An Investigation of a Cold Gas Thruster

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***Abstract*—This project will extend off the work of the SPEX propulsion team's cold gas thruster, from the 2017 spring semester. The goal of the project is to create a cold gas thruster that functions well and provides experience and data from performing a cold burn. A well functioning cold gas thruster has no hinderances in fluid flow and produces maximum thrust by means of optimal expansion. The experience learned here will help in the ultimate goal of integrating such a system in a CubeSat for the initation of atmospheric reentry. The cold gas thruster will be a closed system which contains all the required regulation and control to sufficiently model a realisitic propulsion system for a satellite, this does not refer to the dimensions of the system or the material requirements. It will model a realistic propulsion system by maximized thrust and remote initation of the cold burn.**

Nomenclature

CGT	Cold Gas Thruster
PDD	Project Design Document
RCS	Reaction Control System
RIT	Rochester Institute of Technology
SPEX	RIT Space Exploration

I. Introduction

The objective of this project is create a cold gas thruster. The CGT will allow the team to gain experience in designing, building, and testing propulsion systems. There will be two types of nozzles tested, a minimum length nozzle and an aerospike nozzle. The nozzles will be optimized for ambient conditions.

II. Primary Objective

The primary objective of this project is to create a cold gas thruster capable of sustained cold burns which can be applied to a CubeSat to achieve the reuqired velocity to reenter Earth's atmosphere. This is a system property, however using the thrust over time curves reasonable estimations can be made to say whether or not it is possible. A target specific impulse is 50s. This can be determined from testing by integrating the thrust over time curve. See the equation 1, below, to see why this is possible.

$$I_t = \int_{t_i}^{t_f} F_{thrust} dt \tag{1}$$

$$I_s = \frac{I_t}{m_p g_0} \tag{2}$$

Where m_p is the propellant mass and g_0 is standard gravity, 9.81 ms^{-2}. As seen above, calculating the specific impulse is

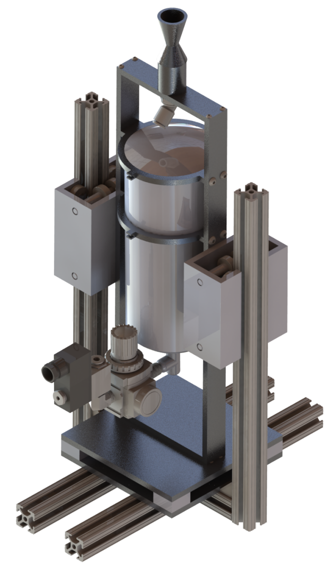

Fig. 1. This is the Solidworks Assembly of the current design of the SPEX cold gas thruster. The piping interface to the nozzle is omitted for clarity.

an easy matter if the data in reliable. It can be unreliable if the system does not perform well or if there is noise in the data. However, from previous testing noise is not a problem but error is slightly. The error in the last tests maxed at 0.05 Newtons, which is no terribly significant but still should be accounted. Vacuum condition availablity is low at RIT, so the team will need to account for ambient conditions. This primarily includes ambient pressure for achieveing maximum thrust, but there are other nuisances. The use of this cold gas thruster will give the team experience in the fabrication of propulsion systems and that can be used for designing more complex systems. These systems could include a CubeSat-sized propulsion system.

III. Benefit to SPEX

This project would be benefical to SPEX because of the pathway it creates. After its completion, SPEX will have a cold gas thruster that be shown to companies, faculty, students, and at any event where SPEX is on display. The CGT's high mobility will make transportation easy, and since the system is heavily dependent on chamber pressure for thrust, it is very safe to show to people when the tank is unpressurized. This project will also be the first foot in the door for CubeSat propulsion. There is also a continuation of this project ready to be initated upon its completion, the reaction control system.

There are many levels of analysis that can be used to design one, but the best way is experimentation (trial & error). This is especially true for cold gas propulsion of this size. The combination of the size of the nozzle and the high reynolds number of the gas does not allow and analytical solution to the optimal dimensions of the nozzle. An analytical solution usually concerns making a conical nozzle. However the thrust loss on these nozzles is maxmized. This is due to the direction of the outgoing flow. The particles travel away from the nozzle at an angle and this increases the horizontal velocity component, and decreases the vertical velocity (the direction pointing out of the nozzle), which decreases the thrust of the system. Since cold gas propulsion is inherently inefficient, due to the fact that their is no chemcial reaction or heat applied to the system, maxmizing the thrust is imperitive.

Last, but certainly not least, is the nozzle determination experience. Because of the flow conditions and dimensions, an analytical solution will not be sufficient. To accurately determine the nozzle size experiementation must happen. This data will be immensely helpful for designing the RCS nozzles and any other CGT nozzles with similar size magnitudes. To do this the team will operate at several different inlet pressures and determine the correct size of these nozzles to create optimal expansion. The team will then plot this data and fit a polynomial approximation to it. This polynomial will serve as a initial guess for future nozzles that will be expanded upon and optimized during testing.

