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Application of 3D-Printing and Commercial Off-The-Shelf Components in the Design of a Micro-Propulsion System

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ABSTRACT

For the universities and private companies that have just been involved in the field of small satellites, it's not easy to develop a propulsion system without special test equipment, rich experience and commercially available astronautics grade components, especially in the countries where the astronautic components sales market has not been fully developed.

Accordingly, a micro propulsion system for small satellites is being developed, which contains welded tanks, a 3D-printed steam storage tank, heaters, solenoid valves and nozzles. HFC-134a is chosen to be the propellant because of its safety and accessibility. The steam storage tank and isolation solenoid valve nearby are used for pressure reducing, which avoids buying an astronautic grade pressure reducing valve from the market and make the propellant vaporized. Additive manufacturing is used to make special-shaped surfaces, reduce welding joints and the time of the steam storage tank production. In order to prevent the liquid propellant from entering the pipeline, the outlet of the propellant tank extends to the middle of the tank through a pipe. HFC-134a liquid will be infiltrated into aluminum alloy tank wall away from the outlet, which avoids the use of a Propellant Management Device (PMD).

A prototype of the system is being developed and tested. A simple thrust measurement method has been developed, and a large amount of experimental data has been obtained. The requirement, selection, design, prototype test and difficulties are reviewed in this paper, to provide a reference for the development of other propulsion systems.

INTRODUCTION

Micro propulsion systems installed on small satellites have a wide range of uses, including altitude control, orbit maneuvering and formation flying. Micro propulsion systems play important roles in many missions. In the Shenzhou-7 mission in 2008, a small satellite(BX-1) with an ammonia propulsion system began maneuvering at a distance of 480 km from the manned spacecraft, and eventually flew around the spacecraft with a semi-minor axis of 3.8km, which verified the role of micro propulsion systems in formation flying, rendezvous and docking[1].

However, universities and private companies in China usually find that the whole propulsion system, or some of the astronautics grade components are difficult to buy directly from the market. Even if some components can be obtained from the state-owned research institutions sometimes, the ability to develop complete propulsion systems independently is still necessary for cost control. Hence a propulsion system is proposed, which meets the following requirements:

- The operational principle should be simple enough, and the components and technology used should be commercially available, to allow the inexperienced customers to develop the propulsion system quickly.
- Similar systems meet the basic maneuvering requirements of small satellites(20-600kg), so the customers can develop a range of products based on the experience of the first system.
- If possible, the design, manufacture and test of the propulsion system should be performed by general manufacturers or the customers themselves, to reduce the difference earned by the special contractors and minimize the cost.

Cold gas propulsion system with propane propellant was used as the first propulsion system of Britain's X-series satellites[2], and SSTL still recommends several cold gas propulsion systems as main choices to small satellites today. Cold gas propulsion systems, using compressed gas or liquefied gas as propellant, are simple and reliable enough to meet these requirements, so this paper mainly talks about them.

The target mission in this paper is to perform the orbit and altitude control of 25kg-class satellites of a constellation in 600km LEO.

DELTA-V REQUIREMENT

When a constellation is launched to multiple planes and each plane is populated by the single launch of several small satellites, the satellites need to be distributed to desired positions in the orbit. This is accomplished by raising the apogee or lowing the perigee and then drifting around the orbit. When a satellite needs to drift to the position 180° relative to the original insertion position, the most delta V is needed, which can be estimated by these equations:

$$\frac{GMm}{r^2} = \omega^2 rm \qquad (1)$$

$$t = \frac{\pi}{\omega_0 - \omega_1} \qquad (2)$$

where ω_0 = initial orbital angular velocity, rad/s; ω_1 = drifting orbital angular velocity, rad/s. Figure 1 describes the delta V requirement of the constellation deployment in LEO in this situation.

