Journal of Engineering Research and Reports

18(3): 1-6, 2020; Article no.JERR.62343
ISSN: 2582-2926

Optimization of Micro-Thruster Cold Gas Propulsion System Design for Space Applications

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Authors' contributions

This work was carried out in collaboration among all authors. Author LIO designed the study, performed the both computation and the numerical analysis, wrote the protocol and wrote the first draft of the manuscript. Author OAC managed the analyses of the study. Authors AVK and IJO managed the literature searches. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/JERR/2020/v18i317207
Editor(s):
(1) Dr. Tian- Quan Yun, South China University of Technology, China.
Reviewers:
(1) Serajul Haque, B. S. Abdur Rahman Crescent Institute of Science & Technology, India.
(2) Manu Mitra, University of Bridgeport, United States.
Complete Peer review History: http://www.sdiarticle4.com/review-history/62343

Original Research Article

Received 15 August 2020
Accepted 18 October 2020
Published 09 November 2020

ABSTRACT

Comparing the complexity of the hardware and the control system, cold gas micro thrusters are much more simplified than other propulsion thrusters. Numerical calculation was carried out for mass requirement, mass flow rate, valves, feed system and computational fluid dynamics with finite element analysis was used for tank, pipe and nozzle design. Four different materials: Structural steel, Stainless steel, Aluminum and Titanium, were considered for tank design. They were subjected to the same conditions for four different tank geometries. The propulsion system was designed to be able to produce between 1 and 2 minutes of continuous thrust and the sudden impulses of between 0.8 and 1 seconds of gas expulsion, with over 20 impulses as desired thrust time. The mass and the volume needed for multiple tank geometries, concepts, and materials were determined. The main performance characteristics of the micro thrusters evaluated were Pressure Distribution, Velocity Profile, Temperature Distribution, Nozzle Efficiency and the corresponding Mach Number Distribution. This work is to provide a stable and controllable platform for testing equipment that can be ultimately applied to space applications.

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Keywords: Micro-nozzle; propulsion system; tank geometries; mass flow rate.

1. INTRODUCTION

A significant variety of propulsion technologies are currently available for spacecraft application. The improvement in propulsion technologies, mission concepts that were previously limited to large spacecraft are now possible with small buses. Interplanetary missions are becoming less costly, and therefore several institutions are assuming more risks to perform science missions with huge expenses.

In recent years, thousands of Nano/Micro spacecraft from all over the world has been launched into space for remote sensing, earth observation, technology verification and telecommunication. The fast-growing functionality and popularity of micro-spacecraft has helped the researcher to push the technology demonstration towards efficient performance and reliability needed for commercial and governmental applications. As the demands are increasing, new technology needs to be pushed into market to meet the requirement, scalability and flexibility of the new designs.

When looking at the small scale propulsion system market in near future, cold gas propulsion system seems more promising that other complex and high temperature based propulsion systems [1]. Cold gas micro propulsion systems are proved to be reliable propulsion system, when tested on larger aircrafts and it has the potential to be miniaturized to meet the requirements of Nano/Micro spacecraft. The major benefits obtained from cold gas micro propulsion system are low budget, mass, and volume. The system mainly consists of a propellant tank, solenoid valves, thrusters, tubing and fittings [2]. When the hardware complexity is compared, cold gas micro thrusters are much more simplified than the pulsed plasma thruster, colloidal thruster and field emission electric propulsion thruster [3]. Desired thrust is produced by allowing compressed gas through the nozzle. Jerman et al., [4] demonstrated the ways to achieve orientation and precise attitude control. The velocity flow was calculated for the Micro thruster with the help of finite volume method. The system was miniaturized for the satellite mass range of 1-20 kg class.

Also, cold gas propulsion system has been designed to maneuver and stabilize high altitude research balloon. These balloons are very crucial to collect the data of weather and chemical composition from stratosphere. Commercial software like ANSYS and Autodesk simulation computational fluid dynamics are used to model the system correctly. A converging nozzle is used and the thrust achieved was 0.0247 N. Other parameters like mass flow rate, inlet pressure and outlet velocities were also analyzed. The FEA analysis for propellant nozzle and tank was also conducted with the help of Autodesk Inventor [5]. Composites are preferred over other material option because it showed light weight with suitable tank radius [6].

