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IMPROVEMENTS ON TWO-PHASE COLD GAS PROPULSION SYSTEMS FOR SMALL SPACECRAFT

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Small spacecraft such as CubeSats are being used to accomplish increasingly complex missions requiring precise relative positioning and maneuverability. This capability is often provided by cold gas propulsion systems, many of which use a two-phase propellant. These systems have the benefit of being simple and inexpensive, but their capabilities are limited by the current technology. There is a need for a next generation of cold gas propulsion systems that are capable of improved performance relative to the heritage systems. This paper outlines the propulsion needs of future CubeSat missions, describes the shortcomings of current systems, and proposes a design concept for the next generation of cold gas propulsion units for use on small spacecraft missions. The key areas for improvement are identified as propellant management, temperature compensation, manufacturing, leak mitigation, and reliability. The proposed next-generation propulsion system, referred to as GTCG2, aims to improve in these areas through the use of advanced additive manufacturing, a novel propellant management system, closed-loop temperature control, and redundancy of key components. This architecture will allow for increased reliability, repeatability of impulses, and impulse density while maintaining a low cost.

INTRODUCTION

Small spacecraft are being used to perform increasingly challenging scientific and operational tasks. Formation flight is garnering the interest of various mission sponsors, and the requisite maneuverability is pushing the capabilities of current small spacecraft propulsion systems. These missions often require precisely controlled and timed impulses to meet relative positioning requirements. They also require high enough thrust to perform impulsive collision avoidance maneuvers. Additionally, proximity operations often require frequent maneuvers, leading to a need for a higher total impulse delivered in a small volume. For missions that use CubeSats, all of these needs must be satisfied by a propulsion system that can fit in a CubeSat form factor. This scenario is common to many upcoming CubeSat formation flying missions including SunRISE, VISORS, and SWARM-EX.[1–3]

Past CubeSat missions such as MarCO, ASCENT, and BioSentinel have used R-236fa-based cold gas systems to meet their propulsion requirements.[4,5] These systems are attractive due to their simplicity, low power draw, and compact size. They have met the needs of these earlier missions, but there are areas for design improvement that will enable more complex missions to be completed in the future.

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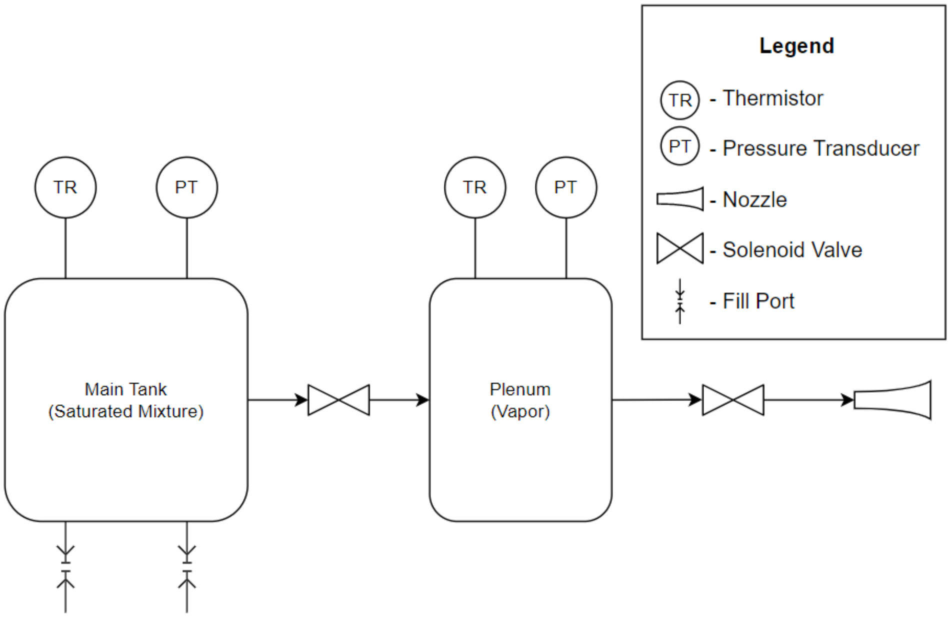


Figure 1 Fluid flow block diagram of a typical CubeSat cold gas propulsion system.

