A Detailed Study and Analysis of Cold Gas Propulsion System

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Abstract - *As we know, propulsion systems are very important for moving a body. One of the many systems of power generation is the cold gas system which we will discuss in this paper. This system utilizes a generally inert pressurized gas to produce thrust. Unlike the conventional propulsion systems, it does not use combustion. It is a cost-effective, simple, and authentic delivery system available in a multitude of applications for guidance and attitude control. Due to its economic benefits, it is being studied extensively. This paper will provide an overview of the operating principle, various propellants, operating principle, equipments, performance characteristics such as thrust and specific impulse, the benefits of cold gas thrusters, and their applications.*

Key Words: Propulsion system, cold gas propulsion, thrust, cost effective, attitude control, performance characteristics

1. INTRODUCTION

Nanosatellites are obtaining great interest from industry and governments for a range of missions including global ship monitoring, global water monitoring, distributed radio telescope in space and Integrated Meteorological / Precise Positioning Missions. There has been a substantial increase in the nano satellite missions, starting from a count of one in 2003 and reaching over 1300 in 2020. These missions are carried out to obtain valuable experimental data [3]. Cold gas propulsion systems play an ideal role when considering small satellites because of their simplicity and feasibility. They have proven to be the most appropriate propulsion systems for low earth orbit (LEO) maneuvers. By far, this system is one of the most mature technologies for small spacecrafts. The desirable properties include design simplicity, cleanliness, safety, robustness, low-power operation, no net charge generation to the spacecraft, and a wide dynamic range. It has the ability to be operated in pulsed or continuous operation. As far as hardware complexity is concerned, it is much more simplified than pulsed plasma thruster, colloidal thruster, and field emission electric propulsion thruster. In this system, thrust is produced by the expulsion of an inert, non-toxic propellant, which can be stored either in liquid or gaseous state. It, therefore, consumes low budget, mass, and volume. The cold gas system primarily consists of a propellant tank, solenoid valves, thrusters, tubing and fittings. The tank houses the fuel required for attitude control of satellite for its operation. As mentioned before, the fuel is used either in liquid or gaseous state. Thrusters provide sufficient amount of force to maintain equilibrium in pitch, yaw and roll dynamism of the satellite [1,5,11]. In addition to all of this, the applications and benefits of this system will also be discussed in the paper. Fig-1 shows the schematic diagram of cold gas propulsion system.

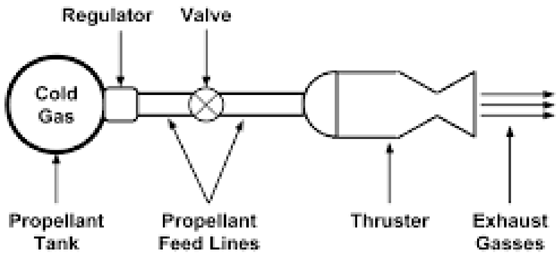

Fig -1: Schematic diagram of cold gas propulsion system from opendesignengine.net

2. SYSTEM COMPONENTS

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

- Tank
- Fill/Vent valve
- pressure transducer
  a) High pressure transducer
  b) Low pressure transducer
- Filter
- Isolation valve
- pressure regulator
  a) High pressure regulator
  b) Low pressure regulator
- Thruster
  a) Solenoid valve
  b) Nozzle

Fig -2.1 shown below provides a detailed diagram of cold gas propulsion system.

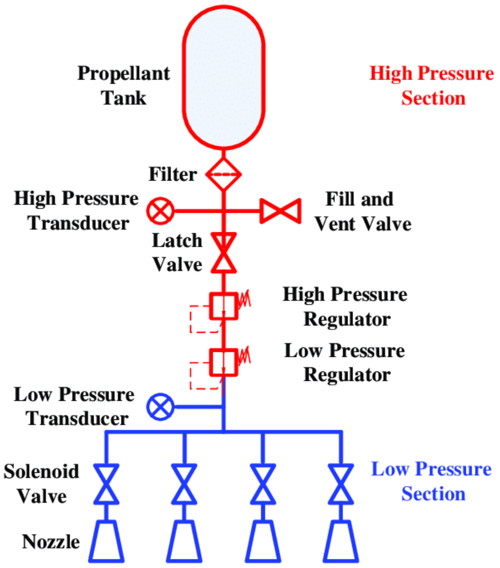

Fig -2.1: detailed diagram of cold gas thruster from researchgate.net

Tank: Propellant tank is used to store the propellant. The propellant is either in liquid or gaseous state (compressed). [4] Fig 2.2 and fig 2.3 show the image of the two types of propellant tanks.

