Design & Implementation of a Cold Gas Thruster

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***Abstract*—This project concerns the design, fabrication, and experimentation of a cold gas thruster. The project's main goal is to provide insight and experience into the design of a supersonic nozzle for small propulsion systems. Secondary goals will include the understanding in the design of high-pressure flow systems, including the necessary precautions and procedures to ensure safe usage. The propulsion subsystem will provide the thrust and consist of a high pressure tank, a regulator, a solenoid, and the appropriate piping and interfaces. The structure subsystem will will hold the propulsion system in place and allow measurement of the thrust and will consist of aluminum sheet metal and t-slotting. This project will be the first step in the design of a cold gas thruster for a CubeSat to allow atmospheric re-entry.**

Nomenclature

g_0	Standard gravity	$\mathrm{m\,s^{-2}}$
I_t	Total Impulse	$\mathrm{N\,s}$
I_{sp}	Specific Impulse	s
m_p	Propellant Mass	kg
t_f	Final time	s
t_i	Initial time	s
CGT	Cold Gas Thruster	
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. The type of nozzle that will be tested is a minimum length supersonic nozzle. There is ambient pressure, thus the nozzle will be optimized for ambient conditions.

II. Primary Objective

The primary objective of this project is to create a cold gas thruster for on-ground experimentation. The goal for the data is to be able to design a nozzle for a small propulsion system, where boundary layer effects are dominant, but also to achieve an specific impulse of 50s. Using the thrust over time curves, the specific impulse can be calculated numerically using MATLAB. The data will be transferred and analyzed there using the following equations as a basis[1].

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

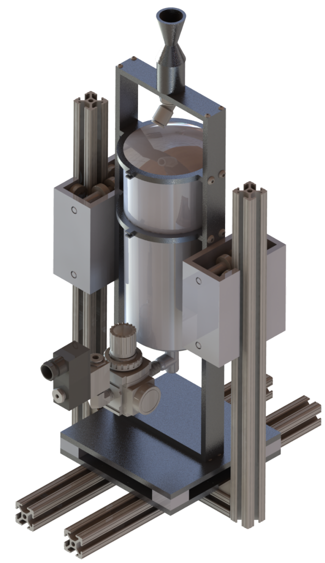

Fig. 1. The Solidworks Assembly of the Spring 2017 design of the SPEX cold gas thruster. The piping from the solenoid to the nozzle is omitted for clarity.

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

Data error found from past experimentation was 5% of the thrust. This error is due to the quality of the load cell. It has an inherent inaccuracy. This amount of error is acceptable. The performance analysis will not be detrimentally affected. The risk mitigation includes zeroing the load cell just before the test. This will erase the effects caused by initial weight placed on the load cell. This initial weight comes from the aluminum sliding fixture which holds the nozzle and the plumbing system.

III. Benefit to SPEX

This project can be benefical to SPEX because of the experience given to SPEX in propulsion system design and experimentation. The experience includes learning how to contruct flow systems, design nozzles for a small propulsion system, and an understanding of the design complexites. These can help avoid roadblocks in future designs. 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 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)[2]. 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[1]. 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.

IV. Implementation

This project will include 4 to 5 weeks of design, 3 to 5 weeks of fabrication, and 4 to 5 weeks of data analysis. The project will start off with a redesign discussion of the test stand, optmizing it for new conditions if necessary. 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. At the end of the data analysis the final report will be the main focus. The aim is to complete it by the beginning of winter break so the team can focus on the new project when they return for the Spring 2018 semester.

A. Deliverables

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

1) Physical Deliverables: 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. Aluminum is a great material for its balance of strength, machinability, and weight. Steel is very difficult and hardous to machine and is very heavy, although its strength is greater than aluminum. Plastics are tedious to machine as they tend to melt to the cutting blade and that casues the machining to stop frequently to clean off the blade. The propulsion has a very large pressure drop and this will cause a large temperature drop. A plastic structure will effected greatly by this and will harden to the point where fracture could occur very easily. 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.

