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Flight Qualification Tests of a Cold Gas Propulsion System for a Small Satellite

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Abstract

Cold Gas Propulsion Systems have shown their good capability for attitude control and small velocity change orbit maneuver for many years. They offer several advantages like wide range of thrust from low thrust level suitable for fine and accurate attitude control of microsatellites up to high thrust levels suitable for orbit maneuvers. They also offer high reliability and flexibility at an attractive cost and time of development. Therefore, to perform a small orbit maneuver to increase the altitude of a small 60 kg-satellite from 300 to 400 km with a velocity change about 50 m/s, cold gas propulsion system has been chosen, and consequently designed and developed in Iran in 2011. The system has a total wet mass of 14 kg while carries 6 kg of Nitrogen stored at high pressure of 330 bar in a full composite 6 kg-tank. The high pressure is abated to 16 bar passing a two-stage-pressure regulator while the pressure before and after regulator is observed by two high and low pressure transducers respectively. The thrust produced by the system is 1 N at a specific impulse of 70 s. Finally, to have the system qualified for space application on the aforementioned satellite according to European Cooperation for Space Standardization (ECSS), it has to pass several environmental as well functional tests. The different elements in the system as well as the whole assembled-system have successfully passed various environmental tests including shock, random and sinusoidal vibration tests, EMC/ESD tests, thermal cycle and thermal vacuum tests. Furthermore, they have been double-checked for size, dimension, and power, if applicable. In addition, the system has undergone several stages of functional tests including measurement of thrust, life cycle tests, etc. The paper intends to take a glance at the flight qualifications tests of the cold gas propulsion system.

Introduction

Cold gas propulsion systems use an inert cold gas as the propellant (working fluid). Besides the propellant, cold gas systems consist of one or more engines (cold gas thrusters), a propellant storage tank, and some tubing. As propellant any gas may be used. However, in practice mostly nitrogen and helium are used. This is because these gases are highly inert (do not react) and have a reasonably low molecular mass. Compared to nitrogen, helium offers the advantage of a specific impulse being about 2.5 times higher than for nitrogen, allowing for a significant reduction in propellant mass, but at the expense of an increased storage volume or pressure (about a factor 7) and a higher cost. The thruster essentially consists of a nozzle and a valve. The nozzle accelerates the high pressure cold gas to a high velocity, whereas the valve regulates the thrust generation timing (on/off switching). The storage tank stores the cold gas prior to its use under high pressure to limit the tank volume. The tubing connecting the tank and the thruster(s) is necessary for feeding the gas from the storage tank to the thruster(s). The thrusters are usually operated in a blow-down mode (pressure decreases; compare the pressure in a balloon during emptying). The energy required for propulsion is fully contained in the pressurized gas. No heating of the gas takes place. Instrumentation might be present for estimation of propellant remaining.

Cold gas systems have been used on many early spacecraft as attitude control systems. Today, these systems are mostly used in cases requiring low total impulse of up to 4000 Ns or where extremely fine pointing accuracy or thrust levels must be achieved or the use of chemical propellants is prohibited for safety reasons. Furthermore, because of its simplicity; very low thrust levels of several tens of mN are attainable with minimum impulse bits in the range of 0.1 mN-s. Specific impulse values typically are low, in the range of about 68 s for nitrogen gas. Low specific impulse can be considered as the main downside of a cold gas propulsion system.

Cold gas propulsion system has been applied on a number of satellites including COS-B, OTS, EURECA, ASTRO-SPAS, HIPPARCOS, EXOSAT and STRV-1C and -1D. It is also incorporated on the Dutch SLOSHSAT, which supposedly was launched in 2005.1) Cold gas technology is available commercially from companies like STERER, Marotta, and Moog (USA), DASA (Germany), Rafael (Israel) and Bradford Engineering (The Netherlands).