OVERVIEW OF HERITAGE SYSTEM ARCHITECTURES

In many heritage R-236fa-based systems, the propellant is stored as a two-phase fluid in a main propellant storage tank, and a second smaller tank referred to as the plenum is used to maintain a portion of the propellant as a vapor.[3,5–7] The vapor is then used for spacecraft actuation. The two tanks are connected via a solenoid valve. The vapor in the plenum is exhausted through a thruster valve and then through a converging-diverging nozzle to generate thrust. A system diagram for one such system is shown in Fig. 1.

In the heritage propulsion systems developed by the Georgia Tech Space Systems Design Lab (SSDL), the pressure in the plenum drops as the system actuates. When the plenum's pressure drops below a predetermined cutoff value, it must be refilled. Propellant from the main tank is routed through the refill valve into the plenum. Refilling is stopped when an adequate pressure value has been reached. The refilled plenum is not allowed to reach saturation pressure and therefore should not contain any liquid in its equilibrium state.

The use of a two-phase propellant in the design introduces considerable complications, but it also has many benefits. The most immediate benefit is the volumetric efficiency of storing a liquid propellant. CubeSat propulsion systems are frequently volume-limited, so greater importance is placed on the volumetric specific impulse of the propellant rather than the traditional mass-based specific impulse metric. Two-phase propellants such as R-236fa have an exceptionally high volumetric specific impulse.[5] Additionally, these propellants self-pressurize, eliminating the need for auxiliary pressurization systems.

The construction detail of current systems varies depending on the designer. The systems developed by the SSDL are additively manufactured, with recent systems such as the SWARM-EX propulsion system being SLA printed from SOMOS PerFORM and previous systems being made from Accura Bluestone.[5] These materials were chosen for their mechanical properties, ease of manufacturing, and low cost. Additive manufacturing allows these systems to occupy complex geometries and fully utilize the available volume within a small spacecraft. This manufacturing technique also allows fluid flow paths to be included within the structure of the propulsion system, eliminating the need for external tubing which occupies additional volume. Commercial systems such as those developed by VACCO for use on the MarCO mission are made from welded aluminum.[6]

The systems developed by the SSDL implement COTS components whenever possible to simplify the design and decrease the cost of the system. These cost-saving measures are implemented with the goal of making the propulsion system affordable to university CubeSat projects.

AREAS FOR IMPROVEMENT

In order to better meet the needs of future CubeSat formation flight missions, cold gas propulsion systems will need to be improved. To better understand areas for improvement, the issues with current systems must be fully understood. Issues in the area of propellant management, environmental effects, material selection, leakage, and volumetric efficiency are described in detail throughout this section.

Propellant Management

The most obvious area for improvement in these systems is the propellant management device. The current design using two tanks, one of which only holds vapor, is not volumetrically efficient. This issue is exacerbated when systems with exceptionally low volumes are designed. In these systems, the plenum occupies a significant portion of the total system volume, thus detracting from the available space for propellant storage. This leads to a lower total impulse capacity of the system.

The two tank design requires that the plenum be refilled from the main tank when its pressure drops below a predefined cutoff value. This leads to the need to refill the plenum multiple times during large maneuvers. In systems designed by the SSDL, the thruster must stop firing while the plenum is refilled. This property can be thought of as limiting the effective average thrust that the system can deliver for long-duration maneuvers. As the pressure in the plenum drops between refills, the thrust output of the system also decreases, which must be taken into account. Spacecraft guidance strategies must be designed with these characteristics in mind.

Furthermore, care must be taken when refilling to prevent liquid from existing in the plenum. This can occur because a saturated mixture of propellant flows from the main tank to the plenum during refilling. The liquid in this mixture begins to vaporize in the lower pressure of the plenum, but this vaporization is not instantaneous. This results in the plenum pressure continuing to rise even after refilling has stopped. If a sufficient amount of liquid has entered the plenum, it will reach saturation pressure prior to all of the liquid vaporizing. This results in a saturated mixture existing in the plenum, leading to unpredictable and possibly diminished performance. Because the flow rate of propellant into the plenum and the vaporization rate of liquid propellant depend on many factors, the development of an efficient and reliable refilling strategy is challenging. Ultimately, a conservative and time-consuming refill strategy must be employed to ensure that the plenum contains only gas. The exact parameters of this strategy vary between each system due to variations in flow restriction and tank volumes, which further complicates implementation.

