made up of a diffusor pipe for the thruster, a sliding gate valve, the first and the second stage ejectors, and a silencer.

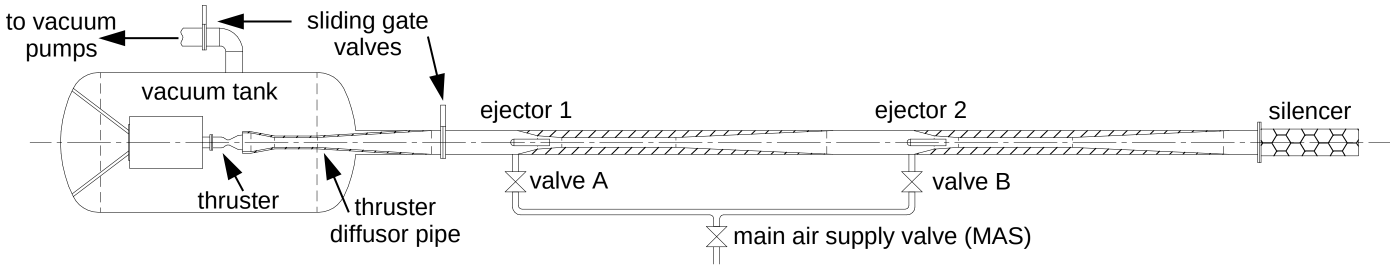

Figure 7. Schematic of the TS-2 ejector system

The thruster is mounted on a thrust measurement balance inside the vacuum tank. The nozzle exit of the thruster is normally positioned slightly inside the diffusor pipe in the vacuum chamber.

The sliding gate valve is pneumatically operated and is closed at all times when the ejector is not running. This ensures that the vacuum pumps can maintain low pressure level in the vacuum tank. The main air supply valve (MAS) and the valves to control each ejector are pneumatically operated. Air to operate the pneumatic valves is supplied by an auxiliary air compressor located in a service room on the back of the building.

3.2.3 High pressure system

High pressure air to run the ejector system is supplied from two large interconnected pressure vessels. The vessels are located in the (air storage) building extension, adjacent to the test room. They have each a volume of 13 m^3, thus giving a total volume of 26 m^3. The pressure capacity of the storage vessels is 200 bar. The pressure vessels are charged from two 4-stage piston high pressure compressors. The compressors are of type Ingersoll Rand Type 30 Model 15T4 with nominal power of 15 kW. The nominal capacity for each compressor is 988 l/min of air at normal temperature and pressure (1 bar, 288 K) and delivering a pressure of 242 bar after the last stage. Before entering the pressure vessels the air passes through an air dryer. A safety valve on the pressure vessels secures that the pressure level in the vessels does not exceed 200 bar. Figure 8 shows a schematic of high pressure air system.

