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# Cold Gas Propulsion System – An Ideal Choice for Remote Sensing Small Satellites

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## 1. Introduction

Cold gas propulsion systems play an ideal role while considering small satellites for a wide range of earth orbit and even interplanetary missions. These systems have been used quite frequently in small satellites since 1960's. It has proven to be the most suitable and successful low thrust space propulsion for LEO maneuvers, due to its low complexity, efficient use of propellant which presents no contamination and thermal emission besides its low cost and power consumed. The major benefits obtained from this system are low budget, mass, and volume. The system mainly consists of a propellant tank, solenoid valves, thrusters, tubing and fittings (fig. 1). The propellant tank stores the fuel required for attitude control of satellite during its operation in an orbit. The fuel used in cold gas systems is compressed gas. Thrusters provide sufficient amount of force to provide stabilization in pitch, yaw and roll movement of satellite. From design point of view, three important components of cold gas propulsion systems play an important role i.e. mission design, propellant tank and cold gas thrusters. These components are discussed in detail in section 3. Selection of suitable propellant for cold gas systems is as important as above three components. This part is discussed in section 2 of this chapter. Section 4 describes the case study of cold gas propulsion system which is practically implemented in Pakistan's first prototype remote sensing satellite PRSS.

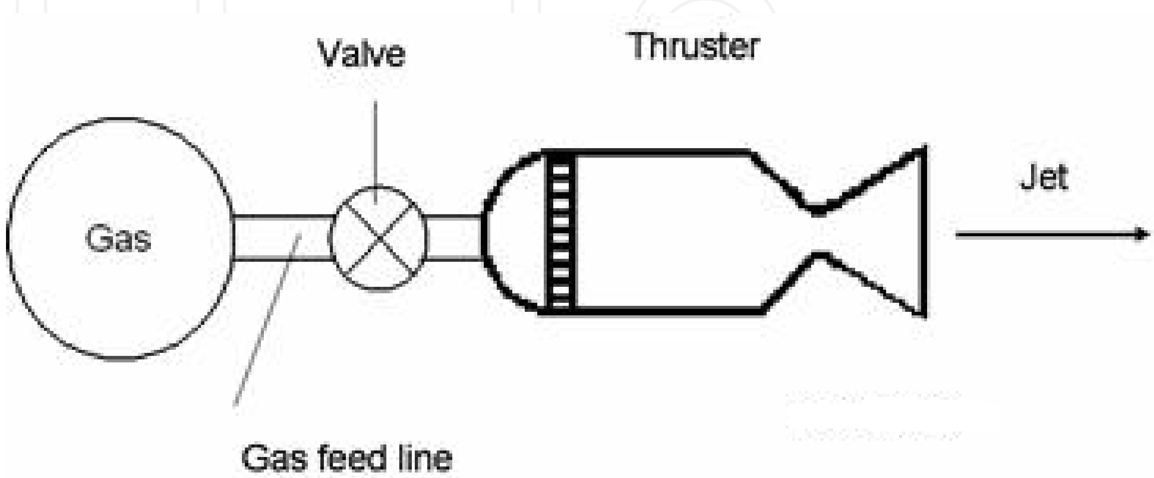


Fig. 1. Schematic of cold gas propulsion system

## 2. Cold gas propellants

Table 1 shows typical performance values for selected cold gas propellants. Nitrogen is most commonly used as a cold gas propellant, and it is preferred for its storage density, performance, and lack of contamination concerns. As shown in table below, hydrogen and helium have greater specific impulse as compared to other propellants, but have a low molecular weight. This quality causes an increased tank volume and weight, and ultimately causing an increase in system weight. Carbon dioxide can be a good choice, but due to its toxic nature, it is not considered for cold gas systems.

Another good alternative propellant could be ammonia, which stores in its liquid form to reduce tank volume. Its specific impulse is higher than nitrogen or other propellants and reduces concerns of leakage, although it also necessitates a lower mass flow rate. Despite the benefits, ammonia is not suitable for this system as one alternative to decrease the system size and weight includes pressurizing the satellite and allowing the entire structure to act as a propellant tank, as previously mentioned. In this system, the ammonia could cause damage to electrical components.

| Propellant | Molecular Weight (Kg/Kmole) | Density (g/cm$^3$) | Specific Thrust (s) | |
|---|---|---|---|---|
| | | | Theoretical | Measured |
| Hydrogen | 2.0 | 0.02 | 296 | 272 |
| Helium | 4.0 | 0.04 | 179 | 165 |
| Nitrogen | 28.0 | 0.28 | 80 | 73 |
| Ammonia | 17.0 | Liquid | 105 | 96 |
| Carbon dioxide | 44.0 | Liquid | 67 | 61 |

Table 1. Cold Gas Propellant Performances

## 3. Cold gas propulsion system design

### 3.1 Mission design

In order to design a cold gas propulsion system for a specific space mission, it is important first to find out the $\Delta V$ requirements for the maneuvers listed in table 2. Table 2 gives information about all the operations performed for spacecraft attitude and orbit control. However, cold gas systems are used only for attitude control and orbit maintenance and maneuvering (table 3).