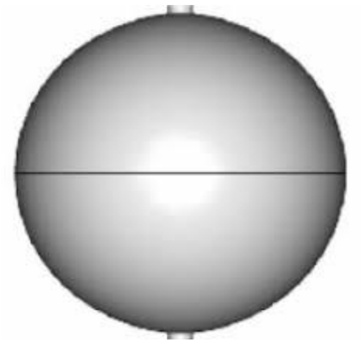

Fig -2.2: Spherical tank diagram from IntechOpen

Fig -2.3: the Adelis-SAMSON propellant tank (left) and illustration of a cross section view of the Adelis-SAMSON propellant tank (right) from mdpi.com.

Pressure transducer: Two pressure transducers are used in the system: High pressure transducer and low-pressure transducer. The high-pressure transducer is located immediately after the tank, which is used to show the tank pressure. The low-pressure transducer, on the other hand, is used after the regulators and before the thruster to measure the pressure of the flow entering the thruster. This is basically the inlet pressure to the thruster nozzle. Fig 2.4 presents the image of a pressure transducer.

Fig -2.4: pressure transducer from emerson.com

Filter: The filter is used in order to eliminate the contaminants present in the propellant. It is placed after the high-pressure transducer and before the regulator of the system. Fig 2.5 shows the image of a filter.

Fig -2.5: gas pressure Filter fromOmnidea-rtg.de

Isolation valve: It is used to isolate the tank from the thruster. It acts as a shut-off valve which opens whenever the system is going to generate thrust and shuts when the thrust generated is to be cut off.

Pressure regulator: Pressure regulator is used in order to regulate the pressure throughout the system.

Fig 2.6 shows the images of cold gas thruster components and their position.

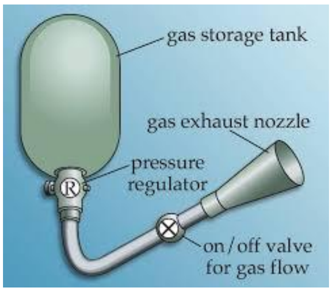

Fig -2.6: cold gas thruster diagram indicating pressure regulator, propellant tank, and isolation valve position from faa.gov

Fill/Vent Valve: This valve is used to fill the propellant tank. Moreover, it is also used to provide venting to prevent the blockage of fuel flow. Fig 2.7 shows the image of fill/vent valve [8].

Fig -2.7: Fill/Vent Valve from Researchgate.net

Thruster: Cold gas thruster consists of two parts: solenoid valve and nozzle. The solenoid valve opens and closes the propellant flow to the nozzle. With the help of this, the thrust production frequency can be adjusted. Moreover, the period can also be controlled. The working principle of a solenoid valve is as follows: When no voltage is applied to the valve, the line to the nozzle is cut off by the gas pressure and the force of spring. On the other hand, when the voltage is applied, a magnetic field is created, which forces the spring to open the line. After passing the solenoid valve, propellant enters the converging-diverging nozzle. Here, the propellant accelerates to supersonic velocity. The exhaust gas velocity depends on plethora of factors such as inlet pressure, exhaust pressure, nozzle profile such as area ratio, diverging angle, etc. Fig 2.8 shows an image of the thruster [7,8].

Fig -2.8: nozzle image from Omnidea-rtg.de

3. OPERATING PRINCIPLE

A Cold Gas Propulsion System depends on the process of controlled ejection of compressed liquid or gaseous propellants to generate thrust. A cold gas propulsion system requires only one propellant without an oxidizer due to the absence of a combustion process. As the result, the design intricateness of the system is minimal. The major components comprise of a propellant storage tank and a nozzle. Due to its simple design, the system has a lower mass and lower power requirements for regulation purposes. Nevertheless, these merits come at the cost of a consistently decreasing thrust profile over a period of time. The thrust produced is directly proportional to the pressure of the propellant inside the propellant storage tank. The tank pressure decreases over the course of the mission due to the use of the propellant stored in the tank. Consequently, the maximum thrust produced by the system decreases [3].

4. COLD GAS PROPELLANTS

Higher atom weight of the expelled gas is desirable as per to the third Newton law. Together with the contamination free property, the moderately low boiling and melting temperatures are preferable features for a propellant gas from system point of view; however, mass efficient storage of the gas is a major concern. Fig 10 illustrates the common propellants used in cold gas propulsion system [8].

Xenon is a capable cold gas propellant. It is a heavy and inert, but there are some challenges associated with it when using this gas. Since its viscosity increases with temperature within a certain range, it implies that the specific impulse, Isp, for a Xenon system becomes very low if the gas is heated [8].

Nitrogen is most commonly used as a cold gas propellant. It is highly preferred for its storage density, performance, and contamination free characteristics.

As shown in fig 10, hydrogen and helium have higher specific impulse as compared to other propellants, but have a low molecular weight. This property causes an increase in tank volume and weight, consequently causing an increase in system weight.

