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Multidisciplinary Design of Space Blowdown Cold Gas Propulsion System without Pressure Regulator by Genetic Algorithms

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Abstract. Cold gas propulsion systems have relatively lower technologies in comparison to other propulsion systems and cost less than them. In this study, for a titanium alloy structure which uses nitrogen gas, first, a blowdown propulsion system without a regulator (pressure controller) was designed, and the minimum mass quantity of the whole system was calculated using genetics algorithm based on the design variables. Given the facts that: 1) the equipment placed after the regulator do not need to be very powerful, so they are lighter; 2) systems which do not have regulators should have a total impulse equal to the system with regulators under the same conditions and, therefore, should have a higher pressure and more primary propellant in the tank, a system with a regulator was designed in order to observe if the weight of the regulator and the conditions of such systems could overcome these two conditions.

Keywords: Multidisciplinary Design, Cold Gas Propulsion System, Blowdown, Genetic Algorithms

1. INTRODUCTION

Cold gas is one of the simplest and reliable ways to create thrust that has been long used in Space application [1].

Cold gas propulsion systems are typically used for satellite attitude control, which requires:

- A high degree of reliability
- Low system complexity, no combustion involved
- Low Δv
- Extremely safe operation
- No contamination of the satellite's external surfaces from exhaust gases [2]
- Relatively low total impulse ($\Delta v < 50\ m/s$)[3]

The gas is stored in a high-pressure tank. Typically, the gas feeds from the tank through a regulator, which reduces the gas pressure.

Although this feature is not necessary, it has two advantages:

1. The hardware outside the regulator operates at lower pressure and therefore has lower strength requirements.
2. The thruster operates at a constant pressure until the tank pressure drops below the regulator pressure; this feature ensures more consistent levels of thrust.

However, since the purpose is to minimize the system total mass, system weight gain is one of the disadvantages associated with regulator [2].

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Since the blowdown systems which lack a regulator should have a thrust equal to the systems equipped with a regulator, more propellers should be inserted in the tanks, and the other system parts must also be designed properly to match the change, so the resulting construction should be heavier and stronger.

In this study, the weight of the system in both situations – with and without a regulator – according to the above conditions and, specifically, with a higher initial weight of the construction was investigated.

Before thruster there is a two-state on-off valve that turns the flow on and off and then the flow enters the thruster which generally consists of a cap, a cylindrical chamber and a convergent-divergent nozzle.

Also along the way there can be pressure and temperature sensors, on-off valve and fuel filters which prevent the contamination going into thruster and feeding duct [4],[5].

2. OPTIMIZATION

The objective is to minimize the system total mass with genetic algorithms.

A minimization problem can be stated as follows.

Find **X** which minimizes F(**X**), Subject to the constraints

$$g_j(\mathbf{X}) \leq 0,\ j = 1, 2, \ldots, m \qquad (1)$$
$$l_j(\mathbf{X}) = 0,\ j = 1, 2, \ldots, p$$

The objective function is f(X), and g_j (**X**) and l_j (**X**) are known as inequality and equality constraints, respectively.

In this problem, only upper and lower bound constraints were used irrespective of their functions, and the constraints are somehow introduced directly in the problem because defining the constraints separately for the algorithm prolongs the calculation time. The quality of involving the constraints is dealt with in the design process. The genetic algorithms are based on the survival-of-the-fittest principle of nature and reproduction, crossover, and mutation are used in the genetic search procedure are the basic elements of natural genetics.

Since this algorithm is based on the survival of the fittest principle, it tries to maximize a function called the fitness function. Therefore, this algorithm is suitable for solving unconstrained maximization problems. It can be used to solve problems with continuous and discrete variables and, since the thickness variable is discrete, it is very useful.

In this problem, the initial population is 100 and the selection function is stochastic uniform; thought, the algorithm can be rewritten for other selection functions like roulette or tournament, 2 elite child in any population, mutation function, Gaussian function, 0.8 crossover fraction and scattered function. This function creates a random binary vector and selects the genes where the vector is a 1 from the first parent, and the genes where the vector is a 0 from the other parent and then combines the genes to form the child [6], [7].