Tsiolkowski equation and its corollaries are used to convert these velocity change requirements into propellant requirements.

$$\Delta V = g_c I_{sp} \ln\left(\frac{W_i}{W_f}\right) \tag{1}$$

$$W_f = W_i \left[1 - \exp\left(-\frac{\Delta V}{g_c I_{sp}}\right)\right] \tag{2}$$

| *Task* | *Description* |
|---|---|
| Mission Design | (Translational velocity change) |
| Orbit changes | Convert one orbit to another |
| Plane changes | |
| Orbit trim | Remove launch vehicle errors |
| Stationkeeping | Maintain contellation position |
| Repositioning | Change constellation position |
| Attitude Control | (Rotational velocity change) |
| Thrust vector control | Remove vector errors |
| Attitude control | Maintain an attitude |
| Attitude changes | Change attitudes |
| Reaction wheel unloading | Remove stored momentum |
| Maneuvering | Repositioning the spacecraft axes |

Table 2. Spacecraft Propulsion Functions

| *Propulsion Technology* | *Orbit Insertion* | | *Orbit Maintenance and Maneuvering* | *Attitude Control* | *Typical Steady State $I_{sp}$ (S)* |
|---|---|---|---|---|---|
| | *Perigeee* | *Apogee* | | | |
| *Cold Gas* | | | *Yes* | *Yes* | *30-70* |
| *Solid* | *Yes* | *Yes* | | | *280-300* |
| *Liquid* | | | | | |
| *Monopropellant* | | | *Yes* | *Yes* | *220-240* |
| *Bipropellant* | *Yes* | *Yes* | *Yes* | *Yes* | *305-310* |
| *Dual Mode* | *Yes* | *Yes* | *Yes* | *Yes* | *313-322* |
| *Hybrid* | *Yes* | *Yes* | *Yes* | | *250-340* |
| *Electric* | | *Yes* | *Yes* | | *300-3,000* |

Table 3. Principal Options for Sapcecraft Propulsion Systems

$$W_p = W_f \left[ \exp\left( \frac{\Delta V}{g_c I_{sp}} \right) - 1 \right] \quad (3)$$

In case of cold gas propulsion systems, the pressure, mass, volume and temperature of the propellant are interconnected by general gas equation.

$$PV = mRT \quad (4)$$

### 3.2 Tank design

Satellite propellant tanks used in cold gas propulsion systems are either spherical or cylindrical in shape. Tank weights are a byproduct of the structural design of the tanks. The load in the walls of the spherical pressure vessels is pressure times the area as shown in figure 2. The force $PA$ tending to separate the tanks is given as,

$$PA = P\pi r^2 \tag{5}$$

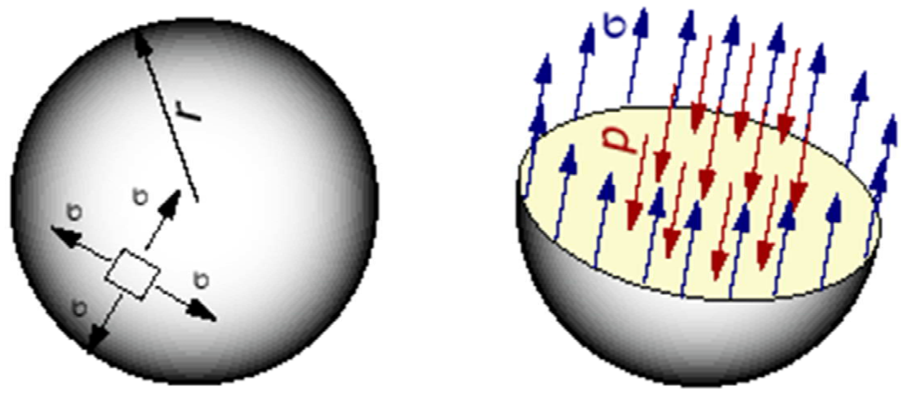


Fig. 2. Spherical Tank Stress

Stress $\sigma$ is calculated as,

$$stress = \sigma = \frac{load}{area} = \frac{P\pi r^2}{2\pi rt} = \frac{Pr}{2t} \tag{6}$$

The thickness of the tank is accurately calculated by including joint efficiency in eq. (7) and is given as follows,

$$t = \frac{P \times r}{2\sigma e - 0.2P} \tag{7}$$

In case of cylindrical pressure vessel, the hoop stress is twice that in spherical pressure vessels. The longitudinal stresses in cylindrical pressure vessels remain the same as in spherical pressure vessels. To determine the hoop stress $\sigma_h$, a cut is made along the longitudinal axis and construct a small slice as illustrated in figure 3.