Propane has been used as cold gas propellant in microsatellites in past decades. Butane has been demonstrated as a potential propellant in the cold gas propulsion system on SNAP-1, a 6.5 kg nanosatellite [8].

Sulfur hexafluoride is one of the most interesting gases owing to its heavy molecular weight. It is heavier than Xenon and sublimates at barely -64°C at a pressure of 1 bar. is nonflammable and non-toxic. It is believed to be a strong candidate for cold gas micro propulsion systems under development [8].

Carbon dioxide can be a good choice; however, due to its toxic nature, it is not considered for cold gas systems.

Another good alternative can be ammonia, which is stored in its liquid form to reduce tank volume. Its specific impulse is higher than nitrogen or other propellants. Moreover, reduces concerns of leakage. It also necessitates a lower mass flow rate. Despite all these benefits, ammonia is not suitable for this system because to decrease the system size and weight, pressurization of the satellite must be carried out, allowing the entire structure to act as a propellant tank. In this system, the ammonia could cause damage to electrical components [1]. The properties of the common propellants have been shown in fig 4.1.

Propellant	Molecular Weight (Kg/Kmole)	Density (g/cm³)	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

Fig -4.1: cold gas propellant performances from IntechOpen.com

5. PERFORMANCE CHARACTERISTICS

In order to design a cold gas propulsion system, it is imperative to find out the ΔV that is the change in velocity requirements for the maneuvers. As mentioned before, cold gas systems are used only for attitude control, orbit maintenance, and maneuvering. Tsiolkovsky's equation and its corollaries are used to convert the change in velocity requirements into propellant requirements.

$$\Delta V = g_c I_{sp} \ln\left(\frac{w_i}{w_f}\right)$$

$$w_f = w_i\left[1 - \exp\left(-\frac{\Delta V}{g_c I_{sp}}\right)\right]$$

$$w_p = w_f\left[\exp\left(\frac{\Delta V}{g_c I_{sp}}\right) - 1\right]$$

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

$$PV = mRT$$

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

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

We can also write it as,

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

$$F = P_e A_e$$

For satellites, the thrusters are designed for infinite expansion, which means for vacuum conditions, where the ambient pressure is taken as zero. The thrust equation for infinite expansion is given as,

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

The area ratio is given as,

$$\frac{A_e}{A_t} = \frac{1}{M_e}\left[\left(\frac{2}{\gamma + 1}\right)\left(1 + \frac{\gamma - 1}{2} \cdot M_e^2\right)\right]^{\frac{\gamma+1}{2\gamma-1}}$$

The pressure ratio is given as,

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

The specific impulse (Isp) for cold gases can be calculated as,

$$I_{sp} = \frac{C^*}{g}\gamma\left[\left(\frac{2}{\gamma-1}\right)\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}\left(1-\frac{P_e}{Pc}\right)^{\frac{\gamma-1}{\gamma}}\right]^{\frac{1}{2}}$$

Pressure at throat can be calculated as,

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

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

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

The exit velocity is given as,

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

The above equations are helpful in designing of a cold gas thruster [1].

6. APPLICATIONS

As mentioned before, the most ideal application of cold gas propulsion system are micro and nano satellites. Cold gases are suitable for small buses due to their very low grade of complexity and are inexpensive and robust. They can be used when a minor total impulse is required. Primary advantages include a small impulse bit for attitude control applications and the association of small volume and low weight [2,6]. Recently, new designs have enhanced the ability of these systems for nanosatellite buses such as 3U CubeSats as shown is Fig 6.1.

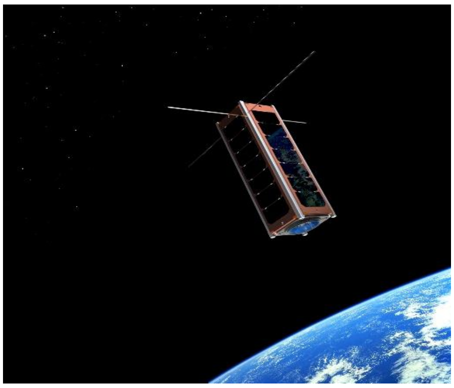

Fig -6.1: cubesat from NASA jet propulsion laboratory

They are also used in astronaut propulsion units such as hand held and manned maneuvering units as shown in Fig 6.2. In these units, a pressurized gas is used. Although the patent of handheld maneuvering unit does not specify the device as a cold gas thruster, it does state that the propulsion unit utilizes the pressurized gas escaping through the nozzle to produce thrust [9].

Fig -6.2: Manned Maneuvering Unit from lockheedmartin.com

Not only can cold gas system be used for space applications, but also for various other applications. One of the most intriguing futuristic applications of cold gas system in propelling the hyperloop pods to travel faster [10]. The concept has been shown in Fig 6.3.