As we know that popular propellants like argon, helium, nitrogen, nitrous oxide, hydrogen, ammonia, carbon dioxide are widely used in cold gas thrusters, and this present study would allow us to validate its considerable effect using Nitrogen gas as propellant [7]. In the calculation, these propellants will differ from the compressed air only by molecular mass and specific heat capacity. In this work, multiple concepts and numerous tank geometric designs were considered for four different materials which were used for the final design. Nitrogen gas will be used at various pressures to demonstrate the functionality in terms of thrust, nozzle performance and chamber effectiveness of the micro thruster.

2. COLD GAS PROPULSION SYSTEM DESIGN

2.1 Cold Gas Propellants

The process gas for the overall system design was chosen to be Nitrogen, which is preferred for its storage density 0.28 grams/cm^3, availability, cost effectiveness, and non-reactivity and its molecular weight roughly 28 grams/mole. Also the theoretical specific thrust is around 80s [2].

2.2 Design Concept and Numerical Model

The proposed system is intended to offer relative position, attitude control, station keeping and de-orbit of smaller spacecraft. Main performance characteristics of the prototype thrusters, evaluated by means of simplified isentropic relations for the design are Thrust level, Impulse bit, Mass and Power consumption these performance parameters are selected to provide the spacecraft with the ability to maintain relative orientation and position in the face of disturbance torques.

2.3 Preliminary Tank Baseline Properties

The static pressure within the nitrogen tank was made with respect to the mass. The mass flow rate of the gas in which the unit will be operating is 0.0057 kg/second of nitrogen exhaustion from the nozzle. The density of the nitrogen gas within the micro thruster, which is a function of the temperature and pressure are 4.136854 megaPascal and 298 Kelvin respectively, as given by the ideal gas law PV= mRT is 46.9707 kg/m^3. The propulsion system was designed to be able to produce between 1 and 2 minutes of continuous thrust and the sudden impulses of between 0.8 and 1 seconds of gas expulsion, with over 20 impulses as desired thrust time.

The mass that the tank must encapsulate was calculated to be 0.114 kg of Nitrogen gas, this calculated volume of 2.43×10^{-3} cubic meters, or 2.43 liters, allowed for a baseline volume needed for the proper amount of thrust time within the propulsion system. This volume criterion was crucial in developing the tank size that would be proper for the mission requirements.

2.4 Tank Concepts

The tank design concepts are shown in Fig. 1. The static, dynamic, rotational, and point loads on any surface of the tank were analyzed using Solid Work with ANSYS Fluent. The program inputs material properties and loading conditions and results in graphical outputs of stress analysis of each material under consideration (Stainless steel, Structural steel, Aluminum and Titanium) are shown in Fig. 2a to 2d.

The Table 1 shows the maximum values of the stress, across the four materials and their geometric configurations. The most suitable configuration is the hemispherical cylinder, the configuration has minimum sharp edges that prevent stress concentration while also having enough linear component to deal with the longitudinal and hoop stresses in equal proportion induced in the tank. The flat top cylinder is most awful especially in terms of the maximum stress induced, this may be attributed to the all-linear top which is not suitable for dealing with hoop stresses i.e. the major stress component in a pressure vessel. Table 1, all martials satisfy the design requirements of minimizing the stress to different extents the best material is seen to be titanium.

Table 1. Maximum stress values across the 4 materials

Material	Shape	Max stress (MPa)
Stainless Steel	Flat Top Cylinder	583.14
	Oval Top Cylinder	191.8
	Hemispherical Cylinder	130.41
	Spherical Vessel	177.7
Structural Steel	Flat Top Cylinder	579.45
	Oval Top Cylinder	192.58
	Hemispherical Cylinder	130.93
	Spherical Vessel	178.31
Aluminium	Flat Top Cylinder	590.28
	Oval Top Cylinder	190.18
	Hemispherical Cylinder	129.35
	Spherical Vessel	176.46
Titanium	Flat Top Cylinder	600.14
	Oval Top Cylinder	187.5
	Hemispherical Cylinder	127.64
	Spherical Vessel	174.54