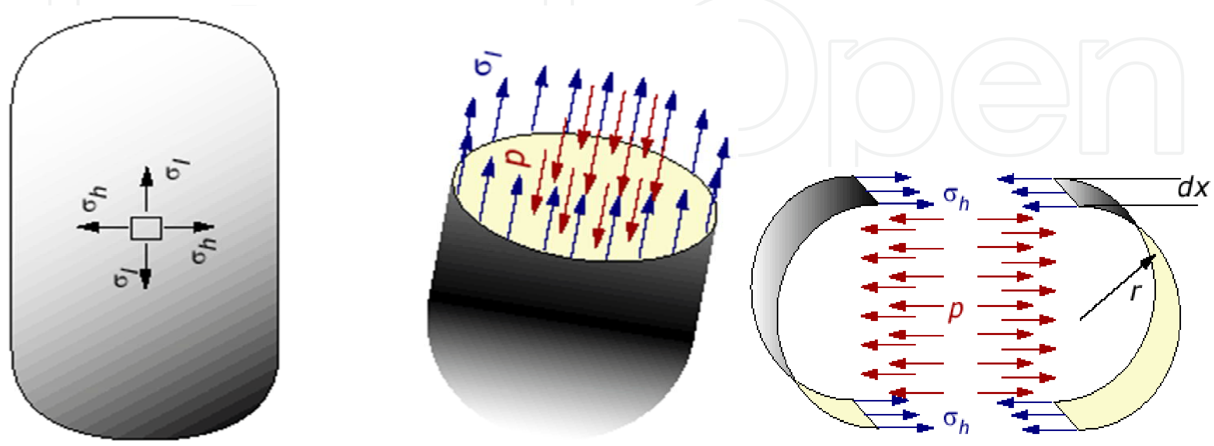


Fig. 3. Cylindrical Pressure Vessel Stresses

The equation may be written as,

$$2.\sigma_h.t.d_x = p.2.r.d_x$$

$$\sigma_h = \frac{pr}{t} \tag{8}$$

### 3.3 Thrusters design

Thrusters are the convergent-divergent nozzles (fig. 4) that provide desired amount of thrust to perform maneuvers in space. The nozzle is shaped such that high-pressure low-velocity gas enters the nozzle and is compressed as it approaches smallest diameter section, where the gas velocity increases to exactly the speed of sound.

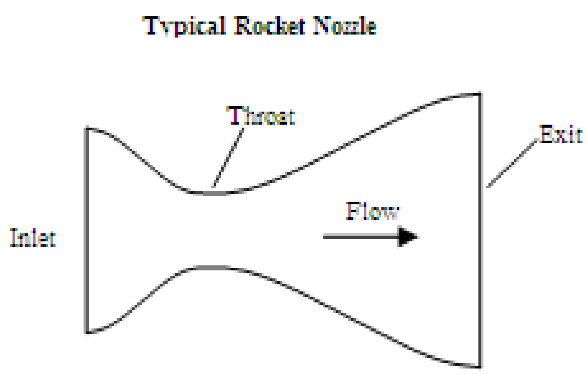


Fig. 4. Convergent-Divergent Nozzle

Thrust is generated by momemtum exchange between the exhaust and the spacecraft and by the pressure imbalance at the nozzle exit. According to Newton's secomd law the thrust is given as

$$F = \dot{m} V_e \tag{9}$$

or we may write as,

$$F = \frac{\dot{w}_p}{g} V_e \tag{10}$$

$$F = P_e A_e \tag{11}$$

In case of satellites, the thrusters are designed for infinite expansion i.e. for vacuum conditions where ambient pressure is taken as zero. The thrust equation for infinite expansion is given as,

$$F = A_t P_c \gamma \left[ \left( \frac{2}{\gamma - 1} \right) \left( \frac{2}{\gamma + 1} \right) \left( 1 - \frac{P_e}{P_c} \right) \right] + P_e A_e \tag{12}$$

The area ratio and pressure ratio is given as,

$$\frac{A_e}{A_t} = \frac{1}{M_e}\left\{\left(\frac{2}{\gamma+1}\right)\left(1+\frac{\gamma-1}{2}M_e{}^2\right)\right\}^{\frac{\gamma+1}{2\gamma-1}} \quad (13)$$

$$\frac{P_e}{P_c} = \left(1+\frac{\gamma-1}{2}M_e{}^2\right)^{\frac{\gamma}{\gamma-1}} \quad (14)$$

The specific impulse ($I_{sp}$) for cold gases ranges from 30-75 seconds and may be calculated as,

$$I_{sp} = \frac{C^*}{g}\gamma\left\{\left(\frac{2}{\gamma-1}\right)\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}\left(1-\frac{P_e}{P_c}\right)^{\frac{\gamma-1}{\gamma}}\right\}^{\frac{1}{2}} \quad (15)$$

Pressure at throat can be calculated by the following formula

$$\frac{P_t}{P_c} = \left(1+\frac{\gamma-1}{2}\right)^{-\frac{\gamma}{\gamma-1}} \quad (16)$$

The characteristics velocity ( $C^*$ ) can be calculated by following formula

$$C^* = \frac{a_0}{\gamma\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}} \quad (17)$$

The exite velocity is given as

$$V_e = \sqrt{\frac{2\gamma RT_c}{\gamma-1}\left(1-\frac{P_e}{P_c}\right)^{\frac{\gamma-1}{2}}} \quad (18)$$

The above equations are helpful in designing of a cold thruster.