The fluid management challenges associated with these systems are not simply theoretical. Liquid was shown to exist in the plenum on the MarCO mission, which led to challenges predicting performance, though the observed behavior was also attributed to leakage across the valve between the main tank and plenum.[4] Liquid was also observed to exist in the plenum during testing of the SWARM-EX and SunRISE propulsion system development units. Strategies have been implemented to mitigate these issues, but they generally come at the cost of performance losses in other areas.

Environmental Effects

Even with a reliable refilling strategy, liquid can still form in the plenum due to temperature variation. The plenum is nominally refilled to 95% of the saturation pressure of the propellant and has an upper temperature limit of 50°C. The nominal mass of propellant in the plenum at this upper limit can be calculated as

$$m_p = 0.95 * \rho_{v,50} V_p, \tag{1}$$

where $\rho_{v,50}$ is the density of the saturated vapor at 50°C and V_p is the volume of the plenum. If the plenum is allowed to cool to 0°C after filling at 50°C, it can be shown that a plenum containing only vapor at the saturation density could not contain the full mass m_p. Using the known saturation properties of the propellant and the calculated mass in the plenum, Eq. 2 can be solved to show that liquid will compose 80.1% of the mass of propellant in the plenum after it is cooled, with the volume of liquid at 0°C represented by $V_{l,0}$ and the density of the liquid represented by $\rho_{l,0}$ while the density of the vapor at 0°C is represented by $\rho_{v,0}$. It can further be shown that a temperature drop of less than 5^oC can result in the condensation of liquid within the plenum.

$$m_p = V_{l,0}\rho_{l,0} + (V_p - V_l)\rho_{v,0} \tag{2}$$

The issue of propellant condensing in the plenum can be resolved by incorporating a temperature controller into the design of the plenum, but it is a further complication of the design and draws additional power. Despite these complexities, some systems such as those used on the MarCO CubeSats have employed this strategy.[6]

Another issue associated with temperature fluctuation is the variation of pressure in the main tank and plenum. A fact of using a two-phase propellant is that the main tank will maintain itself at the saturation pressure of the propellant. This pressure varies significantly with temperature. Over an operating range of -5°C to 50°C the saturation pressure of R-236fa varies by a factor of 6.7 (from 12.6 psi to 84.7 psi).[8] This large variance increases the difficulty of obtaining repeatable performance from the system. This is an inherent design challenge when using a two-phase propellant. For applications such as momentum dumping, the issue of less repeatable performance may not be as critical, but in missions demanding precise relative positioning, this lack of repeatability could be problematic.

Manufacturing

The systems developed by the SSDL are additively manufactured. This allows for highly efficient use of the complex geometries required within CubeSats. The materials used have traditionally been high-stiffness photopolymers that are manufactured through a stereolithography process, with SOMOS PerFORM being the current material of choice. These materials are easy to print, which eliminates most concerns about manufacturability that would further complicate the design. However, there is recent concern that the electrically insulative material may be capable of building up

Figure 2   Cutaway view of SWARM-EX propulsion system printed structure prior to cleaning.

an electrostatic charge that could damage onboard electronics under certain conditions. No damage has yet been observed, but it is considered a risk to the lifetime reliability of the device and the spacecraft.

The material has also proven to be challenging to clean to the specifications required for some missions. This problem is believed to be the result of a combination of factors including the manufacturing process, the material itself, and the restrictive geometries designed into these systems. A cross-section of the printed structure for the SWARM-EX propulsion system is shown in Fig. 2. Much of the debris in this image is likely a result of dividing the structure with a band saw, but it is clear that the internal surfaces are not smooth and some printing artifacts are visible in the corners. Additionally, varying quantities and sizes of debris have been found in structures that were not cut open. Combining surface roughness, printing artifacts, and restrictive entrance geometries with a plastic that appears to be prone to shedding particles leads to a host of cleaning problems.

Many commercially available cold gas propulsion systems utilize a traditionally machined and welded tank structure, with aluminum and titanium being common materials.[6, 9] These systems do not face the charge build-up issues associated with SOMOS PerFORM. The cleaning processes for these materials are also well documented, and the materials themselves are strong and durable. While these qualities are enticing, the traditional machining and welding process is limiting. These systems cannot be designed to conform to highly complex volumes. Despite the standardized cubic nature of CubeSats, it is often desirable to utilize conformal tank geometries, and the inability of traditionally machined systems to do this poses a problem.