Typical price for a cold gas thruster was about 20,000 Euro in 2000 including documentation. Without documentation, and for larger quantities, considerable price reductions (about a factor 4 or more) could be obtained per unit. Typical prices for other cold gas propulsion system components are in the range of Euro 5,000 - 25,000 (1994), excluding costs for documentation and qualification.[1-6)]

Several types of space thrusters have been developed at Sharif University. The activities began to develop PPTs [7-9)] since late 2008, cold gas propulsion system [10)] since late 2010, and resistojet [11-12)] since late 2011. Cold gas propulsion system was considered to be designed to perform an orbital maneuver for a 60 kg microsatellite to raise its orbit altitude for 150 km, with a velocity change slightly less than 50 m/s. The system was designed to produce approximately 1 N of thrust using N2 as propellant discharging from a nozzle located at the satellite center of mass. The system total mass was about 14 kg with 5 kg of propellant in a full-composite 6 kg tank. All the different parts of the system including thruster, tank, pressure regulator, fill/vent valve, isolation valve, etc. were designed and developed which is comprehensively reviewed elsewhere.[10)]

Finally, to have the system flight qualified for space application on the aforementioned satellite according to European Cooperation for Space Standardization (ECSS), it has to pass several environmental as well functional tests. The different elements in the system as well as the whole assembled-system have successfully passed various environmental tests including shock, random and sinusoidal vibration tests, EMC/ESD tests, thermal cycle and thermal vacuum tests. Moreover, the size, dimension, and power of the system have been double-checked with respect to satellite requirements. In addition, the system has undergone several stages of functional tests including measurement of thrust, life cycle tests, etc. The paper intends to take a glance at the flight qualifications tests of the cold gas propulsion system.

Cold Gas Propulsion System

The design and development of the cold gas propulsion system is briefly reviewed and the various elements of the system are introduced. Although it is comprehensively discussed elsewhere.[10)]

The system total wet mass is about 14 kg. Table 1 presents the mass divisions of the system.

The system consists of various parts which are listed below in the order of the main system:

- Fill/Vent valve
- Tank
- HP pressure transducer
- Filter
- Isolation valve
- HP pressure regulator
- LP pressure regulator
- LP pressure transducer
- Solenoid valve
- Thruster

Table 2 shows the general characteristics of the system.

Table 1 Cold gas system mass divisions.

Element	Mass (kg)
Tank (dry mass)	6
Propellant	5
Thruster	0.3
HP regulator	0.65
LP regulator	0.45
Fill/Vent valve	0.282
Isolation valve	0.4
Pressure transducers	0.3
Filter	0.15
Connections	0.45
System Total Mass	**14**

Table 2 Cold gas system characteristics.

Inlet pressure	16 bar
Thrust	≈ 1 N
External leakage	10-6 scc/sec
Working cycle	Over 10,000
Valve response time	Less than 50 ms
Power	Max 10 W
Voltage	12 V
Mass flow	≈ 5 gr/s
Thruster mass	Max 300 gr
Propellant	GN2
Propellant mass	6 kg
Tank storage pressure	330 bar
Empty tank volume	16.5 Lit
Tank exterior size	42 cm diameter × 30 cm height
Specific impulse	70 s

The tank is filled through a fill/vent valve mounted on it and a filter is located at the tank output. The system employs two pressure transducers. The first one which is a high pressure sensor is mounted after the tank to measure the tank pressure up to 400 bar. The system pressure diminishes passing a two-stage pressure regulator to 16 bar. A low pressure transducer is located downstream of the regulator to sense the pressure entering the thruster. Upstream of the thruster, a solenoid valve is located to control the flow to the thruster and time the thrust production based on the command.

The thruster consists of a conical convergent – divergent nozzle with 0.75 mm throat diameter, 3 mm outlet diameter, and an area ratio of 16:1. Simulation of the flow inside the nozzle utilizing CFD method showed that thrust is near 1 N for the given nozzle geometry and at nozzle inlet pressure of 16 bar and also specific impulse is 70 s. Figure 1 shows a picture of the thruster and Fig. 2 indicates the cold gas thruster propulsion system with respect to its schematic.