## 4. Case study

The author has personally leaded and guided the satellite Research and Development Centre research team of Pakistan Space and Upper Atmosphere Research Commission in designing and development of cold gas propulsion system of prototype of Pakistan's first remote sensing satellite (PRSS). Satellite research and development center Karachi has produced an inexpensive and modular system for small satellites applications. The cold gas propulsion resulting from the effort is unique in several ways. It utilizes a simple tank storage system in which the entire system operates at an optimum design in line pressure. In order to minimize the power consumption, the thrusters are operated by solenoid valves that require an electric pulse to open and close. Between the pulses the thruster is magnetically latched in either the open or closed position as required. This dramatically reduces the power required by the thruster valves while maintaining the option for small impulse bit. Flow rate sensors are used in the system in order to avoid any failure i.e. complete pressure lost during opened valve position. The system uses eight Thrusters of 1N each functioning with inlet pressure of 8 bars. By integrating these thrusters to the spacecraft body, pitch, yaw and roll control as well as $\Delta V$ can be accomplished. The choice of suitable propellant also plays an important role in designing cold gas systems. Compressed nitrogen gas offers a very good combination of storage density and specific impulse, as compared with other available cold gas propellants. The use of Hydrogen or helium requires much larger mass, because of their low gas density. Since the propellant is simple pressurized nitrogen, a variety of suitable tank materials can be selected. The tank designed and developed for this mission is Aluminum 6061 spherical tank which stores 2 kg of gaseous nitrogen. The whole system is well tested before mounting on the honeycomb PRSS structure.

### 4.1 Introduction to PRSS

PRSS is a prototype satellite which is not developed for flight in future. The purpose of this work is to design, develop and test a small satellite on ground so that the experience can be utilized in near future on engineering qualified and flight models. The CAD model of PRSS is shown in fig. 5. This model is developed in PRO/E wildfire 2.0 software.

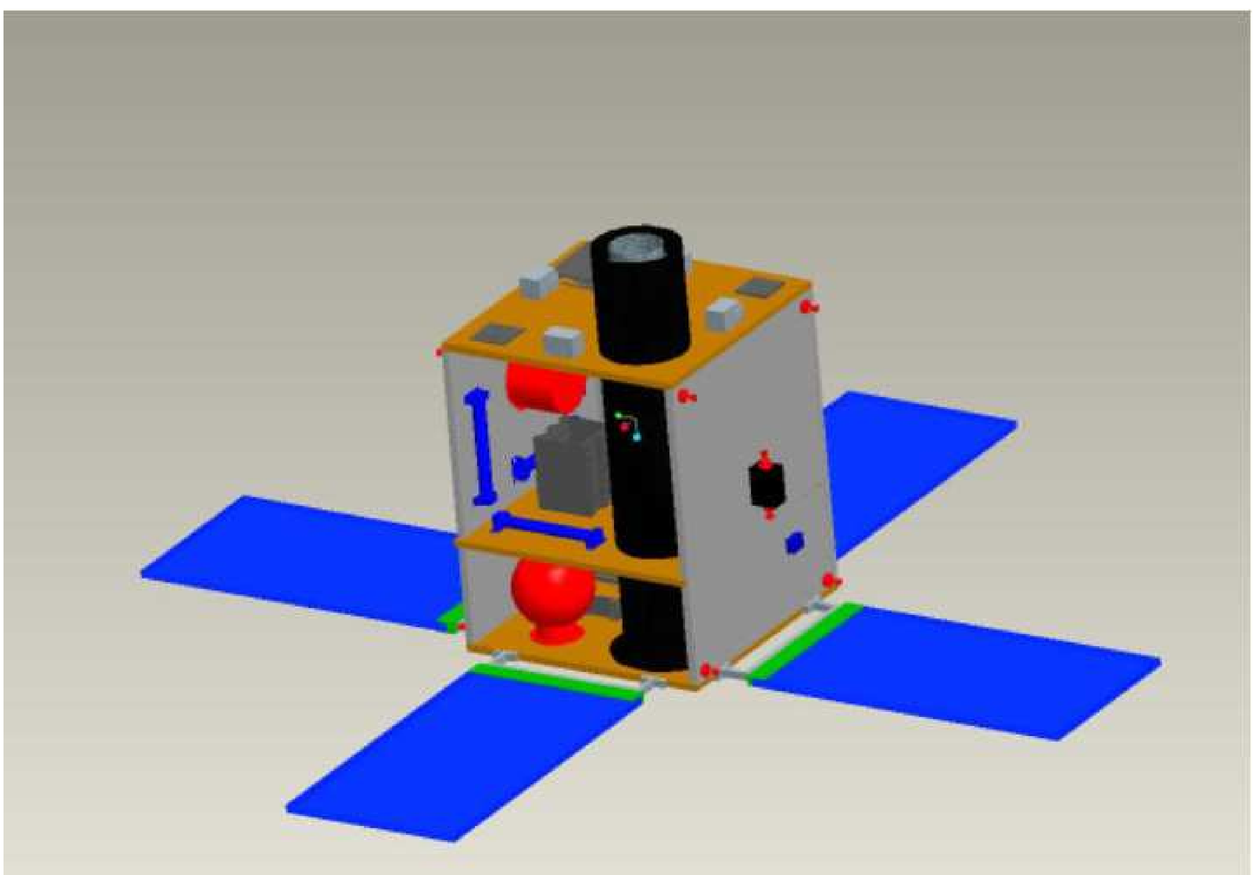

Fig. 5. CAD model of PRSS

The satellite mainly consists of

- 1 Telescope

- CCD Camera
- Optics Electronics
- Cold Gas Propulsion System which includes 8
- thrusters, 1 propellant tank and regulators and
- fittings
- 3 Reaction wheels
- 3 Gyros
- 3 Torque Rods
- 3 Digital Sun Sensor DSS
- RF systems & Antennas
- On Board Computer Electronics
- Power System
- 4 Solar Panels on each side of the cube
- Honeycomb Aluminum Structure

All the above mentioned systems have been integrated successfully on Al 6061 honeycomb structure which is cubical in shape with dimensions 1 m x 1m x 1.2 m. All subsystems have been designed for 3 years satellite life. PRSS has an overall weight of 100 kg and therefore falls into the category of small satellites.