3. DESIGN INTRODUCTION

For cold gas propulsion systems many different gases have been used, including hydrogen, helium, nitrogen carbon dioxide, methane, argon and other gases [2],[8].

The following table contains some of the most common types of such propellants features.

Table 1. Some of propellants features that usually are used in cold gas propulsion systems [9],[10]

Propellant	Isp(Measured) (sec)	Isp(Theory) (sec)	Ratio of specific heat	Density (Kg/m^3)	Molecular weight
Hydrogen	272	296	1.409	0.02	2
Helium	165	179	1.667	0.04	4
Nitrogen	73	80	1.4	0.28	28
Argon	52	57	1.667	0.44	39.9
Methane	105	114	1.299	0.19	16

Generally, nitrogen is the first choice in choosing gases. This is because: its storage is simpler than helium and hydrogen (it is cryogenic); there is a lower risk of leakage, and it needs bigger and heavier tanks compared to hydrogen and helium due to their low density.

In cases where nitrogen is not suitable for solving the problems, argon can be a suitable replacement [11], [5].

Characteristics of some of common materials structures is provided in table 2, titanium has been selected from among them. To read more about how to choose the suitable gas and material for cold gas propulsion systems can be referred to [5], [12].

Table 2. Characteristics of some of these materials used in the structure of gas propulsion tanks [9].

Material	Titanium	Titanium Alloy	Magnesium Alloy	Beryllium Alloy	Steel	Carbon fiber composites	Glass fiber composite	Aluminum Alloy
Allowable stress (MPa)	620	770	290	450	950	2000	1700	460
Density(Kg/m^3)	4500	4500	1800	1900	8000	1600	1800	2800

Due to different pressure, the temperature and density of gases change; thus, considering the isentropic relations, the pressure and density at different pressures can be calculated.

$$\frac{P_2}{P_1} = \left(\frac{\rho_2}{\rho_1}\right)^{\gamma} = \left(\frac{T_2}{T_1}\right)^{\frac{\gamma}{\gamma-1}} \qquad (2)$$

As specified in the above equation, if we have the temperature and density for each of these gases at a specific temperature, then it is possible to calculate the temperature and density in various pressures. Pressure and density can be calculated using the tables of thermodynamic in a special way. For nitrogen at a 1atm pressure and a temperature of 25 ° C, density is 1.13 [9].

4. DESIGN PROCESS

In this paper, the process of designing a blowdown cold gas system without a regulator is conducted in a stepwise fashion. At the same time, these values are obtained for a cold gas system with a regulator. The design process is generally similar in both methods with a few differences, the most obvious of which is the presence or absence of regulators. The regulators are chosen based on the inlet and outlet pressures of the gas, working temperature, working cycle, inlet and outlet sizes, and the capacity coefficient of the flow.

The regulators – with due attention to working pressure, quality, and the manufacturer – weigh between 0.3 and 0.5 kilograms. For example, the regulators made by Moog Company are designed for working pressures near 20 bars, are made of steel, and their weight is 0.3 kilogram. Another example is the regulator made by Tescom Company, which is designed for the inlet pressure of 241 bars and outlet pressure of 7 bars, is made of steel, and weighs 0.5 kilogram.

The objective is calculating and comparing the minimum total mass of the propulsion system in both cases. Both of them enjoy similar conditions. In both cases, the amount of the thrust is 1N; the working time is 120 second; the length and diameter of the tank are 2 cm and 1 cm, respectively; the propellant is nitrogen; the structure is made of titanium alloy, and the outlet pressure is 0.1 bar.

In both cases two design variables are considered, that is, the initial pressure inside the chamber (P_c) and the radius of the propellant storage tank (R_{Tank}). The pressure is limited to the range of 0.5-100 bars, and the radius is limited to the range of 0.001-1 m.