IV. Implementation

This project will include a lot of design and data analysis. Once the design phase is complete, testing the system will be the primary concern of the team. The project will start off with a slight redesign of the test stand, optmizing it for new conditions if necessary. Then comes the design of the nozzles. The team will need to effectively and efficiently determine the appropriate chamber and inlet pressures with varying nozzle dimensions to create the polynomial curve approximation that will be an integral part of the rest of the research on the topic. Once that is complete, the testing and experimentation phase begins. After the culmination of this phase, the team can try to design, fabricate, and test an aerospike nozzle, only if time permits. There are benefits to aerospikes but there are also disadvantages. The advantages are concerned with the region of optimal expansion. The aerospike nozzle can match the ambient pressure over a larger region and therefore can produce more thrust. However, the disadvantages are increased thermal loading, which is not terribly important here but is worht mentioning, and high design and fabrication complexity. This is the projected path for the investigation of the cold gas thruster.

A. Deliverables

The deliverables of this project will be split into to two sections, physical and non-phsyical.

1) Physical Deliverables: The physical deliverables of this project with the CGT. This includes the propulsion system and the test stand. The propulsion system will include a regulator, a solenoid, a tank, a nozzle, piping, and the interfaces all connected in a series. The test stand will include the t-slot frame with the tank frame. They will be made entirely of aluminum. The interfaces between the aluminum parts will also be included. This consists of the various t-slot connections and the bolts and washers that connect the aluminum sheets.

The system will also be displayed at Imagine RIT 2018. This will include a full poster and data representation.

2) Non-physical Deliverables: The non-physical deliverables of this project will be the project culmination report which will include a very detailed examination of the projects results. These results include the expected performance versus the test performance, the nozzle dimension polynomial approximation, the structure performance, and the propulsion system performance. The structure performance is basically a section that discusses the reasoning behind the initial design and any problems that were found during testing. The propulsion system performance will be very similar to this except it will focus on slightly different aspects, such as the mass flow under various ambient conditions and temperatures.

B. Milestones

There is a preliminary plan for the semester that is displayed in further detail in Appendix A. The following list will display the description and timing of the different phases; design, sanity tests, experimentation, and data analysis.

1) Design Phase: This will be the first phase and reappearing after the culmination of the experimentation phase. Goals are to design the propulsion system, re-design the test stand, design the minimum length and aerospike nozzle

Projected End Date: Week 4 (maybe 5 if schedule slips, but no later)

2) Build & Preliminary Test Phase: This phase is concerned with the building of the system. The test stand is already built. However a few revisions might be applied, then the team will need to re-build to the new design. The main part of the building stage will be the construction of the propulsion system. This has not been built yet therefore, that is where most of the work will be. Once the system is built, it will be tested at component-level then tested at system-level. This is to ensure there are no catastrophic problems during the experiment. There will be no data collected during this phase.

Projected End Date: Week 6 (7 if fabrication takes longer than expected)

3) Experimentation: This phase is primarily concerned with the testing of the CGT. This includes gathering all the necessary data and experience to create the polynomial approximation and to aid in the RCS phase and CREST phase of space propulsion research. The testing will consist of 5 tests for each different chamber pressure. These chamber pressures will be; 80, 90, 100, 120, 140, 160, 180, and 200 Psi. There will be a total of 40 tests, if time permits there can be more but this is the goal as it will serve as sufficient data for data analysis. The data will be averaged for each chamber pressure and then plotted against the nozzle area ratio. Then a tenth-order polynomial will be fit to the curve and used to determine a first-order approximation of the nozzle area ratio for future cold gas propulsion systems.

Projected End Date: Week 9 (10 if schedule slip occurs)

4) Data Analysis: This phase is concerned with the analysis of the data collected from the CGT testing. The polynomial approximation will be completed during this phase for the minimum length nozzle. It is also the phase where the performance analysis takes place. This will inlcude the ultimate calculation of the specific impulse of the thuster and if it attains the values we need to achieve the necessary velocity change for orbital decay to initiate atmospheric reentry.

Projected End Date: Week 14 or 15 (not terribly important since the team does not theoretically need to be at RIT to conduct this analysis)

5) Final Report: At the end of this project a final report will be made to report the outcome. It will outline the design process, fabrication process, and testing process. It will also include the nozzle theory used in the calculations along with all the relevant assumptions and exterior information as needed. The report will provide all the test data and data analysis results. The final product for the report will be the discussion of the polynomial curve-fit. This will be an extremely useful tool for future similar cold gas propulsion systems and must be discussed in depth with an example of how it will be used.