Leakage

An ever-present issue in pressurized systems is leakage. This can be problematic for spacecraft propulsion systems, both because the propellant is being lost and the leak may impart unexpected forces on the spacecraft. Two separate propellant leaks were detected on orbit during the MarCO mission, and leaks have been detected repeatedly during ground tests on the SunRISE and SWARM-EX propulsion systems at Georgia Tech (GT).[10] The leaks observed at GT have generally occurred at valve attachment points, though some have been observed at o-ring interfaces. While the leaks are easily resolved on the ground, there are concerns that thermal cycling may result in the development of additional leaks after launch. This has been observed in at least one case in SSDL-built engineering development units. Futures systems will benefit from limiting the number of potential locations for leaks to form and mitigating the stresses induced by thermal cycling.

IMPROVEMENTS

In light of the issues associated with current state-of-the-art cold gas propulsion systems, a series of improvements are suggested to move towards a design capable of meeting the demands of future CubeSat formation flight missions.

Propellant management is one of the largest issues faced by these systems. Companies such as VACCO and CU Aerospace have adopted the methodology of placing a heat exchanger in line between the propellant tank and the nozzle.[6,9] This heat exchanger vaporizes the propellant and on some systems can also heat the propellant gas to achieve improved performance. This solution introduces additional complexity and power draw, and a plenum is still required on current systems, which reduces volumetric efficiency. An analysis of the systems developed by the SSDL indicates that an additional power input of at least 7 W would be required to vaporize the nominal mass flow rate of propellant from the thruster at a 20 mN thrust level. This amount of power is achievable in a CubeSat form factor and would offer a robust solution, but it is less attractive due to the need for a plenum. A system with a single nozzle could be developed without a plenum, but in order to ensure repeatable impulses, a propellant management device (PMD) would be required. This device would act as a trap and ensure that a single-phase propellant was consistently delivered to the heat exchanger until the acceleration of the spacecraft drove the remainder of the propellant to the tank outlet.[11] This system would not be sufficient on a spacecraft with multiple nozzles and directions of acceleration.

An alternative to the use of a heat exchanger is the implementation of a PMD that relies on surface tension or electromagnetic forces to ensure that only vapor leaves the propellant tank. PMDs based on surface tension have a significant history in spacecraft propulsion systems but are generally designed for fluids such as hydrazine and a pressurant gas, not two-phase refrigerants.[11–14] Additionally, the need to position a gas bubble rather than a liquid propellant considerably complicates their design, as does the conformal tank geometry. Electromagnetic PMDs have significantly less design heritage, but they may be well-suited for this application. Of particular interest are magnetic positive positioning devices, which position fluids using a magnetic field.[15,16] These devices can be designed to use permanent magnets, and they occupy a small volume. A detailed description and analysis of these systems is presented by (Ref. 17). Despite their attractive qualities, their limited heritage may complicate their design and implementation. There are additional concerns related to possible interference between the permanent magnet and sensors onboard the spacecraft, though some of these issues may be mitigated through appropriate positioning of the magnet.

The issues associated with varying system temperatures are relatively simple to solve compared to complex fluid management issues. If the tank(s) on any future system were to implement a resistive heater, they could be temperature controlled to ensure consistent propellant tank pressure and to prevent condensation of the propellant where undesirable. Systems developed by the SSDL already have sensors in place to measure the pressure and temperature of the propellant tank and plenum, so no additional sensors would be necessary. The main disadvantage of implementing a temperature control system is increased power consumption. This will vary from system to system based on a number of factors and would have to be budgeted.