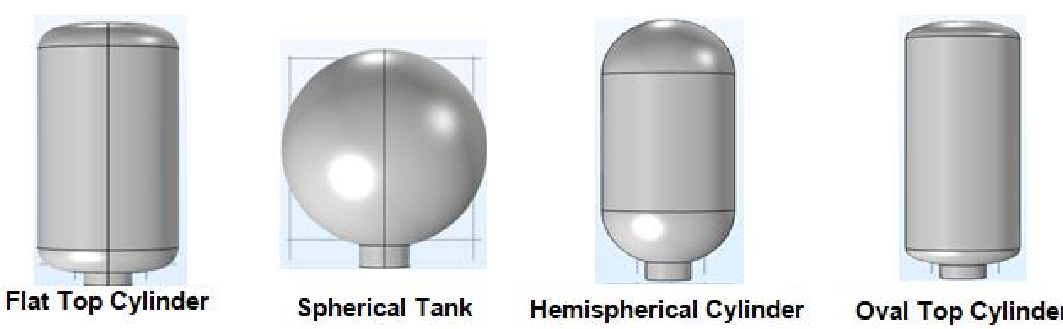

Fig. 1. Shows the three dimensional renderings of the 4 different geometries of tank

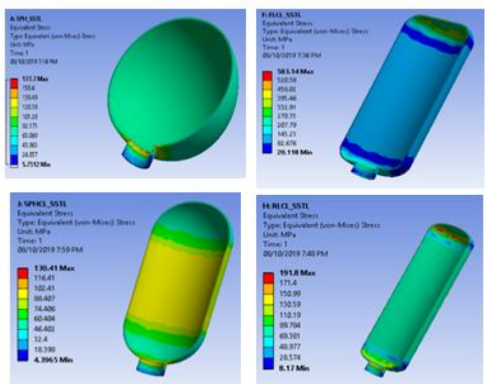

Fig. 2a. Stress analysis of stainless steel

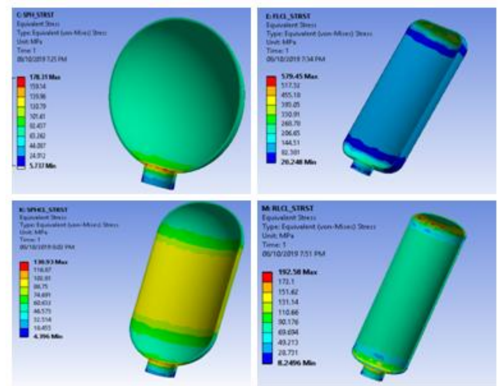

Fig. 2b. Stress analysis of structural steel

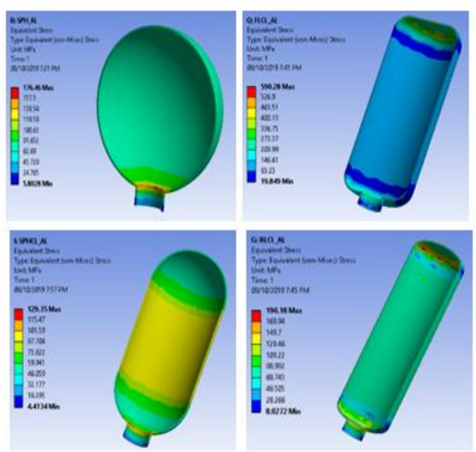

Fig. 2c. Stress analysis of aluminum

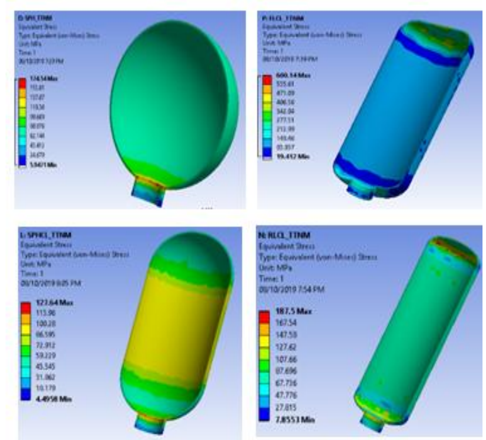

Fig. 2d. Stress analysis of titanium

3. MICRO-THRUSTER NOZZLE DESIGN

Design of the nozzle was characterized around meeting the desired thrust value with the key parameters summarized in Table 2. Using compressible flow fluid dynamics, it can be shown that the most efficient design utilizes a converging-diverging geometry, as this will maximally accelerate the propellant flow through the thruster and optimize the efficiency of the propellant. The design considerations for prototype nozzle designs are based on the mass flow rate, exit velocity, exit pressure, exit temperature and thrust which are driving variables in determining the optimal nozzle geometry.

The Fig. 3 shows the maximum values of the stress, strain and deformation across the geometric configuration and stainless steel materials considered.