As mentioned before, the requirement of the problem is producing a thrust equal to 1 N in 120 s. In a system containing a regulator, the pressure after the regulator –the pressure inside the tank- remains constant because of having a regulator and, therefore, the outlet pressure of the thruster, the output flow rate and, as a result, the specific impulse (Isp) remain constant.

Until the time the internal pressure of the storage tank (P_{Tank}) reaches the pressure of the chamber (P_c), the system will continue to work. At this time – when the pressure is equal to the pressure of the chamber- some fuel will obviously remain there. This residual fuel is called the propellant dead mass, the amount of which has been calculated in the next sections.

In case the system lacks a regulator, the chamber pressure is equal to the internal pressure of the propellant storage tank at any moment because they are connected directly. As a result, since with the passage of time the gas inside the tank is evacuated, the pressure of the propellant storage tank and, thus, the pressure of the chamber, the outlet pressure of the thruster, the output flow rate, the amount of thrust, and the amount of specific impulse reduce. Since the total amount of the thrust given should be 1 N in 120 s, the area under the thrust-time diagram should be equal to 1*120, which is called the total impulse (I_{total}).

The objective in this problem is optimizing the total mass of the propulsion system. As indicated before, the total mass includes the mass of the propellant storage tank, the total mass of the propellant, and the mass of the thruster which itself consists of the cylindrical chamber, the cap, convergent and divergent nozzles, the regulator – in case there is one-, and other accessories mass.

$$M_{Total} = M_{Tank} + M_{Prop} + M_{Thruster} + M_{\sigma} \quad (3)$$

5. DESIGN

1. First the outlet Mach number is calculated using the isentropic relation. This part is similar in both methods and the outlet Mach number remains constant during the working time.
2. By using the amount of thrust along with having the outlet Mach number, the amount of the flow rate can be calculated. In case a regulator exists, this flow rate remains constant till the end of the process, and in the blow down case without a regulator, the amount of this rate is equal to the amount of the initial flow rate.

3. By having the amounts of flow rate, the size of the exit area can be calculated, and by having the size of the exit area and nozzle expansion ratio relation with the outlet Mach number, the area of the throttle can be calculated.
4. By having the above amounts in cases where a regulator is absent, all the masses can be calculated. It is noted that these amounts should be calculated at the worst moment which in this case is the initial moment. The points mentioned above provide a general format in which the required amounts of each relation, such as temperature changes and gas density at different pressures, should be calculated.

As said before, the amounts of the thrust, flow rate, specific impulse, tank pressure, thruster's outlet, etc. vary with time, and these amounts should be calculated.

5. First by having the density of the propellant and the tank radius as the design variable, the initial mass of the propellant can be calculated.
6. By having the initial mass and initial flow rate from the previous steps, the propellant mass after dt seconds –dt should be small enough- can be calculated.
7. By having the propellant mass after dt seconds and the tank radius as the design variable, the secondary pressure after dt seconds can be calculated.
8. By having the secondary pressure after dt seconds and the outlet Mach number, the outlet pressure of the thruster after dt seconds can be calculated.
9. By having the outlet pressure of the thruster after dt seconds and the outlet Mach number, the secondary flow rate can be calculated.
10. After obtaining these amounts we should go back to step 6 in order to calculate the amounts at 2*dt seconds as well, and after 120 seconds we enter the loop.

In each passage inside the loop the amount of the total impulse is calculated. There are two conditions for exiting the loop: the 120 seconds must be over, and the difference between the calculated amount of total impulse and 1*120 must be acceptable.

In order to automatically remove the amounts which do not meet the above conditions, we can eliminate them by increasing their mass using an automatic function instead of adding a separate constraint function to the genetics algorithm and, consequently, increasing the calculation time. Please note that in case of having a regulator – since the pressure of the chamber is different from the pressure of the propellant storage tank – first we should calculate the mass of the dead propellant and then, by having the amounts of initial flow rate and the total time, we can calculate the amount of the consumed propellant. Then we should sum up these amounts and, by using the result, we can calculate the pressure of the storage tank and, finally, calculate the mass of the pressure tank.