The cleanliness and charge build-up issues caused by the use of SOMOS PerFORM and the restrictive geometry of the additively manufactured propulsion systems developed by the SSDL are not easily solved without losses in other areas. One alternative is to continue to additively manufacture the propellant tanks, fluid routing components, and nozzles, but to move to a direct metal laser sintering (DMLS) process and a material such as aluminum. The processes for cleaning an aluminum part are well documented, and aluminum would not face the charge build-up issues associated with PerFORM. Manufacturing the propulsion system from aluminum would also allow for threaded components to directly interface with the printed structure, which would save space. This alternative would restrict the design freedom achieved by the materials currently used though. DMLS processes impose many design constraints that would need to be accounted for such as an inability to produce parts with large overhangs and a need to remove unused powder from the internal cavities in the part. Manufacturing parts using DMLS is also generally more expensive than SLA, which is undesirable, however, a quote for a 0.7U aluminum propulsion system printed structure indicates that the part may cost less than \$3000 in 2023. This quote includes the cost of all post-machining processes with the exception of the expanding section of the nozzle. Despite the possible downsides, systems with certain geometries could be well suited to a DMLS manufacturing process, and many missions would likely benefit from it.

Aluminum is not the only alternative material option. There is also the potential to manufacture the printed structure using a different material compatible with the SLA printing process. There are electrostatic discharge-safe materials that can be SLA printed. The larger issue is identifying the material compatibility and space safeness of the selected material. The chosen material would also have to be easily cleanable, though it is possible that a chemical post-treatment or a sealant coating could mitigate some of the cleaning concerns associated with these materials. Further investigation of these alternatives is warranted.

A final issue in need of resolution is propellant leakage. This problem has a number of root causes and will require a number of steps to solve. At the heart of most of the leaks observed in the SSDL and detected on other systems is an unreliable interface such as an o-ring or a fitting. A good general practice is to eliminate as many of these interfaces as possible. This could be done by welding metal components together or using custom components, such as a combined valve stem and filter. These are generally expensive solutions though. Another solution would be to improve the existing interfaces. The o-ring grooves on the systems designed by the SSDL are either printed or machined into the surface of the printed structure. Significantly improved surface finishes are achieved by machining these features rather than additively manufacturing them. There is a cost associated with post-machining, but it is likely a minor expense when compared to the rest of the system.

In order to mitigate leaks caused by thermal cycling of the system, a strain relief could be designed into the system. In current systems designed by the SSDL, the valves are attached to stainless steel manifolds at both their inlet and outlet, and these manifolds are attached to the printed structure of the system. When the propulsion system heats or cools, stresses are induced on the valves and their attachment points due to the difference in coefficients of thermal expansion between SOMOS PerFORM and the valve body material. One possible mitigation strategy is to place a right angle bend in the inlet and outlet valve stems similar to what is shown in Fig. 4. The stress could then be transferred into minor bending of these components rather than direct tension of the valves and their attachment hardware. This solution may make it challenging to efficiently position the valves within

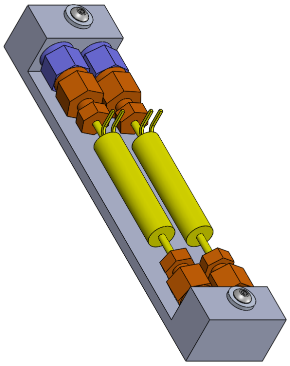


Figure 3 Single piece valve manifold concept for stress reduction.

the propulsion system, but it is a lightweight and low-cost solution. There are also some concerns about the effects of repeated bending stresses applied to the valve stem and body that warrant further study.

Another possible solution is to manufacture the valve manifold blocks out of a single piece of stainless steel rather than two separate blocks as shown in Fig. 3. This would allow for much of the stress to be imparted on the manifold, rather than the delicate valves. This would come at the cost of increased system mass and a minor increase in the volume of the manifold. It would, however, allow for the valves to be efficiently packaged and attached to the system.

A final, though likely more costly solution would be to implement a bellows system into the manifold. In such a system, one end of the valve would be rigidly attached to a manifold block, while the other would be connected to a piston, which fits into a cylinder on the other manifold block. A seal is formed between the piston and cylinder using o-rings. This solution would largely eliminate thermal stresses in the valves, but the tolerances required to achieve an effective seal may be challenging to attain while maintaining a relatively low cost.

IMPROVED SYSTEM CONCEPT

The improvements discussed above may each be beneficial on their own, but when combined, they form the foundation of a significantly improved CubeSat propulsion system. The proposed next generation of cold gas propulsion systems, entitled Georgia Tech Cold Gas 2 (GTCG2), will aim to maintain the low cost and complexity of the current generation of cold gas systems while implementing these improvements. An initial concept design is shown in Fig. 4, with the tank heater shown in red, PCB shown in green, valves shown in yellow, filters shown in purple, fittings shown in orange, and printed structure shown in blue. The propellant management device is not shown.