### 4.2 System design

Cold gas propulsion systems use thrusters which utilize smallest rocket technology available today. These systems are well known for their low complexity when characterized by low specific impulse. They are the cheapest, simplest and reliable propulsion systems available for orbit maintenance and maneuvering and attitude control. Cold gas Propulsion systems are designed for use as satellite maneuvering control system where a limited lifetime is required. Their specific impulse ranges from 30 seconds to 70 seconds, depending on the type propellant used. They usually consist of a pressurized gas tank, control valves, regulators, filters and a nozzle. The nozzle can be of bell type, conical, or a tube nozzle. SRDC-K will be using a standard conical nozzle, with a $16^0$ half-angle and nozzle area ratio of 50:1. A schematic of a cold gas thruster system used by PRSS is shown below in Fig 6. System weight is mainly determined by the pressure in the thrust chamber. The increased chamber pressure results in increase propellant tank and piping masses, therefore, an optimum pressure must be used so that the system weight can be minimized. Nitrogen is stored at 100 bar pressure in propellant tank. Fill and drain valves facilitates filling and venting nitrogen from the system. Eight Thrusters are connected to solenoid valves and propellant tank with PTFE tubing which can carry a pressure of more than 20 bars. The inline and the thrusters operating pressure is 8 bars. The system also contains pressure transducer before and after pressure regulator to sense the tank pressure and inline pressure respectively.

### 4.3 Propellant tank design, development and testing

The propellant tank as shown in fig. 7 is a standard spherical pressure vessel. It is being designed and built by SRDC-K, with the detailed analysis also being performed at SRDC-K. In order to reduce costs the tank is being welded by two hemispherical Aluminum parts.