6. OPTIMIZATION CONCLUSION

The following table contains some of Optimization Conclusion by genetic algorithms such as outlet Mach number, throttle area, thruster exit area, tank radius, chamber pressure and total mass for two system type, without regulator and with regulator.

Table 3. Optimization Conclusion by genetic algorithms

System	outlet Mach number	throttle area (m^2)	thruster exit area (m^2)	tank radius (m)	chamber pressure (bar)	total mass (Kg)
Without Regulator	3.9119	3.1518e-5	3.1217e-05	0.166	13.49125	0.57965
With Regulator	2.5145	3.7978e-06	1.01504e-05	0.190	1.74756	0.91171

In figure 1, thrust changes, in figure 2, flow rate changes, in figure 3 specific impulse and in figure 4 chamber pressure changes of two systems, with regulator and without regulator in during time are shown as follow:

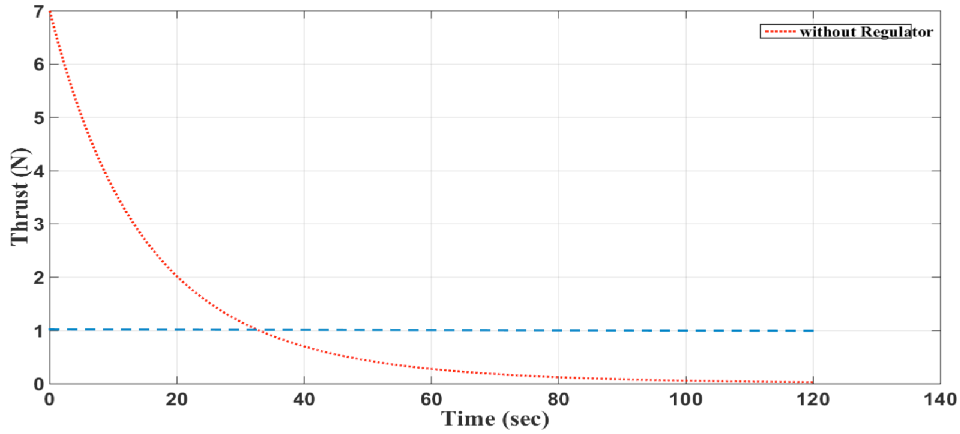

Figure 1. Thrust changes of two systems, with regulator and without regulator in during time

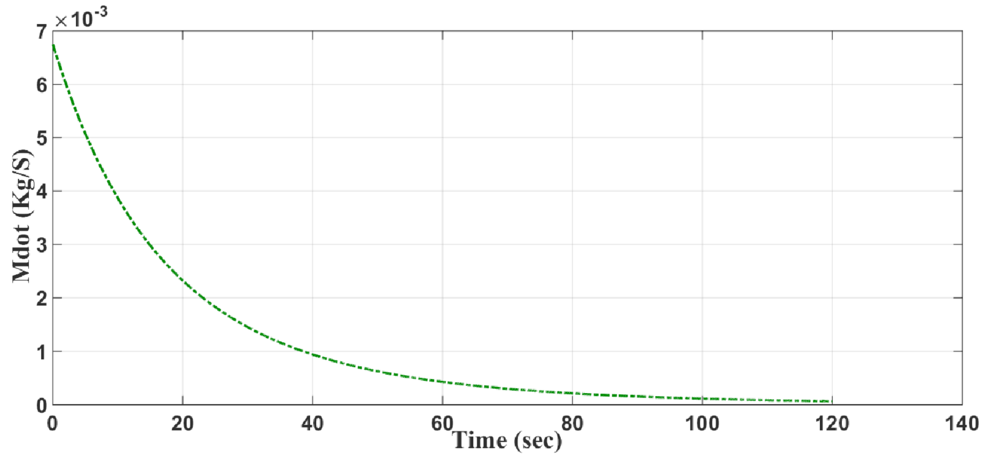

Figure 2. Flow rate changes blow down cold gas without regulator in during time, and with regulator is constant=0.0014