4. COMPUTATIONAL SIMULATIONS

Numeric computer simulations were employed to validate the analytical model used to design the thruster nozzles. ANSYS software was used for this compressible flow simulation. A test geometry identical to the prototype nozzle geometry was modeled, having an inlet and exit diameter of 0.00953m and 0.0125m respectively, a throat diameter of 0.00717m, and a length of 0.03661m. There is no-slip condition along the walls of the nozzle, with an input condition of 689475.7 Pascal gas pressure, at the throat of 389191.06 Pascal and an exit condition of 101352.9 Pascal. Analytical calculation for flow velocity at nozzle inlet, throat and exit are 408.05m/s, 264.6m/s and 878m/s respectively.

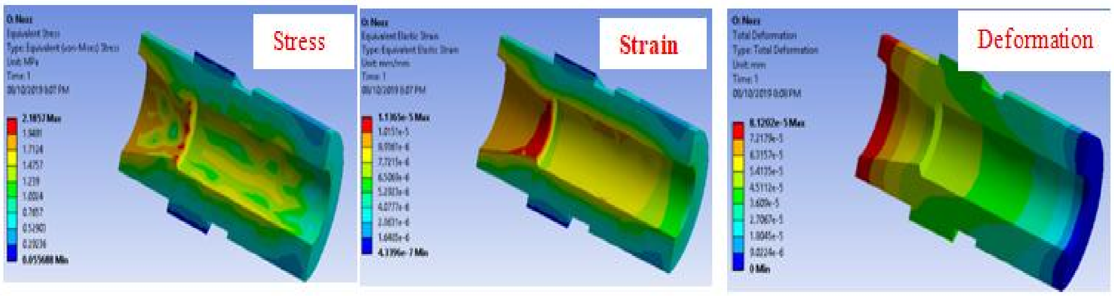

Fig. 3. Values of the stress, strain and deformation of stainless steel Nozzle

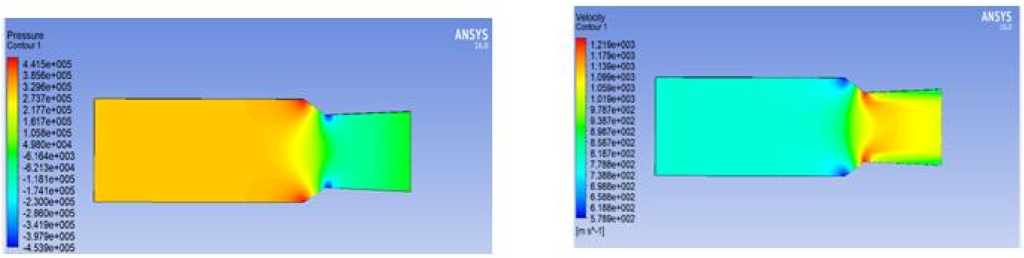

Fig. 4. Pressure contour of the nozzle

Fig. 4 shows pressure contour of the nozzle while Fig. 5 shows the flow velocity profile through the nozzle. The results of the computational simulations were inspiring in that they accorded the analytical value with less than 2% error, which is an impressively consistent result.

Table 2. Nozzle operating parameters and thrust prediction

Mach No @ Nozzle Inlet	0.4
Mach No @ Nozzle Throat	0.98
Mach No @ Nozzle Exit	1.98
Expansion Area Ratio	2.1725
Thrust Coefficient	1.701
Characteristic Velocity	399.8m/s
Temperature @ Exit	217K
Temperature @ Throat	270K

5. CONCLUSION

The main purpose of this work is to adequately optimize the performance of Micro-Thruster Cold Gas Propulsion System to allow engineers consider it as a practical propulsion system option for space application. As a result of this work, the size, mass and the cost of these systems has been significantly reduced. This design project has succeeded in laying the groundwork for a future Nano/Micro spacecraft mission augmented by propulsive capability and reduction of the size, mass, power, and cost of system.

ACKNOWLEDGEMENTS

This paper and the research behind it would not have been possible without the exceptional support of my supervisor, Prof. Adeboye Olatunbosun. His enthusiasm, knowledge and exacting attention to detail have been an inspiration. We thank Engr. Ogedengbe I. I. for his assistance with is wealthy experience in CAD. We like to show our gratitude to the Ag. Director AAELab for his so-called insights.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
http://www.sdiarticle4.com/review-history/62343