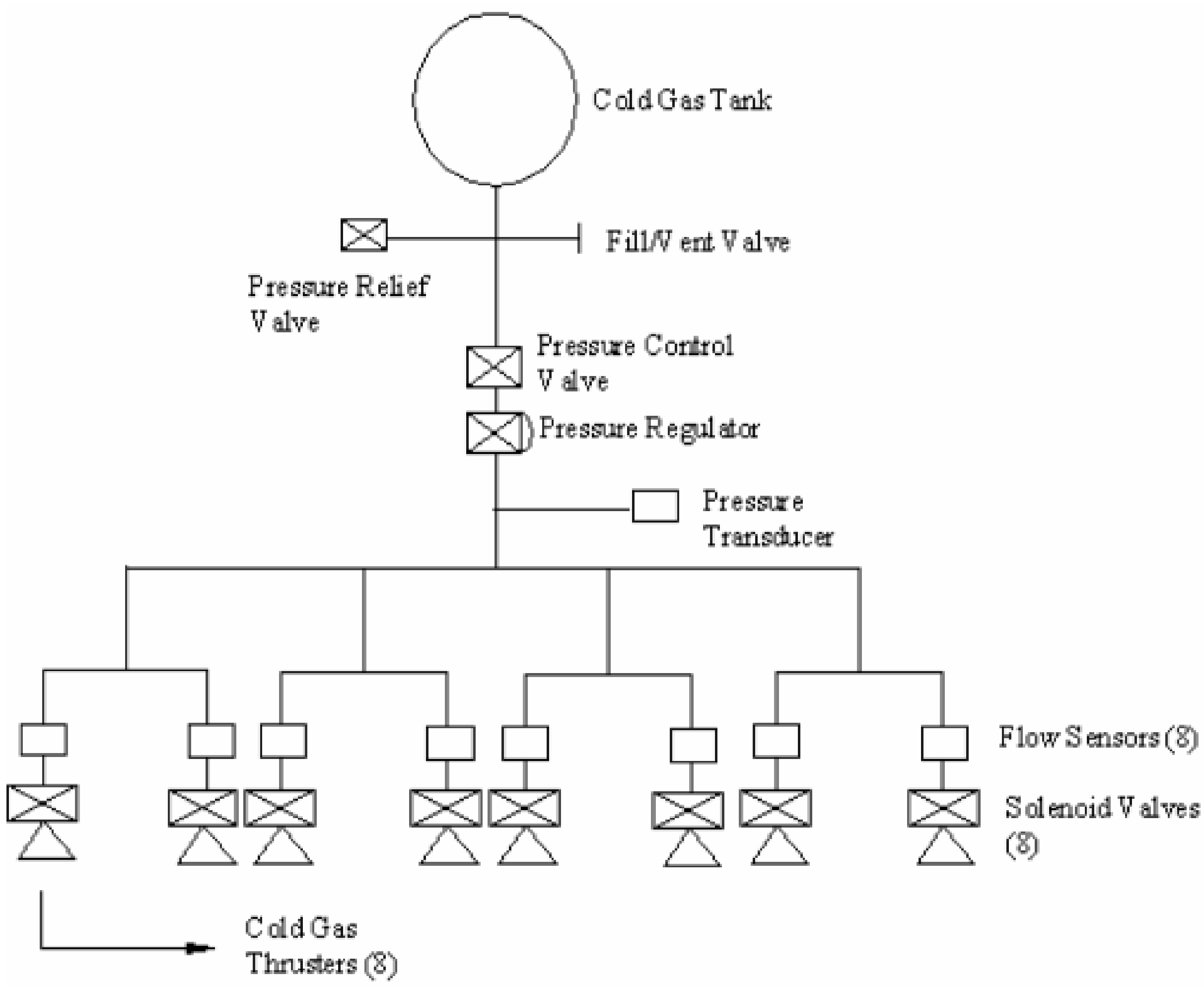


Fig. 6. Cold Gas Propulsion System for PRSS

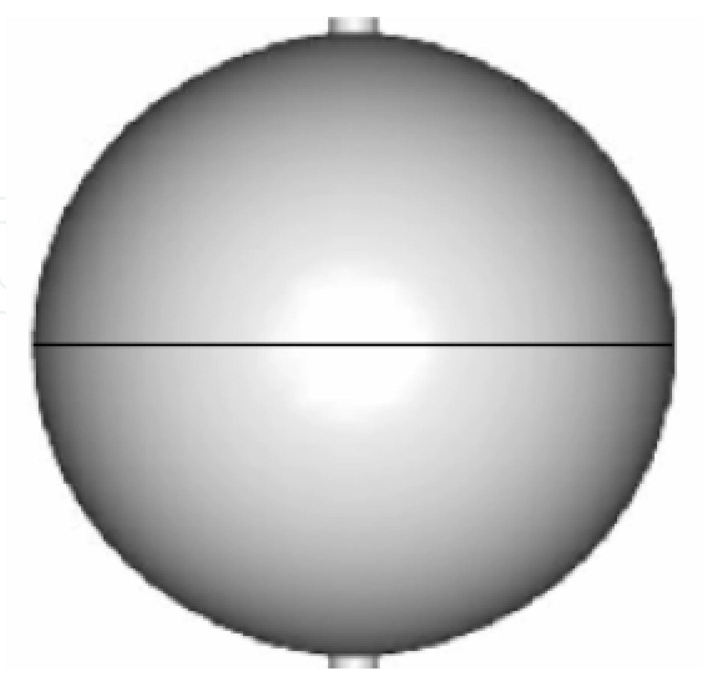

Fig. 7. Propellant Tank

The hemisphere has a wall thickness of 4.2 mm and a factor of safety of 1.5 is used. This gives a minimum theoretical burst pressure of 200 bars. ASME section VIII pressure vessel code is used for the designing the spherical propellant tank. Table 4 presents the calculated values of design tank design parameters. Titanium could have been another choice for the designing of propellant tank. The space grade of titanium is TiAl4V. The weight of the propellant tank would have been less with titanium as compared with aluminum but the cost in manufacturing titanium tank is much higher as compared with aluminum.

| *Parameters* | *Designed Parameters* |
|---|---|
| Propellant | $N_2$ Gas |
| Tank volume | 0.016 $m^3$ |
| Operating pressure | 100 bars |
| Proof pressure | 150 bars |
| Burst pressure | 200 bars |
| Thickness of tank shell | 0.0042 m |

Table 4.

The tank design analyses included stress analysis for the tank shell. This approach used assumptions, computer tools, test data and experimental data which are commonly utilized on a majority of the pressure vessels for successful design, fabrication, testing and qualification. The following factors have been taken in to consideration for performing stress analysis on the tank shell.

- Temperature environment
- Material properties
- Volumetric properties
- Mass properties of the tank shell material
- Mass properties of fluid
- Fluids used by the tank
- External loads
- Size of girth weld
- Resonant frequency
- Tank boundary conditions
- Residual stress in girth weld
- Load reaction points and
- Design safety factors

The validation of tank shell design has been done by stress analysis and also the resonant frequencies have been obtained. The propellant tank is subjected to the following sequence of acceptance tests,

- Preliminary visual examination
- Ambient proof pressure test
- External leakage test
- Penetrant inspection

- Radiographic inspection
- Mass measurement
- Final examination
- Cleanliness verification

The ambient hydrostatic proof pressure test is conducted at 130 +20/-0 bars for a pressure hold period of 300 seconds. Post acceptance test, radiographic inspection of the girth weld and penetrant inspection of the entire external surface are conducted to verify that the tank is not damages during acceptance testing. All units successfully passed acceptance testing. After the conclusion of acceptance testing one propellant tank was subjected to the following sequence of qualification tests prior to delivery:

- Proof pressure cycling test
- MEOP pressure cycling test
- External Leakage test
- Radiographic inspection
- Penetrant inspection
- Burst pressure test
- Visual inspection
- Data review

The propellant tank assembly has successfully completed all acceptance and qualification level testing. The tank meets or exceeds all requirements that provide the low cost solution to the spacecraft.

After successful testing, propellant tank is then mounted on PRSS structure as shown in fig. 8.