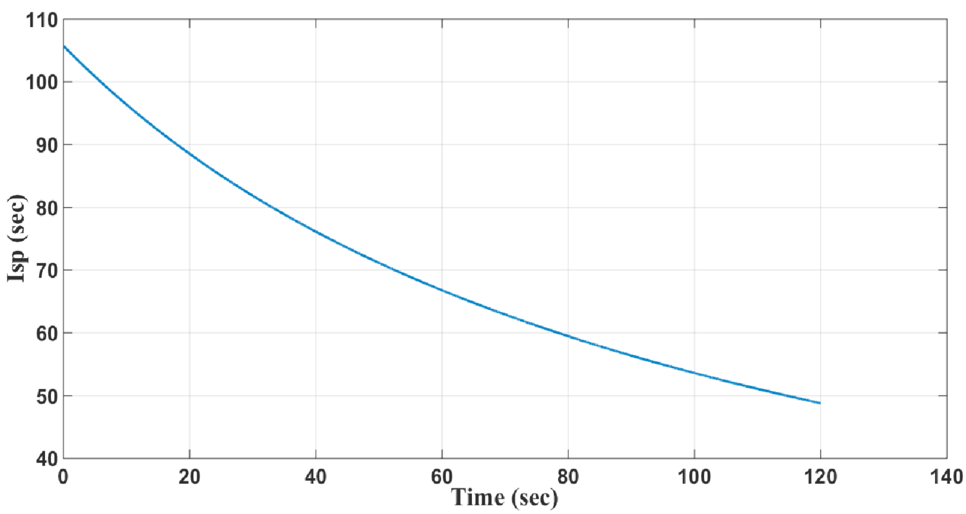

Figure 3. Specific Impulse changes blow down cold gas without regulator in during time, and with regulator is constant= 72.26

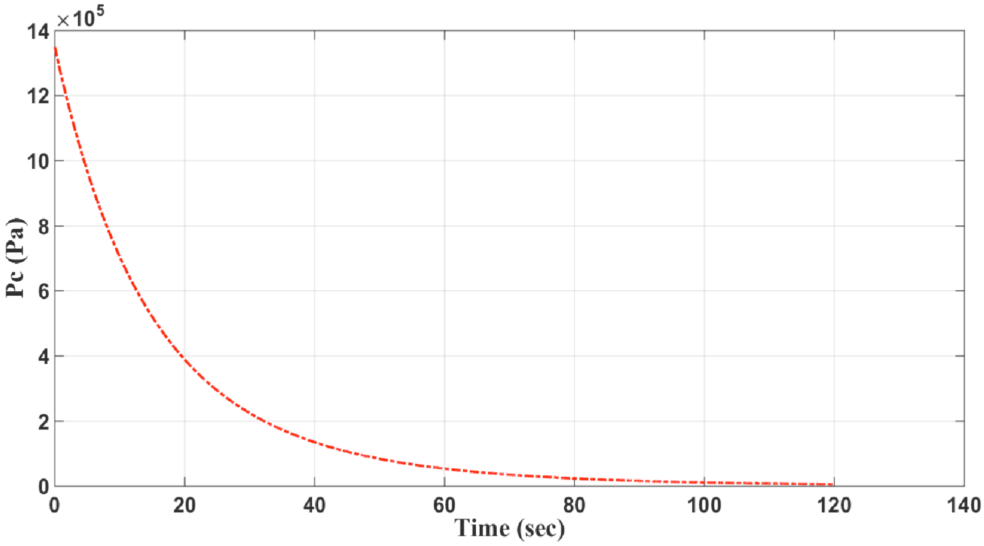

Figure 4. Chamber pressure changes blow down cold gas system without regulator in during time

7. CONCLUSION

As the results indicate, the systems which include regulators have a higher weight than the systems lacking them. In other words, due to their working at a lower working pressure, the equipment which is placed after the regulator should not be very powerful, but this feature was not enough to overcome the weight of the regulator. However, its other advantage, i.e. maintaining a more consistent level of trust, still remains. Of course, it is worth mentioning that the disadvantage of weight increase can be overcome by using a lighter regulator made of lighter materials such as aluminum.

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