There will also be an arduino connected to a computer that will use Simulink for data acquisition. The arduino will be a conduit to relay the data from the load cell to Simulink. There will also be an arduino to control the use of the solenoid. The solenoid will be activated from the Simulink program, which will coincide with the beginning of data acquisition.

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 structural performance is a section that discusses the reasoning behind the initial design and any problems that were found during testing. The problems to be avoided will be, unecessary frictional loss due to bad connection points or instability of the test stand due to bad interfacing between structural components. 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. The propulsion performance will mostly be measured through the data analysis. This effects the specific impulse. It will also concern the expansion of the flow, as the maximum thrust will occur when the exit pressure equals the ambient pressure and thus the shocks in the flow will expand optimally. This will be observed through schlieren lensing, as it has been performed before during nozzle testing. This was performed in the Spring 2017 semester for flow visualization. The procedure was; turn the lights off, put the nozzle on the air hose, put a white piece of paper on a table, put it parallel to the table, initiate the cold burn, use a phone light to project the flow onto the white paper below it. Then distance between the nozzle and the light and the table were toggled until the best focus point was found. Figure 2 shows the exiting flow from a 3D printed nozzle.

B. Milestones

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

1) Design Phase: The goals are to design the propulsion system, the test stand, the nozzle. At the end of this phase

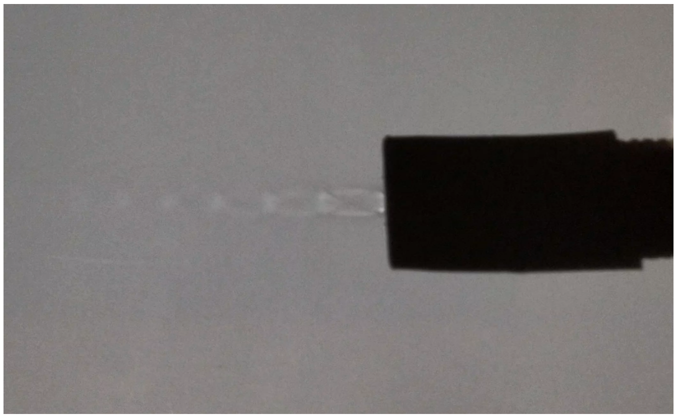

Fig. 2. The flow is seen here exiting a small 3D printed supersonic nozzle. The procedure was not unlike schlieren lensing, however the clarity was much lower.

there will be a full system CAD model and a series of CAD nozzles to be fabricated. This CAD model is essential for the next phase, as the fabrication will use it as a guide (inlcuding drawings for machinists).

Projected Duration: 2–3 weeks

2) Build & Preliminary Test Phase: This phase is concerned with the building of the system. The test stand is already built. However if minor revisions are necessary, then the team will build the new design (any re-design will concern the dimensions of the tank fixture and will therefore not take long as it is a simplistic system). The main part of the building stage will be the construction of the propulsion system. 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 Duration: 3–5 weeks

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 Duration: 2–3 weeks

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 Duration: 3 weeks

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 Duration: 2 weeks

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 can be adequately learned by reading the introductory chapters of *Rocket Propulsion Elements* by Sutton[2]. Chapter 1 through 4 will provide a sufficient basis of understanding for this project.

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. MATLAB is easy to learn and is very powerful. It is a very common choice for data analysis for mechancial engineering projects where the core skill set

Propulsion System Part List

Part	Cost	McMaster Part #
Tank	$ 131.35	7822A11
Regulator	$ 182.50	49305K21
Solenoid	$ 100.49	4711K511

is not computer science. This is not hard for anyone who has coded before.

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 Earl Brickman Machine Tools and Manufacturing Lab. 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 budget that includes margin for cost overruns is $600. 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 bill of materials is displayed in Appendix B. The table, displayed below, outlines the most expensive parts that the team will need to purchase for the propulsion system, these parts are worst-case scenario in cost and measures will be taken to try to alleviate these costs.