The GTCG2 concept will be composed of an additively manufactured propellant tank and main structure with integrated fluid routing components. This structure will be manufactured from aluminum in a DMLS process. While this choice may increase cost and complicate the design, it is deemed worthwhile because of the improved properties of the material. Nozzles and o-ring grooves will be post-machined into this structure along with all mounting interfaces. Ports for mounting sensors, fill ports, and valves will also be machined directly into the structure, eliminating the need for separate mounting plates used on previous systems and thereby conserving valuable space within

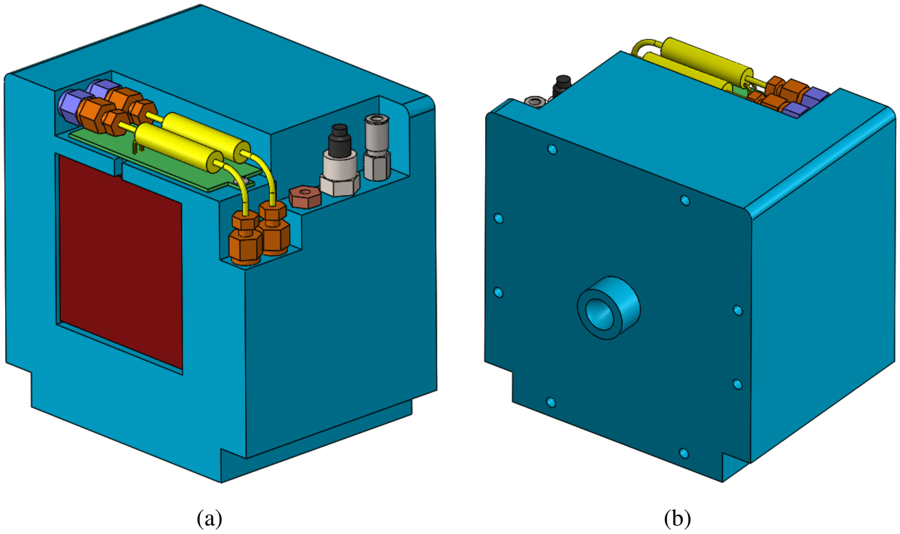

(a) (b)

Figure 4 GTCG2 concept design.

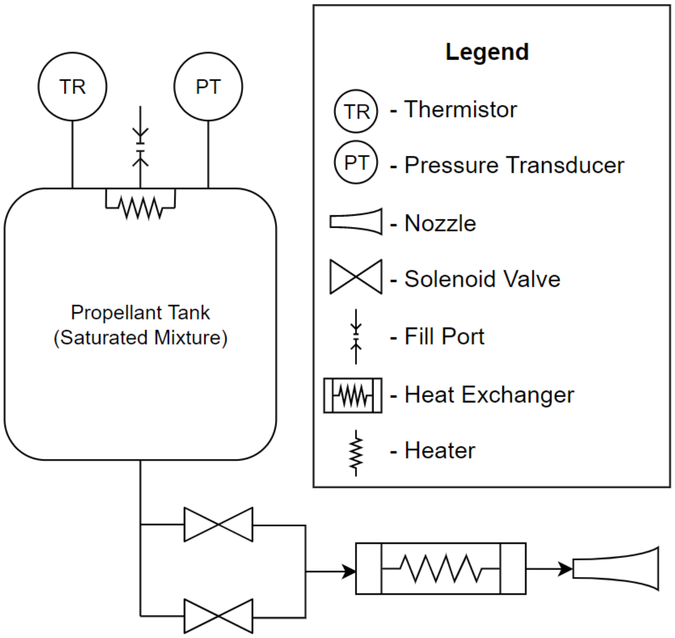
the system while decreasing the number of potential leak points.