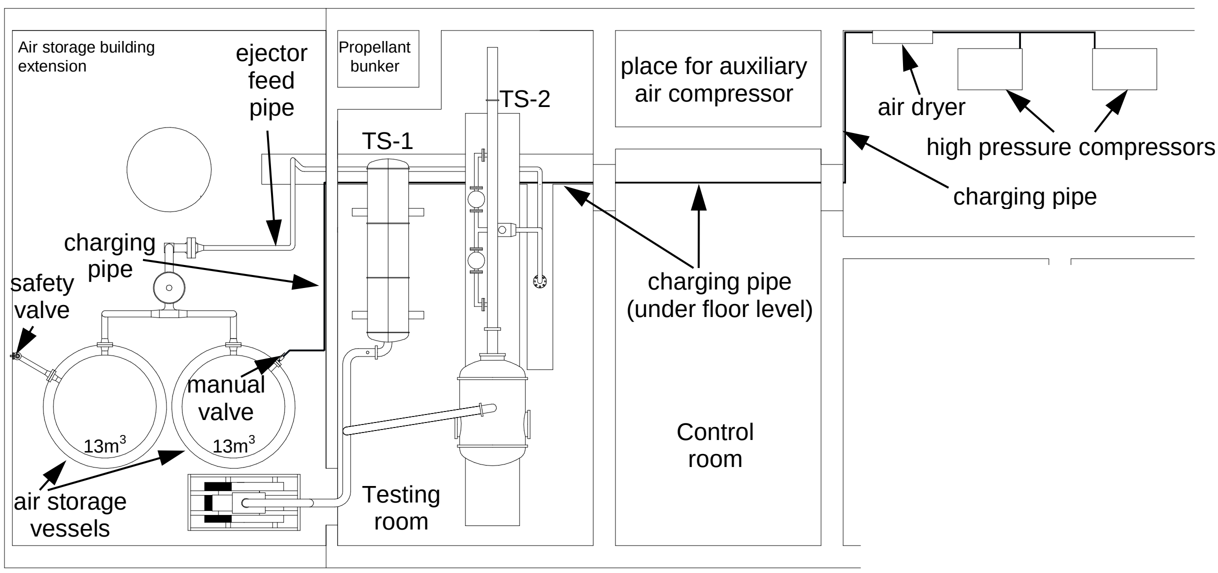

Figure 8. Schematic of TS-2 high pressure air system viewed from above

3.2.4 Control system

The ejector system is controlled from a dedicated PC connected to a National Instrument compactRIO real time system. The compactRIO system is based on an 8 slot chassis with modules for digital input, digital output, analogue current input, analogue current output, and temperature input. A real time control system written in Labview RT is used to control the ejectorsystem, the sliding gate valve and the cooling system of TS-2.

3.2.5 Running the ejector system

The procedure of how to launch, start, run, and close down the control system is not described in detail. Only a short description of a normal run sequence of the ejector system as executed by the ejector control system is given:

1. Open the main air supply (MAS), figure 9
2. Regulate ejector valves A and B to pre-set pressures, figure 10
3. Open the sliding gate valve
4. Wait a pre-set time or until termination by the operator while the hot fire sequence is executed
5. Close the sliding gate valve
6. Close ejector valves
7. Close MAS valve

The run sequence is programmed as a run case that the control system executes after a start command from the operator. Normally for a run case, the waiting time at point 4 (above) is 600 s. The hot fire sequence is normally shorter than 600 s and the operator terminates the wait, on command from the test leader, by pressing the manual override button which makes the control system continue in the run case sequence with point 5 (above).