Fig. 8. Installation of Propellant Tank on PRSS Structure

### 4.4 Thrusters design, development and testing

This system uses 8 thrusters (fig 9.a) of 1N mounted on PRSS as shown in fig. 10. These thrusters have been designed and developed for infinite expansion i.e. for vacuum


(a) Cold Gas Thruster (b) Test Bench

Fig. 9.

Fig. 10. PRSS Structure

conditions and hence, the atmospheric pressure is zero. Area ratio of 50 has been used while the combustion chamber pressure is 8 bars. The characteristics velocity has been calculated and equals to 433.71 m/sec and as result of that the $I_{sp}$ came out to be 73 seconds. Assuming a nozzle efficiency of 98% the nozzle cone half angle has been calculated as $16^0$. Thrusters have been developed using stainless steel material. The use of the stainless steel eliminates the potential for reaction between propellant and thruster and also outgassing concerns. The test bench developed at S/P/T laboratory as shown in fig.9.b is capable of testing cold gas thrusters from 1 to 5N. The system consists of an aluminum plate which is mounted on a ball bearing. The thruster is connected to a plate and fitted with solenoid valve through SS 316 tubing.

The system uses FUTEK load cell which is basically a force sensor to measure the force from the thruster. Pressure data logger and transducer are also connected to the system to measure the pressure during testing.

### 4.5 Propulsion system integration on PRSS structure

All components of propulsion system have been successfully integrated with PRSS structure as shown in fig. 10. The structure has been assembled using Al6061 honeycomb structure with the help of end attachments and inserts. Inserts are designed and developed according to ESA standards and end attachments are developed using AU4G. Thrusters have been mounted on each panel with the help of inserts and titanium bolts. Titanium bolts are used for the purpose of high strength and light weight. Four thrusters are mounted on right face of the structure, four on the left side while set of two thrusters are mounted in the middle of each panel for pitch stabilization. Propellant tank is mounted on the inner side of the top panel with the help of inserts and titanium bolts.

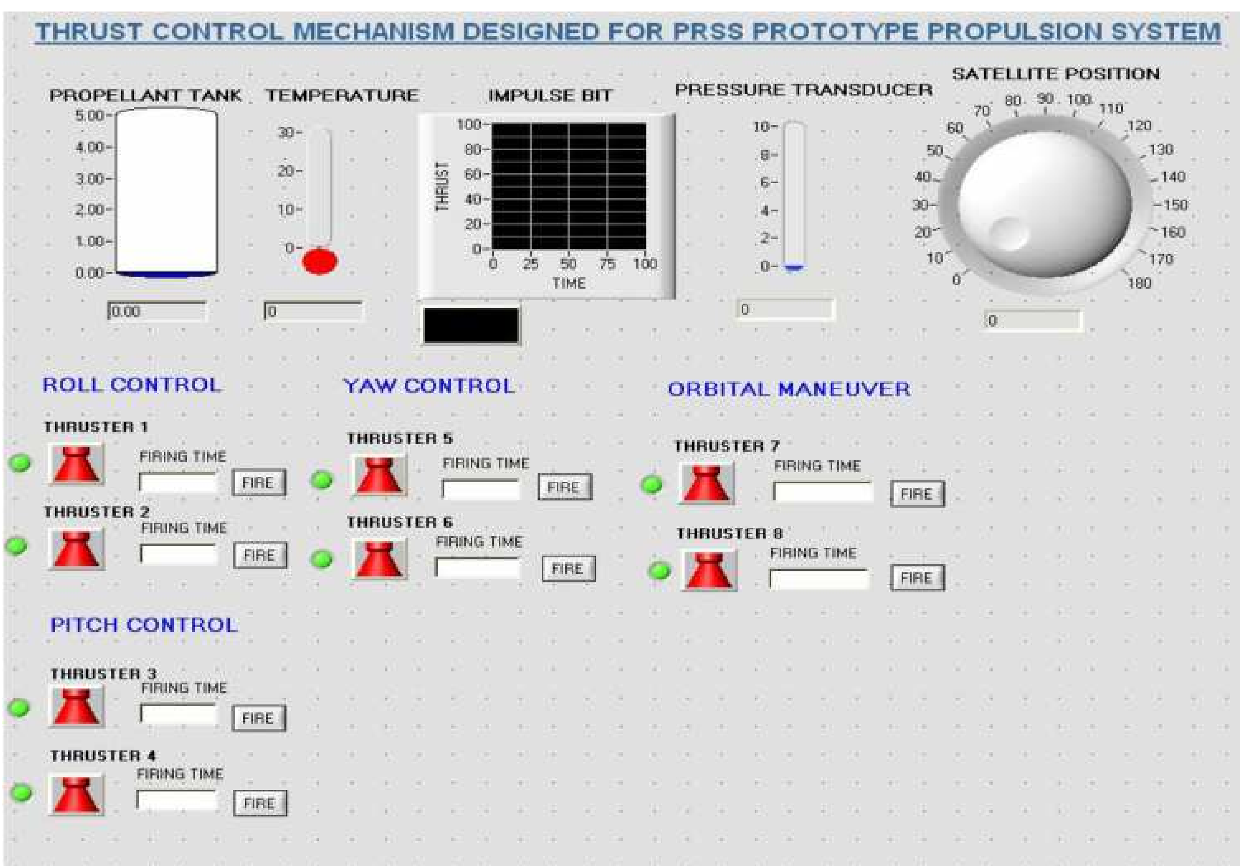


Fig. 11. Thrust Control Panel for PRSS Propulsion System

### 4.6 Thrust control mechanism

The control panel for the thrust system has been designed on Lab view software as shown in fig. 11 to test the system on ground level. This controller monitors the position of the satellite as well as pressure of the propellant tank and solenoid valves from pressure transducers present in the system. It also observes the impulse bit of the system and the temperature of the propellant tank. Firing time of thrusters is well adjustable on the panel. Ground test of the propulsion system can be monitored by this control system. The test results are listed in table 5.