C. Faculty Support

Facculty support will be necessary. The SPEX propulsion team has consulted faculty about structure and flow system concerns and made the suggested changes. However, the propulsion system has not been tested. It is likely that faculty assistance will be necessary to get the propulsion to a functional stage. This would most likely inlcude the design of an optimally expanding nozzle. Faculty support was needed during the endevour to fabricate the structure and design the flow system. This included the flow system and how it operates. Dr. Garrick, MET department head, assisted the team in the design of the flow system and pointed out unnecessary components, such as the flow straightener. He said that the flow was at such a high reynolds number that straightening it in the size constraints is impossible with our budget. There may be some assistance required if the nozzle performance is far below nominal, but guessing from past work it will not be a problem. This would concern the nozzle design. Nozzle design is very difficult for the necessary size for the CGT, about 1 inch in length and 0.5 inches in diameter. Boundary layer effects are dominent. To accurately design them on a computer would include high level numerical smulation which beyond the team's skill set. If there are recurring problems here, Dr. Olles can be consulted as he has experience with this. 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.

If assistance is needed for the data analysis, Dr. Olles would be a good professor to ask. He has a PhD in rocket science so he could certainly help.

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 proposed 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. The main conern for CREST was the propulsion necessary to de-orbit quickly enough that SPEX can determine its entry location and therefore estimate its landing location.

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. Building an RCS is difficult. But if the team has prior experience with cold gas propulsion, their job becomes significantly easier. The team can refer back to their data for the determination of the appropriate nozzle characteristics.

After the culmination of the cold gas thruster project, 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 and high design and fabrication complexity[1].

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 and Phil Linden and T.J. Tarazevits for creating the PDD process and making it as easy as possible and for their continued help.

REFERENCES

[1] W. J. L. Ronald W. Humble, Gary N. Henry, *Space Propulsion Analysis and Design*, 1st ed. New York, NY: McGraw Hill, 1995.

[2] G. Sutton, *Rocket Propulsion Elements*, 2nd ed. Unknown: Unknown, 1984.

Appendix A
Detailed Fall Timeline

Week #	Plan
1	Introductions & Fall plan discussion
2	Beginner Project: Supersonic Nozzle Design
	Design Phase: Test stand
3	Beginner Project: Nozzle Printing and Testing on weekend
	Design Phase: Propulsion System
4	Design Phase: Propulsion System
5	Design Phase: Arduino and MATLAB design
6	Design Phase: Arduino and MATLAB design
7	Fabrication Phase: Material order and making Solidworks drawings
8	Fabrication Phase: Machining
9	Fabrication Phase: Machining and assembly
10	Experimentation Phase: Test 1
11	Experimentation Phase: Test 2
12	Data Analysis Phase: Data Organization
13	Data Analysis Phase: Noise and error analysis
14	Data Analysis Phase: Performance Analysis
15	Project Culmination Report writing
16	Project Culmination Report finalization

Appendix B
Bill of Materials

Part	Cost	Quantity	Vendor	Part Number	Status
Tank	$131.35	1	McMaster Carr	7822A11	Not acquired
Regulator	$182.50	1	McMaster Carr	49305K21	Not acquired
Solenoid	$100.49	1	McMaster Carr	4711K511	Not acquired
Push-to-connect fitting	$4.33	2	McMaster Carr	5779K116	Not acquired
Aluminum Pipe	$2.45	2	McMaster Carr	50785K172	Not acquired
Nylon Pipe	$8.90	1	McMaster Carr	5548K77	Not acquired
Aluminum Sheet	$7.00	1	McMaster Carr	8975K596	Acquired
Aluminum T-Slot	$6.49	7	McMaster Carr	47065T101	Acquired
T-Slot Corner Frame	$7.98	10	McMaster Carr	5537T51	Acquired
T-Slot Length Frame	$5.66	4	McMaster Carr	47065T235	Acquired
#8 Socket Head Cap Screws	$6.58	1 [100]	McMaster Carr	92196A194	Acquired
Arduino	$10.00	1	RIT Construct	Unknown	Not Acquired
Grand Total	$608.25				