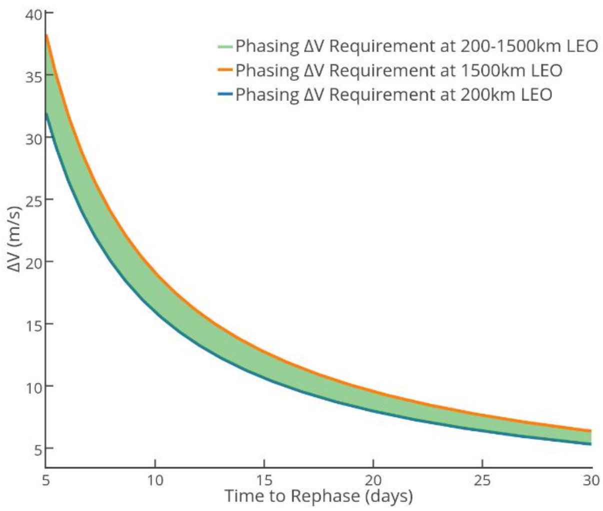

Figure 1: Delta V Requirement of Constellation Deployment

Atmospheric drag can be estimated as

$$f = \rho S v^2 \qquad (3)$$

where S = section area of satellite, m^2; ρ = atmospheric density, kg/m^3, according to the COSPAR International Reference Atmosphere 2012[3] (mean solar and geomagnetic activities). Figure 2 describes the delta V requirement of atmospheric drag compensation in LEO, where m = satellite mass, kg. For typical CubeSat the S/m value is around 0.0075, and the value will be larger if the solar panels are expanded.

The delta V that can be reached by a cold gas propulsion system is usually under 100m/s. This is able to meet the requirement of most short time missions, and the LEO missions whose altitudes are higher than 500km. More delta V requirement might be beyond the capability of a rapidly developed cold gas system. In this paper, the total delta V requirement is set as 35m/s.

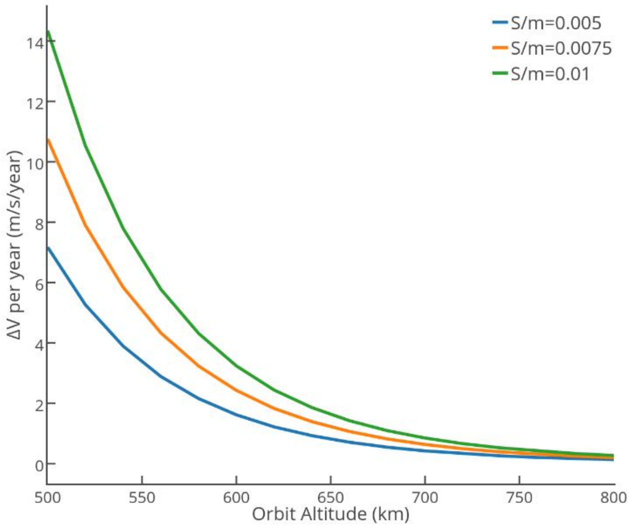

Figure 2: Delta V Requirement of Atmospheric Drag Compensation

PROPELLANT SELECTION

There are several kinds of propellants to be selected for a cold gas propulsion system, which can be classified as compressed gas and liquefied gas. The equation used to calculate the thrust of the system is

$$F = p_1 A_{\min} \sqrt{\frac{2k^2}{k-1}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}\left[1-\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}}\right]} + A_2\left(p_2 - p_b\right) \qquad (4)$$

Where p_1, p_2 and p_b are the inlet, outlet and environment pressure (Pa) of the nozzle; A_{min} = nozzle throat area (m^3) and k = specific heat ratio. The specific impulse is given by

$$I_{sp} = \sqrt{\frac{2k}{k-1} R_g T_1 \left[1-\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}}\right]} + \frac{A_2}{m}\left(p_2 - p_b\right) \qquad (5)$$

Where T_1 = nozzle inlet temperature, K; m = mass flow rate (kg/s) which can be calculated by

$$m = \sqrt{k}\left(\frac{2}{k+1}\right)^{\frac{k+1}{2(k-1)}} \frac{p_1 A_{\min}}{\sqrt{R_g T_1}} \tag{6}$$

The ratio between A_{min} and nozzle outlet area A_2 is set as 130, and the equation is

$$\frac{A_2}{A_{\min}} = \frac{\left(\frac{2}{k+1}\right)^{\frac{1}{k-1}} \sqrt{\frac{k-1}{k+1}}}{\sqrt{\left(\frac{p_2}{p_1}\right)^{\frac{2}{k}} - \left(\frac{p_2}{p_1}\right)^{\frac{k+1}{k}}}} \tag{7}$$

The propellant mass can be calculated by

$$m_{p0} = \left(e^{\frac{\Delta V}{I_{sp} g_0}} - 1 \right) m_{sat} \tag{8}$$

Where m_{sat} is the dry mass of the small satellite (25kg) and the delta V under the target mission is 35m/s.

Volume, mass and vaporization heat of several kinds of commonly used propellants are given in Table 1, in which the temperature and the nozzle inlet pressure are assumed to be 20°C and 0.1MPa.