The GTCG2 system will utilize a single propellant tank to contain its R-236fa propellant, rather than a main tank and plenum. This will improve the impulse density of the system significantly, especially when designing systems with a volume of less than 1U. In order to ensure the consistent delivery of pure vapor to the thruster nozzles, a number of fluid management devices will have to be tested. It is likely that the PMD chosen may be mission-specific, with single-nozzle ΔV systems requiring a less complex PMD than a multi-nozzle system, which will experience accelerations along multiple axes. Multiple propellant management devices are under consideration, with a primary focus on magnetic positive positioning devices and heat exchanger systems with incorporated capillary PMDs. Further investigation and testing will be required before making a selection. Fluid flow diagrams for the primary concepts are shown in Fig. 5.

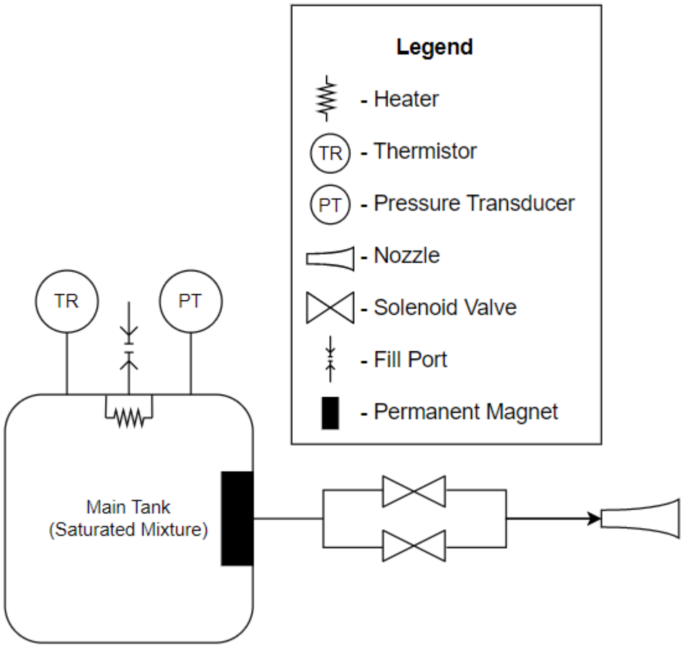
Regardless of which propellant management device is chosen, the new device will be designed to allow thrusters to fire indefinitely until all propellant is depleted. This will be a significant improvement over systems that must frequently cease firing in order to refill their plenum with vapor. This improvement will increase the effective average thrust of the system considerably while also allowing for a constant thrust to be provided during actuation.

In order to achieve the desired increase in repeatability of performance over past systems, GTCG2 will incorporate a heater into the propellant tank. This will allow the system to be maintained at a consistent temperature and therefore a consistent pressure during operations. Stable operating conditions will improve the repeatability of the impulses delivered by the system.

In an attempt to improve system reliability, the GTCG2 system will also aim to incorporate redundant thruster valves when permissible. These redundant valves will be configured in parallel and will mitigate the risk of a valve sticking. This addition comes as a result of a common trend of valve failures leading to reduced performance or total failure of small satellite propulsion systems, an example of which is the LunaH-Map CubeSat. This will be especially beneficial on systems that have a single thruster nozzle and would be rendered inoperable in the event of valve failure. This choice will double the number of thruster valves required by the propulsion system, but on systems



(a) Heat exchanger system concept



(b) MPP system concept

Figure 5 Improved system concept fluid flow diagrams.

with few valves and sufficient volume, it is likely worthwhile.

To reduce thermal stresses on the valves, they will be mounted with a single right angle bend in the outlet stem. This bend will allow the valve to flex during thermal expansion, rather than bearing the entirety of the stress in tension or compression. This choice decreases the efficiency with which the valves can be placed on the system, but it eliminates the need for separate manifold blocks and decreases the number of fluid interfaces. It is also lighter and cheaper than the other options considered.

Through the combination of the aforementioned design changes, the GTCG2 system will be capable of increased reliability and performance while maintaining the low cost and relative simplicity of heritage cold gas systems.

CONCLUSION

Cold gas propulsion systems have been demonstrated on modern CubeSats, but there are areas for improvement. As mission requirements become more stringent, a system with greater capabilities is needed. The GTCG2 system will allow for improved system performance without significant increases in complexity or cost. This new system is being designed with the goal of enabling consistent and predictable performance in a compact form factor. The completed technology will allow CubeSat propulsion systems to meet the requirements of more challenging formation flying missions.

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