Table 3 shows the results of simulation of the thruster for both sea level and vacuum condition. The results are presented for 4 different pressure inlets and the obvious increment of thrust as a result of increasing the nozzle inlet pressure can be seen. Specific impulse and mass flow are also presented in the table. The complete discussion of the numerical simulation and the results are presented elsewhere.[10)]

Table 3 Result of numerical simulation.

	Nozzle inlet pressure (bar)			
	13	14	15	16
Sea level				
Thrust (N)	0.41	0.46	0.51	0.57
Specific impulse (s)	36	37	38	40
Mass flow (g/s)	1.18	1.27	1.36	1.46
Vacuum				
Thrust (N)	0.85	0.91	0.98	1.04
Specific impulse (s)	71	71	71	71
Mass flow (g/s)	1.18	1.28	1.37	1.46

Fig. 1 Photograph of cold gas thruster and solenoid valve as one unit.

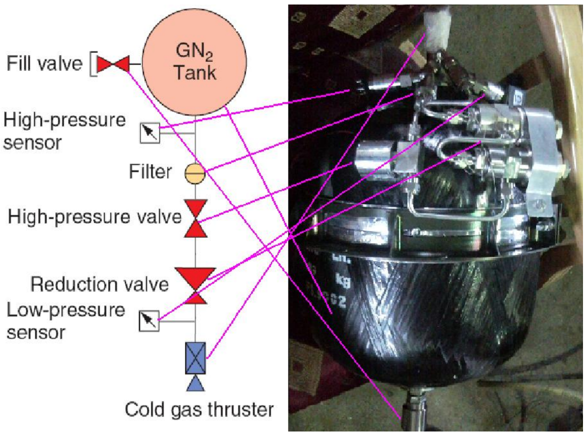


Fig. 2 Photograph of cold gas thruster propulsion system with respect to schematic of the system.

Test standard

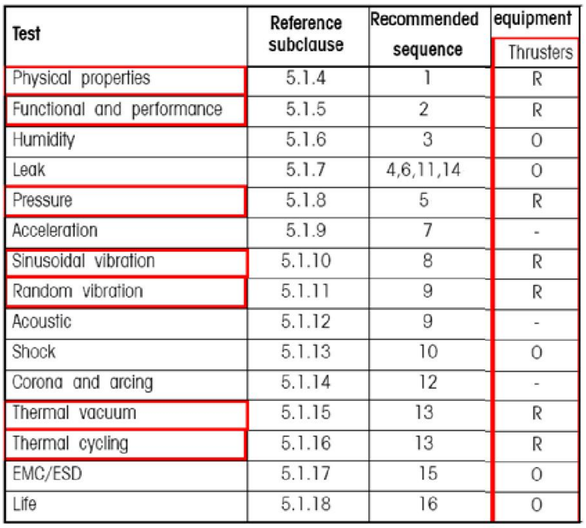
Flight qualification tests have been carried out with respect to the European Cooperation for Space Standardization (ECSS), Space Engineering – Testing Standard (ECSS-E-10-03A).[13)]

Table 4 shows a table taken from this standard showing required and optional tests to space qualify a thruster. Figure 3 also shows flight qualification test procedure for a propulsion system. Considering that, the required tests for thrusters are listed below:

- Physical properties
- Functional and performance
- Pressure
- Sinusoidal vibration
- Random vibration
- Thermal vacuum
- Thermal cycling

In addition, according to the standard leakage test is also needed for a system which uses gases or fluids.