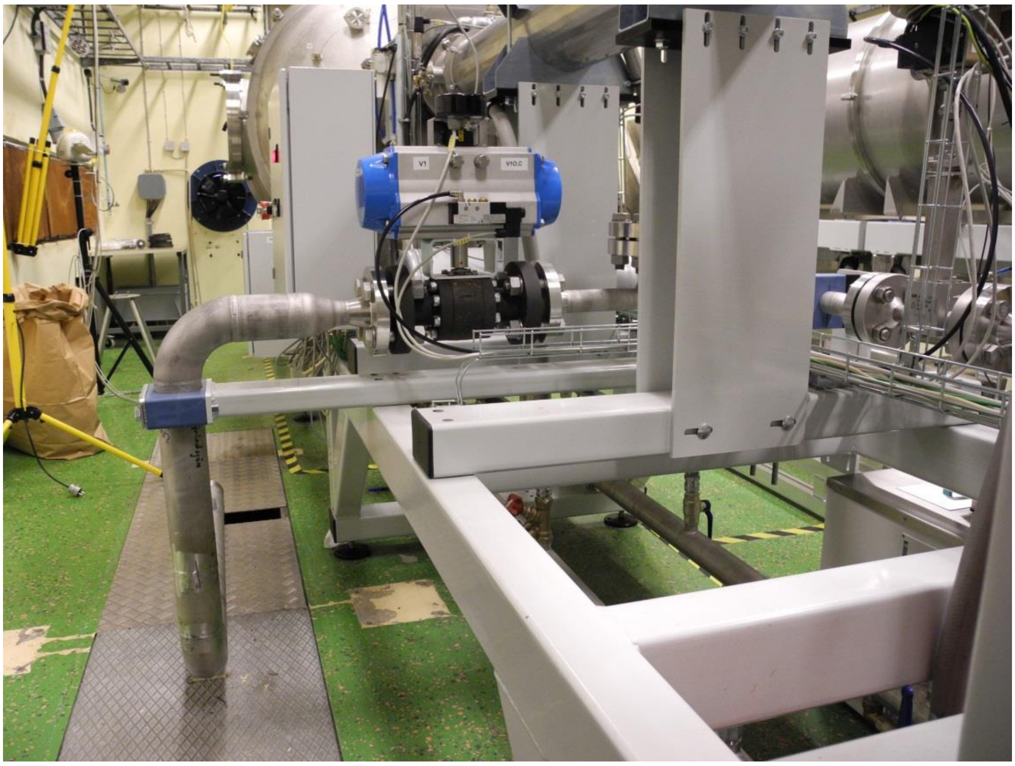

Figure 9. Main Air Supply valve (MAS) for the ejector system

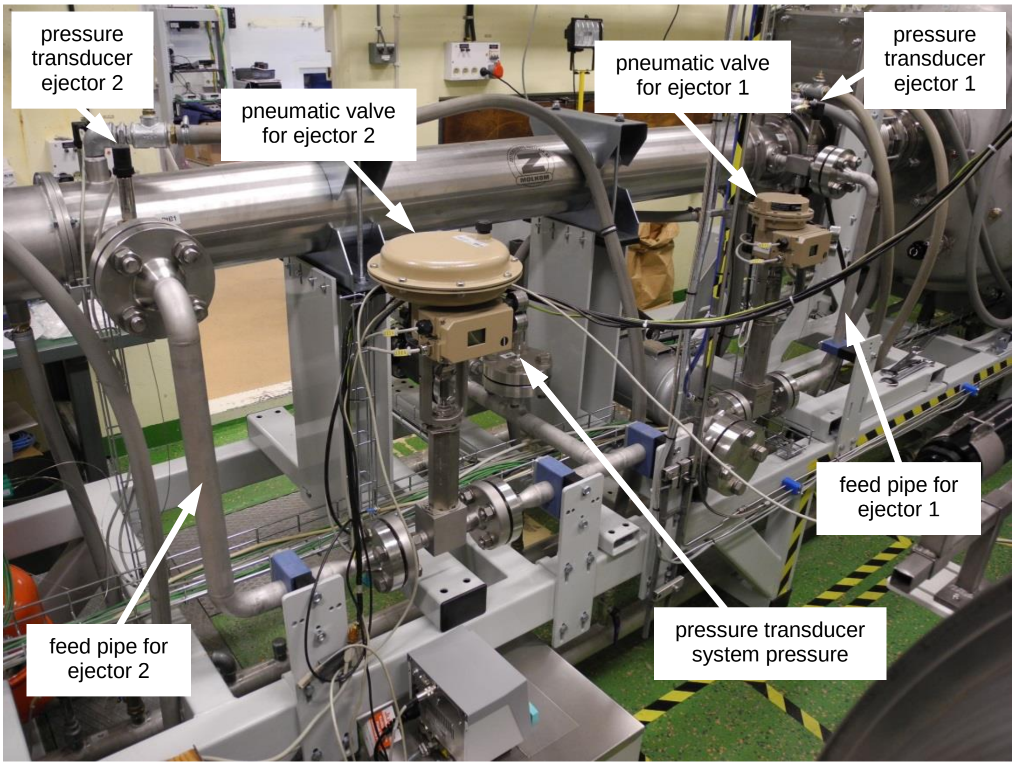

Figure 10. Ejector system pipes and valves

3.2.6 Maintenance vacuum pump

When testing is stopped for the day and is planned to continue the next day, or later, it is desirable to maintain vacuum conditions in the test chamber. This is done by connecting the maintenance pump which is a 2-stage rotary vane pump of type Alcatel Adixen Pascal 2021 SD. The nominal capacity is 20m^3/h and the power consumption is 450 W. Figure 11 show the maintenance pump. The pump is operated from a panel in the control room.