Once this paper is complete it will be given to the advisors of the SPEX research group for review and then further publications will be discussed. The paper would be great for job interviews to display the work you have done in a formal manner, and one that the interviewer can refer back to at a later date.

Projected End Date: End of winter break (the team does not need to be at RIT to write this and they can take advantage of the facilites for testing while they reside there)

This concludes the milestones for this project.

V. Externalities

A. Prerequisite Skills

Creating a CGT will require a few skills, many of which can be learned throughout the project. The design process will require knowledge of systems and how they work together, basic nozzle theory, computer-aided design (CAD), basic electrical engineering, basic coding abilities, and machining. The majors that would be most qualified for satisifing these requirements are mechanical engineering & technology and electrical engineering & technology. But this project is certainly open to all majors because most of these skills can be taught in at least a basic manner.

The basic nozzle theory required here is laid out in several documents that are on the google drive, the best one being Nozzles.pdf. It is very consise and clear. The beginner propulsion project also lays out a lot of the basic theory in relation to minimum length converging diverging nozzles.

The CAD software of choice is Solidworks. It is very common for industry and has all the features that the team will need throughout the process. The education edition also includes the simulation premium package that can allow the team to run flow simulations if needed. The procedure for doing this is complicated but can be learned to a basic degree on youtube.

The basic electrical engineering including setting up and arduino or raspberry pi to read out the data from the load cell and turning the solenoid on and off. It should not be difficult for a first year or second year EE or EET to set this up. If it proves to be difficult, the team can each out to older students or professors for assistance. Dr. Patru would certainly be a great resource for this kind of help.

The basic coding abilites include writing a MATLAB script to analyze and plot data. This is not hard for anyone who has coded before. If it proves to be a roadblock one can look up the MATLAB scripts already in the google drive for reference. These scripts layout all required techniques and a bit more, such as an iterative approach.

The machining will be the most difficult to learn if there are no MEs or METs that have taken the proper courses. Machining can be extremely dangerous and cannot be done without the proper safety training. If no one is trained on the machines one can ask a machinist to make simple parts or submit a job at the Brickmann lab, formula machine shop. They have professional engineers there that can make nearly anything one could need. But their timeline slips often, so leave an appropriate amount of time for them to make the part so it does not interfere with the projects timeline.

B. Funding Requirements

Fortunately, most of the materials for the test stand have been purchased. This eliminates much of the system cost. The most costly part of the project will be the propulsion system (the regulator, solenoid, nozzle, piping, and interfaces). A preliminary, worst-case, scenario was determined by finding most of the parts on McMaster Carr. The total cost was approximately $450. That would be the last part of the system needed before testing can occur. Accounting for unforseen cost then rounding upwards, the consquentical estimated cost is put at $600 for the entirty of the project. A bills of materials is displayed in Appendix B.

C. Faculty Support

Very limited faculty support will be necessary. The SPEX propulsion team has taken care of most of the parts that will need the assistance from faculty. This included the flow system and how it operates. Is it safe and is it necessary? Those questions were answered by Dr. Garrick of the MET department. There may be some assistance required if the nozzle performance if far below nominal, but guessing from past work it will not be a problem. There may also be the need for assistance during the data analysis phase or if the team chooses to perform flow simulations. But it will be a small amount of help.

For the data analysis, if assistance is required for fully understanding it, Dr. Olles would be a good professor to ask. He has a PhD in rocket science so he could certainly help. Also, a SPEX member, Varun, has experience in flow simulation so he could probably understand the data sufficiently too.

D. Long-Term Vision

The long term vision of this project is to be a building block to the next phase of space propulsion research. CREST, a mission that was theorized in the spring of 2016 by James Parkus, relies on a space propulsion system. It is the reason the SPEX propulsion subsystem was formed. Thus, it is natural for the CGT to assist in the furthering of this project as the complication of the propulsion system has been the main concern. The problem found with this was the required velocity change. The CubeSat would need to change its orbital velocity by 122 ms^{-1}, opposite its direction of motion. To do this with a cold gas thruster one needs a certain amount of propellant varing with the chamber pressure. If you increase the pressure, one can hold more propellant but the optimal value of both was far higher than we anticipated. With a spherical tank the chamber pressure would be near 15000 Psi and with a rectangular tank the pressure would be near 8000 Psi. Because this was the first propulsion system we had designed, we were doubtful that NASA would accept these conditions. Therefore, we are making one. This project will also be great for the members to put on their resume. At the end of this project a detailed document will be made which outlines the most important aspects of the project. Then the RCS will build off the momentum created by this project. And the understanding of space propulsion inside SPEX will continue to grow and flourish.