| | *Opening Coil Response @ 8bars, 24 VDC (msec)* | *Minimum Impulse Bit, msec* | *Opening Coil Response @ 10 bars, 24 VDC, msec* | *Minumum Impulse Bit, msec* |
|---|---|---|---|---|
| Thruster # 1 | 2.9 | 6.20 | 3.20 | 6.15 |
| | 3.3 | | 2.95 | |
| Thruster # 2 | 2.95 | 6.60 | 3.30 | 6.15 |
| | 3.65 | | 2.85 | |
| Thruster # 3 | 2.85 | 6.10 | 3.50 | 6.40 |
| | 3.25 | | 2.90 | |
| Thruster # 4 | 2.80 | 5.80 | 2.90 | 6.65 |
| | 3.00 | | 2.75 | |
| Thruster # 5 | 2.77 | 6.02 | 3.25 | 6.25 |
| | 3.25 | | 3.00 | |
| Thruster # 6 | 2.86 | 6.72 | 3.10 | 6.30 |
| | 3.86 | | 3.20 | |
| Thruster # 7 | 2.90 | 6.56 | 3.10 | 6.25 |
| | 3.66 | | 3.15 | |
| Thruster # 8 | 2.80 | 6.53 | 3.25 | 6.40 |
| | 3.73 | | 3.15 | |

Table 5. Minimum Impulse Bit

## 5. Conclusion

In conclusion, this work results in reduction of the size, mass, power, and cost of system. Use of Titanium bolts, Aluminum Inserts, Aluminum Tank, and PTFE Tubing gives great reduction in mass by 35% and ultimately benefits in lowering the cost. Electric Solenoid valves reduce the power consumption by 40%. The main purpose of this work is to document the potentials of low power Cold Gas Propulsion System adequately to allow the engineers and designers of small satellites to consider it as a practical propulsion system option.

## 6. Abbreviations

| | |
|---|---|
| $W_i$ | Initial vehicle weight, Kg |
| $W_f$ | Final vehicle weight, Kg |
| $W_p$ | Propellant weight required to produce the given $\Delta V$ |
| $\Delta V$ | Velocity increase of vehicle, m/s |
| $g_c$ | Gravitational constant, 9.8 m/s$^2$ |
| $P$ | Pressure of the gas, bars |
| $V$ | Volume of the gas, m$^3$ |
| $m$ | Mass of the gas, Kg |
| $R$ | General gas constant, KJ/KgK |
| $T$ | Temperature of the gas, K |
| $A$ | Area, m$^2$ |
| $r$ | Internal radius of the tank, m |
| $t$ | Thickness of the tank wall, m |
| $\sigma$ | Allowable Stresses, MPa |
| $e$ | Joint Efficiency |
| $\sigma_h$ | Hoop Stress |
| $d_x$ | Length of an element in Cylindrical pressure vessel, m |
| $\dot{m}$ | Mass flow rate of the propellant, Kg/s |
| $V_e$ | Exit velocity, m/s |
| $\dot{w}$ | Weight flow rate of propellants, N/s |
| $P_e$ | Exit pressure of the propellant, bars |
| $A_e$ | Exit Area, mm$^2$ |
| $M_e$ | Exit Mach number |
| $P_e$ | Exit pressure, Bars |
| $\gamma$ | Specific heat ratio |
| $I_{sp}$ | Specific Impulse, S |
| $C^*$ | Characteristics velocity, m/s |
| $P_c$ | Chamber pressure in the nozzle, Bars |
| $P_t$ | Pressure at throat, Bars |
| $a_0$ | Sonic velocity of the gas, m/s |
| $T_c$ | Chamber temperature, K |

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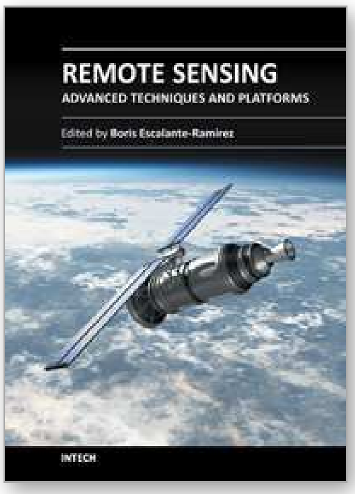


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This dual conception of remote sensing brought us to the idea of preparing two different books; in addition to the first book which displays recent advances in remote sensing applications, this book is devoted to new techniques for data processing, sensors and platforms. We do not intend this book to cover all aspects of remote sensing techniques and platforms, since it would be an impossible task for a single volume. Instead, we have collected a number of high-quality, original and representative contributions in those areas.