Table 1: System Need of Propellants under the Target Mission Requirement

Propellant	Pressure (MPa)	Volume (L)	Mass (kg)	Vaporization Heat (kJ/kg)
Nitrogen	30	3.9	1.2	-
Xenon	30	1.3	3.1	-
Propane	0.84	2.3	1.2	344.3
Butane	0.2	2.2	1.3	367.0
Ammonia	0.86	1.4	0.9	527.4
HFC-134a	0.57	1.4	1.8	182.2
HFC-236fa	0.23	1.5	2.1	148.1

The propulsion system using HFC-134a as propellant needs smaller size, less heating power but more weight. On the other hand, the safety and accessibility of HFC-134a are both attractive for university missions[4] and commercial products[5].

However, HFC-134a has been reported to have greater thrust losses (about 38%) in nozzles[6], and the same problem exists in other Freon propellants[7]. So more experiments on HFC-134a are needed. Although HFC-134a is selected in this paper, the replacement of propellant is easy to perform in a cold gas propulsion system.

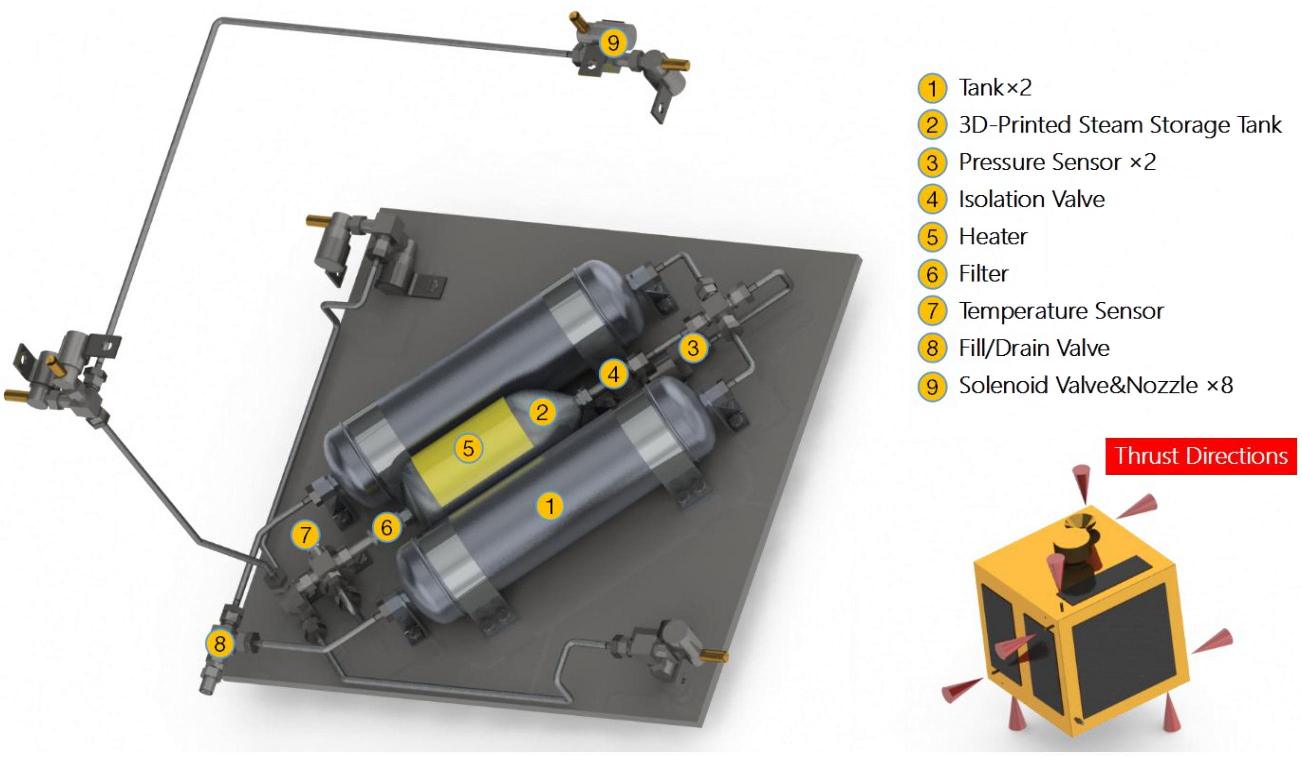

Figure 3: Propulsion System Layout

SYSTEM DESCRIPTION

Welded Tanks with Novel Gas Extraction Method

Similar to other cold gas propulsion systems, the propellant is ejected from the nozzle and produces thrust, depending on its own pressure. Figure 3 shows the layout of the propulsion system.