Figure 11. The maintenance pump

Figure12. Control room for TS-1 and TS-2

4. Propellant System for ECAPS test stands

Thrusters developed by ECAPS use ADN based monopropellants. Gas pressure feeding is used to supply the propellant to the thruster. This means that the propellant is forced out of its tank by displacement with a high pressure gas. During testing the propellant is located in a special safety room adjacent to the testing room. Swagelok electro polished tube with Swagelok VCR fittings connects the propellant tank with the vacuum chamber of the test stand. The propellant feed tube is lead in to the test room from the safety room through a fire sealed hole in the wall. In the test room close to the wall the propellant is lead through a mass flow meter suitable for the flow range of the thruster. The flow meter measures the mass flow of the propellant for performance calculations but the signal is also used to indicate leakage in the propellant feed system.
The propellant safety room contains a frame to hold the propellant tank placed on a scale. The frame and scale are placed in a stainless steel tub designed to contain the propellant in case of a leakage. The scale is used for weighting of propellant and propellant tank. The pressurant (gaseous helium) is feed into the tank at the top and the propellant is let out at the bottom. The main safety valve for leakage in the propellant system is the pneumatic emergency shutdown valve. This valve is closed if the flow meter measures a flow rate higher than a pre-set value (that varies depending on thruster size). Other equipment in the propellant safety room is for fuelling the propellant tank. This consists of a scale for the propellant transfer tank, a peristaltic pump, a 1 µm filter, a manual fuelling valve and a Tygon tube with a dip tube to be placed in the transfer tank. Figure 13 shows the equipment in the propellant safety room, before fuelling.

5. Fuelling using LMP-103S

Although LMP-103S is a low hazard propellant (low toxicity, non-carcinogenic, non-reactive), it is still energetic and must be handled adequately. Other ground handling aspects of LMP-103S are; that it is not sensitive to air or humidity, SCAPE operations are not required and decontamination resulting in significantly less waste and lower risk waste handling in in comparison with hydrazine fuelling.

ECAPS propellant for testing is stored in dedicated storage buildings close to the test facility. The propellant is fetched from the storage building for fuelling. Transfer of the propellant from its plastic transfer tank to the test stand propellant tank is done using a peristaltic pump, figure 13. During fuelling the emergency shutdown valve has to be closed and the gas pressurisation system vented. Fuelling is done by operating the peristaltic pump from the control room. The display of the scale for the transfer tank is monitored by the safety room camera, figure 14.