Table 4 ECSS Space engineering testing standard for thrusters.[13)]



Test	Reference subclause	Recommended sequence	equipment
			Thrusters
Physical properties	5.1.4	1	R
Functional and performance	5.1.5	2	R
Humidity	5.1.6	3	O
Leak	5.1.7	4,6,11,14	O
Pressure	5.1.8	5	R
Acceleration	5.1.9	7	-
Sinusoidal vibration	5.1.10	8	R
Random vibration	5.1.11	9	R
Acoustic	5.1.12	9	-
Shock	5.1.13	10	O
Corona and arcing	5.1.14	12	-
Thermal vacuum	5.1.15	13	R
Thermal cycling	5.1.16	13	R
EMC/ESD	5.1.17	15	O
Life	5.1.18	16	O

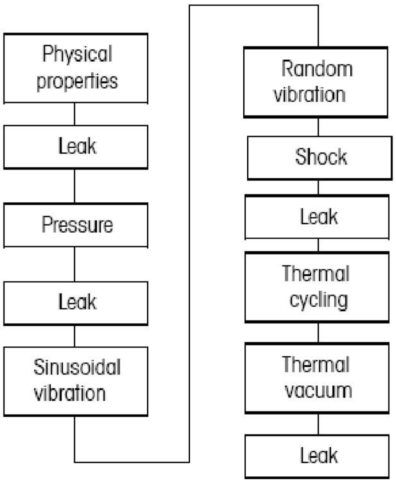


Fig. 3 Flight qualification test procedure for a propulsion system.

Functional Tests

The tests can be generally categorized into functional tests and environmental tests. A list of functional tests which have been done to space qualify the system include:

- Mass and dimension measurements
- Leakage tests
- Performance tests for valves, regulators, and sensors
- Life cycle tests
- Proof pressure and burst pressure tests for all the pressurized elements in the system
- Power measurement (for solenoid valve)
- Pull-in and hold-on voltage measurement (for solenoid valve)
- Insulation resistance measurement (for solenoid valve)
- Mass flow measurement
- Thrust and specific impulse measurement
- Tank effective volume measurement

These tests have been accomplished employing several instruments, measurements tools, and devices including high pressure N2 and He capsules, various valves, pressure regulators, pressure sensors, microbalance, liquid pool, vacuum chamber, mass spectrometer, power supply, multi-meter, megger, and high-precision loadcells.

Each element individually has undergone the required and applicable functional tests according to the standard. In next step, all the different elements of the system have been assembled altogether (Fig 4) to form the compact unit. Then it has been subject to system functional tests. Leakage tests in vacuum chamber using helium as propellant and a helium spectrometer, controlling the pressure at different point of the system, measuring the mass flow are among the conducted tests.

Among the elements, tank, thruster, and solenoid valve are the most important ones for functional tests. Qualification tests for the tank include mass, volume, and dimensional measurements, working pressure/ proof pressure/ burst pressure tests, leakage test, and fill and drain cycle tests. According to the standard, tank was proof pressure tested with water at 480 bar, equal to 1.5 times of its working pressure. The tank could resist the pressure for 5 minutes without any sign of deformation or damage.

The tank was also burst pressure tested with water and it could resist up to 730 bar which is far more than 660 bar, 2 times of its working pressure. Figure 5 shows the tank burst at 730 bar. The tank has also successfully passed over 100 cycles of fill and drain at 350 bar, 1.1 times of its working pressure.

The solenoid valve qualification tests include mass and dimensional measurements, leakage test, performance test, cycle test, power consumption measurement, pull-in and hold-on voltage measurement, proof pressure test, and mass flow measurement.

The solenoid valve was proof pressure tested for 5 minutes at 480 bar, 1.5 times of working pressure without any sign of deformation or damage. It was also life cycle tested and operated (opened/closed the high pressure flow at 330 bar) for 1000 cycles. Figure 6 shows the solenoid valve under operational tests.

Fig. 4 Photograph of cold gas propulsion system.

Fig. 5 Photograph of Tank burst at 730 bars.