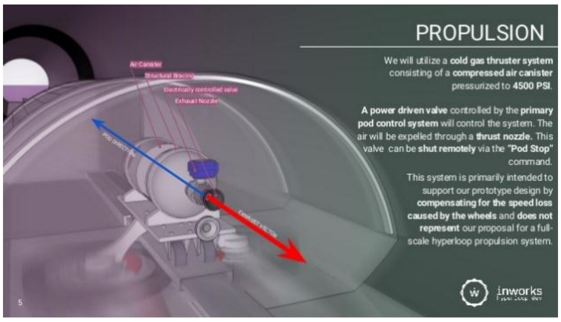

Fig -6.3: Hyperloop pod powered with cold gas thruster from slideshare

7. ABBREVIATIONS

w_i Initial vehicle weight, kg

w_f Final vehicle weight, kg

w_p Propellant weight required to produce the given ΔV

ΔV Velocity increase of vehicle, m/s

g_c Gravitational constant, $9.8\ \mathrm{m}/s^2$

I_{sp} Specific Impulse, S

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, Kelvin

$\dot{m}$ Mass flow rate of the propellant, kg/s

V_e Exit velocity, m/s

$\dot{w}_p$ Weight flow rate of propellants, N/s

P_e Exit pressure of the propellant, bars

A_e Exit Area, mm^2

A_t Throat Area, mm^2

P_C Chamber pressure in the nozzle, Bars

γ Specific heat ratio

M_e Exit Mach number

C* Characteristics velocity, m/s. It is the combustion performance of a rocket engine

P_t Pressure at throat, Bars

a_0 Sonic velocity of the gas, m/s

V_e Exhaust velocity, m/s

T_c Chamber temperature, K

8. CONCLUSIONS

In this paper, we saw that cold gas system has a plethora of advantages because of its simplicity in design, low power consumption, robustness, feasibility, and contamination free property, making it a really ideal system for wide applications. Cold gas propulsion system has helped in reducing the cost of nano and microsatellites exorbitantly., making their production feasible. The simplicity in design reduces the probability of system failure. It also produces thrust without carrying out any combustion. Its contamination free characteristic ensures that the system is not affected in any kind. All in all, it is one of the best systems to be taken in consideration to wherever the following properties are needed.

REFERENCES

[1] Anis, A. (n.d.). *Cold Gas Propulsion System-An Ideal Choice for Remote Sensing Small Satellites.* Retrieved September 5, 2020, from www.intechopen.com

[2] Ranjan, R., Chou, S. K., Riaz, F., & Karthikeyan, K. (2017). Cold gas micro propulsion development for satellite application. *Energy Procedia*, *143*, 754–761. https://doi.org/10.1016/j.egypro.2017.12.758

[3] Tummala, A. R., & Dutta, A. (2017). An overview of Cube-Satellite propulsionTummala, A. R., & Dutta, A. (2017, December 1). An overview of Cube-Satellite propulsion technologies and trends. Aerospace. MDPI Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/aerospace4040. In *Aerospace* (Vol. 4, Issue 4, p. 58). MDPI Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/aerospace4040058

[4] Zaberchik, M., Lev, D. R., Edlerman, E., & Kaidar, A. (2019). Fabrication and Testing of the Cold Gas Propulsion System Flight Unit for the Adelis-SAMSON Nano-Satellites. *Aerospace*, *6*(8), 91. https://doi.org/10.3390/aerospace6080091

[5] Kovo, Y. (2020). *Propulsion*. http://www.nasa.gov/smallsat-institute/sst-soa/propulsion

[6] Zandbergen, B.T.C.. (2013). Micropropulsion systems for cubesats.

[7] Ghasemi, Mojtaba & Rezaeiha, Abdolrahim. (2011). Design and Development of a Flight-model Cold Gas Propulsion System.

[8] Nguyen, Hugo & Köhler, Johan & Stenmark, Lars. (2002). The merits of cold gas micropropulsion in state-of-the-art space missions.

[9] *More Favored than the Birds The Manned Maneuvering Unit in Space*. (n.d.). Retrieved September 12, 2020, from https://history.nasa.gov/SP-4219/Chapter13.html

[10] Naik, P., Unde, J., Darekar, B., & Dhamangaokar, P. R. (n.d.). *Cold Gas Propulsion System for Hyperloop Pod*.

[11] Usbeck, T., Wohlfart, J., Schelkle, M., Usbeck, T., Wohlfart, J., & Schelkle, M. (2004). A Flexible Cold Gas Propulsion System Concept for Different Space Applications. In *ESASP* (Vol. 555). https://ui.adsabs.harvard.edu/abs/2004ESASP.555E..76U/abstract

BIOGRAPHIES

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