Once the CGT is complete, the team can move onto the next phase of space propulsion research. This is the RCS. Reaction control systems are used very frequently in space propulsion and attitude adjustment systems as well as rockets. SpaceX uses them on the falcon 9 for landing orientation adjsutments. You can actually see them burning during landing. It is the burst of white gas coming from the side of rocket. Building an RCS is difficult. But if the team has prior experience with cold gas propulsion, their job becomes significantly easier. Because you need optimal nozzles for an RCS, and as mentioned before , it is nearly impossible to analytically design them. The team can refer back to their data for this.

Acknowledgements

The author would like to thank Dr. Garrick and Dr. Olles for their help in understanding the theory of nozzles and the review of the system before testing.

Appendix A
Detailed Fall Timeline

1) Week 1
   a) Introductions & Fall plan
2) Week 2
   a) Beginner Project: Supersonic Nozzle Design
   b) Test Stand Re-design Discussion
3) Week 3
   a) Beginner Project
   b) Test Stand Re-design fabrication
4) Week 4
   a) Beginner Project testing
5) Week 5
   a) Preliminary CGT testing (just to familarize ourselves with the system and safety procedure)
6) Week 6
   a) Discussion of nozzle design, nozzle design, and printing
7) Week 7
   a) Nozzle Design and printing
8) Week 8
   a) Round 1 of CGT Testing
9) Week 9
   a) Round 2 of CGT Testing
10) Week 10
    a) Data Concatenation and sorting
11) Week 11
    a) Aerospike Dicussion and theory
12) Week 12
    a) Aerospike nozzle design and fabrication
13) Week 13
    a) Aerospike Preliminary testing, make design adjustments if necessary
14) Week 14
    a) Round 1 of Aerospike testing
15) Week 15
    a) Round 2 of Aerospike testing
16) Week 16
    a) Data Analysis

Appendix B
Cold Gas Thruster Preliminary Bill of Materials

Raw Material	Part Name	Price	Quantity	URL	Sub-Total	Received?
	Regulator	$180.00	1	ttps://www.mcmaster.com/#49305k21/=18tsdu	$180.00	No
	Solenoid	$100.00	1	https://www.mcmaster.com/#4711k511/=18seax8	$100.00	No
	Zinc-Plated Steel Hydraulic Hose Fitting	$2.66	4	ttps://www.mcmaster.com/#5340k26/=16xf27	$10.64	Yes
	Arduino	$25.00	1	https://store-usa.arduino.cc/products/a000066	$25.00	Yes
	Hex Drive Rounded Head Screw	$12.00	1	tps://www.mcmaster.com/#91255a269/=16xfb	$12.00	Yes
	Load Cell	$11.00	4	https://www.sparkfun.com/products/10245	$44.00	Yes
0.25 Aluminum Sheet Metal	Vertical Plate	33.35	2	tps://www.mcmaster.com/#8975k443/=16n4m	$66.70	Yes
	Horizontal Plate Topside		1		$0.00	Yes
	Flexible Standard Nylon Tubing	15	1	ttps://www.mcmaster.com/#5548k74/=1711sv	$15.00	Yes
	T-Slotting (1ft)	$6.41	7	tps://www.mcmaster.com/#47065t101/=1711t	$44.87	Yes
	Bracket, 1" Long for 1" High Single Profile Aluminum T-Slotted Framing Extrusion	$5.79	2		$11.58	Yes
	Tank	$130.00	1	ttps://www.mcmaster.com/#7822a11/=18se4x	$130.00	No
0.5" Aluminum Sheet Metal	Ring Clamp	$26.00	2	ttps://www.mcmaster.com/#9246k31/=16n4j8	$52.00	Yes
	Push-to-Connect Tube Fitting for Air	$3.42	2	ttps://www.mcmaster.com/#5779k152/=1711l	$6.84	Yes
1.5" Aluminum Rod	Capsulator 9001	$27.70	1	ttps://www.mcmaster.com/#8974k18/=1711nv	$27.70	Yes
	Nozzle		1		$0.00	Yes
	18-8 Stainless Steel Narrow Hex Nut	$5.50	1	ps://www.mcmaster.com/#90730a411/=1711o	$5.50	Yes
	Extreme-Pressure 316 Stainless Steel Pipe Fitting	$18.67	1	ps://www.mcmaster.com/#51205k112/=1711y	$18.67	Yes
	Threaded Fluid Control Orifice	$2.14	2	tps://www.mcmaster.com/#4830k133/=1711i3	$4.28	Yes
	Barbed Hose Fittings	11.87	2	ttps://www.mcmaster.com/#5346k14/=1711kd	$23.74	Yes
Grand Total					$778.52	

Fig. 2. This is the preliminary BoM that the propulsion team came up with last year. Most of the materials have already been acquired. But the propulsion system materials must still be purchased.