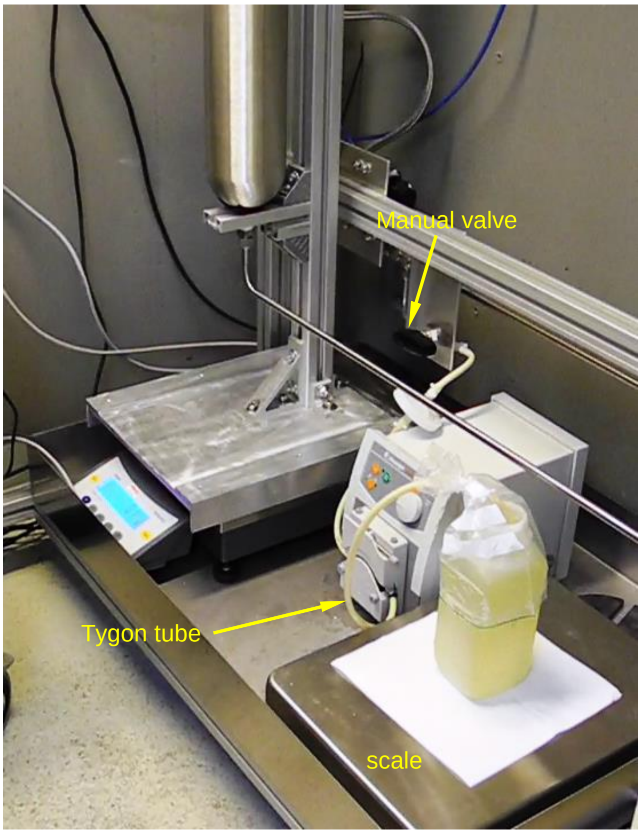

Figure 13. Equipment in the propellant safety room, set-up ready for fuelling

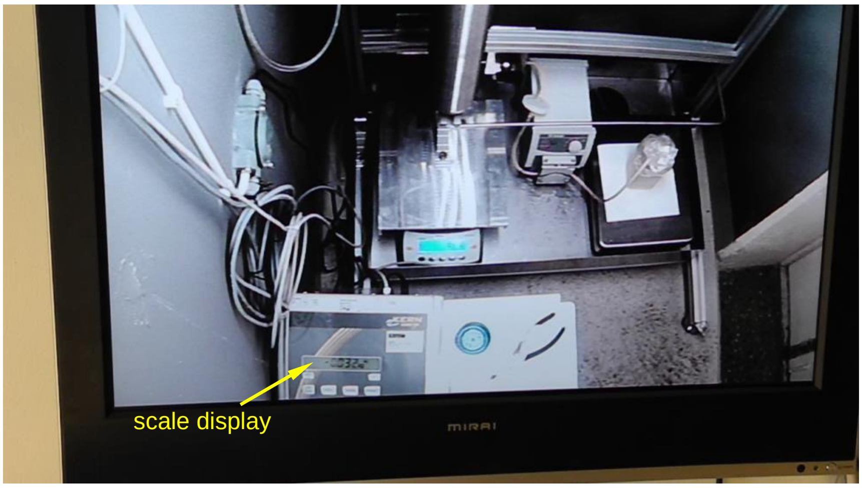

Figure 14. Fuelling viewed from the control room monitor

6. Thermal control systems

For hot fire testing in TS-1 and TS-2 two cooling systems are used. To cool the thrust balance assembly inside the vacuum chambers a cryostat that keeps the temperature of the cooling fluid at 20ºC is used. The coolant fluid used in the cryostat is a 50-50 mixture of denatured alcohol and water. Figure 15 shows the 200N HPGP thruster in its balance assembly and figure 16 during hot-firing in TS-2.

For long term testing in TS-1, a cooling system can be used to keep the vacuum chamber at stable temperature conditions. For cooling the vacuum chamber, diffuser, gate valve, and the ejectors for TS-2 a dedicated cooling system is integrated into the test stand. The coolant used in this system is water and a circulation pump circulates the water through the various parts of the test stand and through a forced air cooler.

7. Hot-Firing

An electrical sequencer is used to set and control FCV single pulses and pulse trains. The data acquisition is performed by a National Instruments PXI system together with a PC based in house developed LabVIEW software. The LabVIEW system background logs all parameters with 1 Hz, and each test run can be logged from 100Hz to 10 kHz. The default used for all parameters is 6 kHz and the resolution is 16-bits. Each test run is automatically assigned its own unique filename with all parameters stored together. The data acquisition system also has a playback function for an easy instant review of the test if needed. The format of the saved data is National Instruments standard TDMS (binary format). The system has a function for thrust calibration that is performed pre and posts the test.