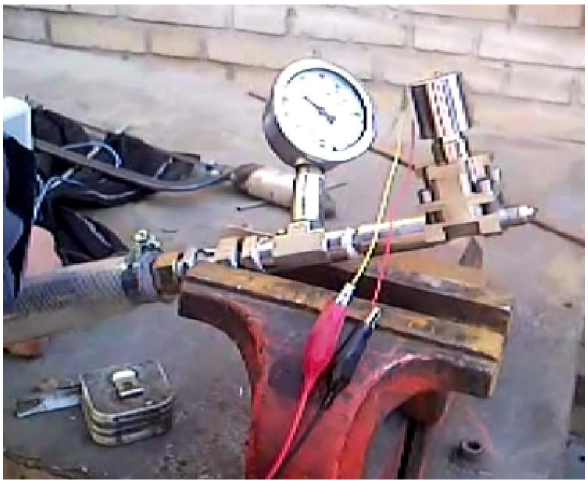


Fig. 6 Solenoid valve under operational tests.

Table 5 lists several functional tests performed on the solenoid valve.

Table 5 Solenoid valve qualification test criteria and results.

	Qualification criteria	**Result**
Power	15 W	13.2 W
Pull-in	< 12 V	9.5 V
Hold-on	~ 0 V	0.5 V
Insulation resistance	Giga Ω	Giga Ω
Mass flow	> 2 g/s	3 g/s
Leakage	100 g/w (w denotes week)	20 g/w
No. of cycles	100 cycle	1000 cycle

The qualification tests for the thruster consist of performance measurements tests and leakage test. The thruster has been leak tested using a helium mass spectrometer (Fig. 7). The permitted internal and external leakage for the thruster is 1 standard cc per hour and 10^{-6} standard cc per sec respectively and the measured amounts are 6×10^{-7} standard cc per sec.

Fig. 6 Thruster leak test with helium in mass spectrometer.

Thrust measurement tests at sea level are also done employing a series of loadcells assembled in together in an assembly capable of measuring thrust while the thruster is assembled on the satellite. Table 6 indicates the results of thrust measurement at sea level condition. Figure 7 also shows the satellite mounted on the thrust measurement mechanism during a test at sea level condition.

Table 6 Thrust measurement results.

	Nozzle inlet pressure (bar)	
	15	16
Thrust measured (at SL)	0.50	0.55

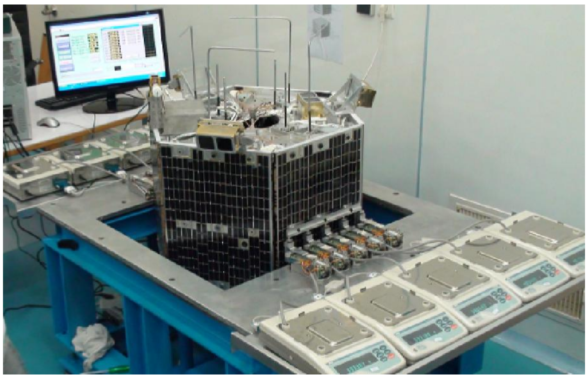


Fig. 7 Satellite mounted on the thrust measurement mechanism.

Moreover, pressure regulator performance has been checked prior to final assembly and the results are shown in Fig. 8. The tests have covered the range of operating pressure and its stable and reliable performance has been proved.

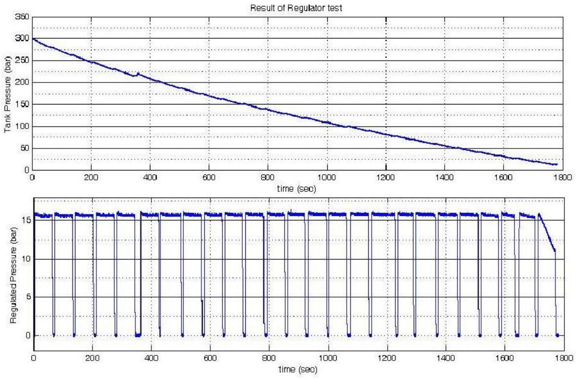


Fig. 8 Pressure regulator final adjustment results.

The whole system mounted on the satellite has also passed several stages of qualification tests according to ECSS.