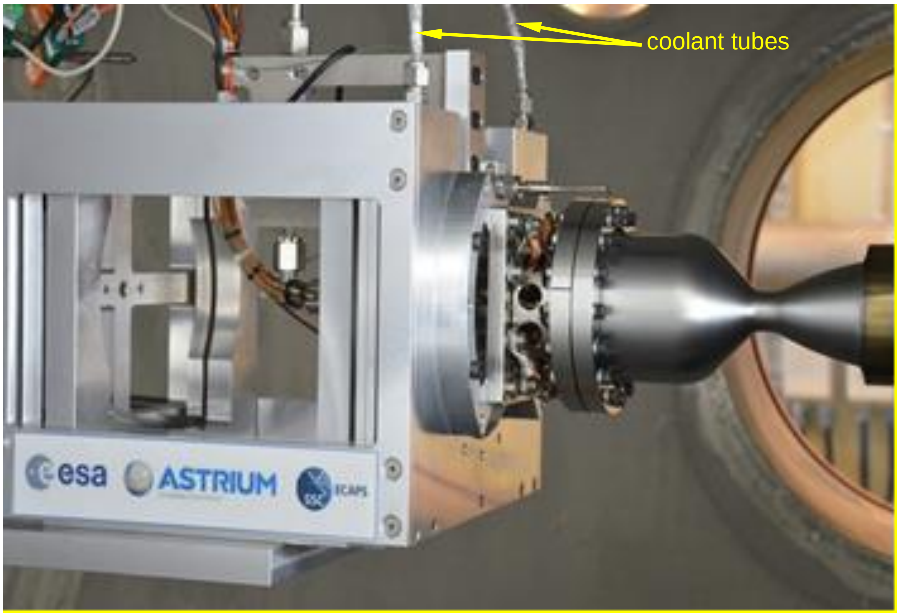

Figure 15. The 200 N HPGP DM thruster in TS-2

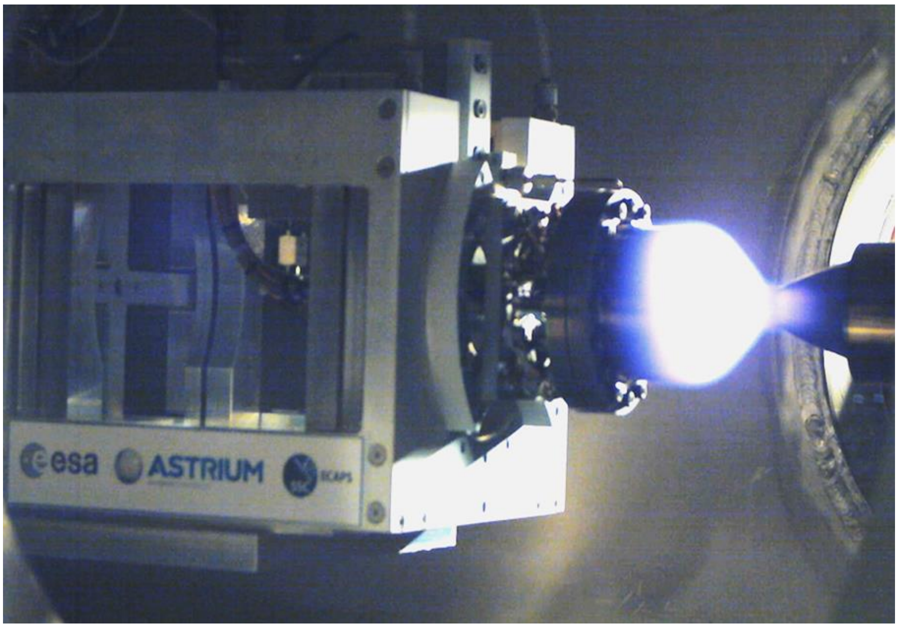

Figure 16. The 200 N HPGP DM thruster during Firing in TS-2

The following parameters are logged:

- Propellant consumption (using scale and flow meter)
- Propellant pressure (measured close to the thruster)
- Thrust (using piezoelectric force sensor)
- Temperatures (using type K and type R thermocouples, and a motor controlled two colour pyrometer outside of the vacuum chamber)
- Flow Control Valve voltage
- Vacuum chamber (thruster ambient) pressure

A video system is used for surveillance with five cameras overviewing the test room, the propellant safety room, and the thruster inside the vacuum chamber.

8. Conclusions

The HPGP thrusters hot fire testing is performed at ECAPS “Green Test Facility”. The facility is completely environmental benign with minimal emissions. Unlike hydrazine, which requires a rigorous regime of safety procedures, HPGP handling does not require specialized safety equipment (such as SCAPE suits) or facility-related precautions (such as scrubbers etc.). This is due to the fact that HPGP has very low toxicity, is extremely stable (very low sensitivity to mechanical shock, air and humidity), is non-flammable and that “self-standing” GSE can be used. Additionally, HPGP has received a transport classification of UN and DOT 1.4S; thus allowing it to be transported on commercial passenger aircraft.

The main function of a test stand is to provide a proper ambient environment for testing thrusters to be used in space applications. In ECAPS hot-firing test facility this is achieved by creating the appropriate vacuum level during testing using a combination of a rotary vane pump and a roots pump which are running continuously during testing in TS-1. Two different systems are used to create vacuum in TS-2. The first system is the same combination of rotary vane pump and roots pump used by TS-1 (connected through a gate valve). The second system is a two stage ejector system which is used intermittently during hot fire sequences. Liquid cooling is used for thermal control of both TS-1 and TS-2.

TS-1 has been operated more than ten years and has primarily been used for the development of the 1N HPGP thruster, but is used for thrusters up to 5N on a regular basis. TS-2 was commissioned in the spring of 2011 and has been used for testing thrusters from 5N up to 200N. The air supply is sufficient for steady state firings of up to one hour for 22N thrusters. For 50N and up to 200N thrusters testing is mainly done in pulse mode operation. The test stand is designed so it can be upgraded with a new ejector system, enabling for hot-firing testing of 500N thrusters.

ECAPS recently supported Astrium with the knowledge how to handle the LMP-103S and adopt a test facility for the hot-firing test campaign of the 200N HPGP DM thruster at Astrium in Lampoldshausen, Germany. In similar manner ATK was supported during the hot-firing test campaign for the 5N HPGP thruster in Elkton, USA.

9. Acknowledgments

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