Environmental Tests

In order to make sure of the appropriate and reliable performance of the propulsion system according the designer goals, the elements of the system as well as the whole assembled system have to be environmentally tested to qualify as a flight model. The environmental tests include structural tests (shock and vibration tests), thermal vacuum and thermal cycling tests, etc.

Thermal cycling tests are carried out on elements like solenoid valve, tank filled with propellant at 330 bar, pressure regulator, and pressure transducers individually for 8 cycles at -40 up to +80ºC for space qualification. The whole system assembled shall also pass thermal cycling acceptance tests that are 8 cycles at -20 up to +50 ºC.

Several elements of the system including thruster, pressure regulator, valves and sensors has been subject to thermal vacuum test according to the standard at 10^{-6} mbar inside the vacuum chamber.

Figure 9 shows the thermal cycle test procedure according to ECSS-E-10-03A.

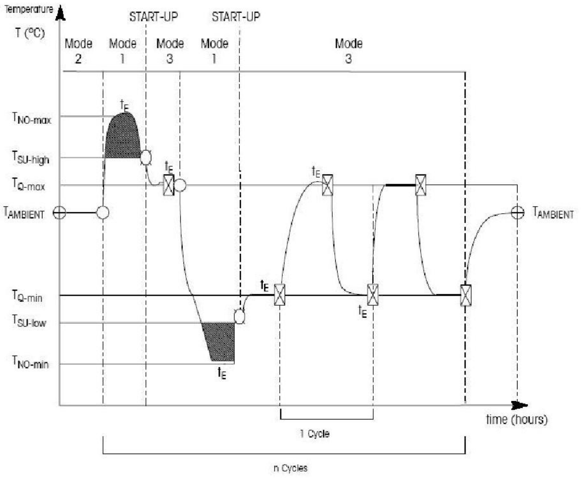


Fig. 9 Thermal cycle test procedure according to ECSS.13)

With respect to the possible hazard for the pressurized systems under available vibrational conditions during launch and seperation of the satellite, they are required to pass numerous shock and vibrational tests prior to qualification as a flight model. Figure 10 shows one of the vibrational tests on a sample pressurized tank.

Tank filled with water at 330 bar has passed the tests listed below:

Constant gravity test at 16 g and 25 Hz for 3 sec.

Random vibrational test at average 13 g for 2 min.

Sinusoidal vibrational test according to Table 7.

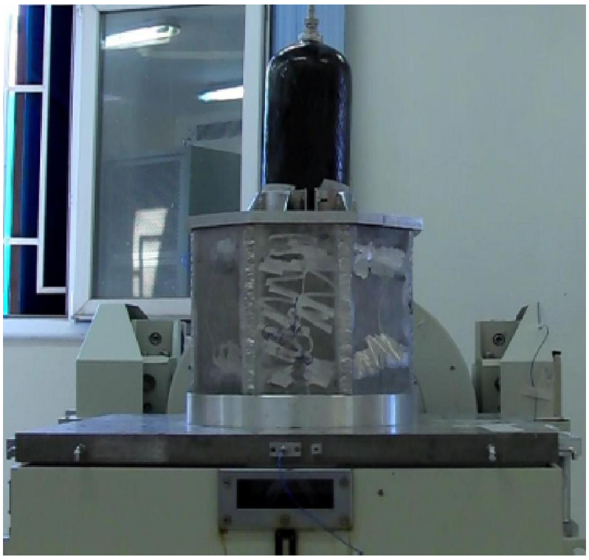


Fig. 10 A sample propellant tank filled with water at 330 bar during vibrational tests.

Table 7 Sinusoidal vibration test.

Frequency (Hz)	25-35	35-45	45-75	85-95	85-170	170-180
g	0.75	10	0.75	1	0.75	1

Conclusion

After design and development of a cold gas propulsion system, to have it flight qualified for space application, it has passed numerous functional and environmental tests according to the ECSS-E-10-03A.

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