When liquefied gas propellant is selected in the mission, there are two issues to consider: slosh control and aiding the extraction of the liquid propellant. Traditional way to solve these issues, as shown in Figure 4, is to install Propellant Management Device (PMD) in the tank, such as sponge and vanes.

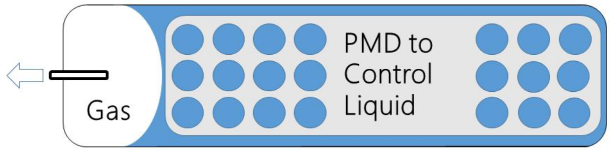

Figure 4: Traditional PMD Installed in Liquefied Gas Propulsion System

However, developers of the propulsion system in universities and some private companies may find:

- Few COTS tanks with PMD. Existing tanks are either too bulky or designed for avoiding the extraction of the gas propellant, rather than the liquid propellant, especially in the countries where the astronautic components sales market has not been fully developed.

- Propellant tanks, usually as the components take most volume in the propulsion system, will affect the general layout and the schedule of other subsystems significantly. So the tank should be designed in a simple way to minimize developing time.

Accordingly, a simple gas extraction method is proposed in this paper, as shown in Figure 5.

Different from traditional PMD, the simplified design utilizes the wall of the propellant tank to control the liquid. Because of the good infiltration between the HFC-134a liquid and the aluminum alloy[8,9], the surface tension will drive the liquid to expand along the wall under micro gravity condition. Finally the gas propellant will be wrapped in the center of the tank, where the balance with minimum energy is achieved. Thus a pipe extended to the middle of the slender propellant tank can extract gas propellant from it, reducing the extraction of liquid at the same time. The theory of two-phase interface deformation in slender tanks has been validated by both experiments in the National Micro-gravity Laboratory of China[10] and tests in the Shenzhou-7 mission (BX-1).

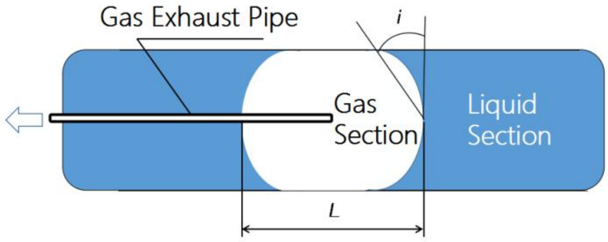

Figure 5: Gas Extraction Method in Slender Cylindrical Tank

Excess capacity is needed to form the gas section in the tank. The Bond number can be calculated by

$$B_N = \frac{\Delta\rho a R^2}{\sigma} \tag{9}$$

Where R = radius of cylindrical tank, m; σ = surface tension, N/m; $\Delta\rho$ = difference in density of the two phases, kg/m^3; a = acceleration, m/s^2. The Bond number can be used for comparison with the charts in Ref.11, to estimate the liquid surface inclination angle i in Figure 5. The excess capacity is estimated by

$$\mathrm{V} = \frac{2}{3}\pi \mathrm{R}^2 \cdot R\tan i + \pi R^2(L - 2R\tan i) = \pi R^2(L - \frac{4}{3}R\tan i) \tag{10}$$

Where L = length of the gas section as shown in Figure 5. When the radius of tank is smaller, the required excess capacity will be smaller. In this system, the diameter, length, maximum acceleration, capacity of the propellant tanks and propellant volume(20ºC) is 72mm, 287mm, 0.013m/s^2, 2.44L and 1.87L, so 23% of the total capacity can be left to form the gas section whose L = 104mm. In fact, excess capacity is also needed in a tank with PMD, to ensure slosh control effect and avoid the pressure becoming too high when temperature increases. A recommended value of a tank with PMD is 13% of the total capacity in the MR-SAT mission[12].

The gas exhaust pipe could be easily welded with the tank, so a tank with PMD could be replaced to some extent. However, this method is only suitable for slender cylindrical tanks when the slosh control requirement isn't strict. The calculations above doesn't show whether the gas region will keep its shape when the liquid boils, so more tests are needed.

Evaporation of Residual Liquid & Pressure Reducing

Pressure reducing valves and electronic proportional valves are widely used in cold gas propulsion systems, because a lower nozzle inlet pressure corresponds to a smaller thrust and more accurate attitude control. However, astronautics pressure reducing valves are also difficult to buy directly from the market sometimes. So a steam storage tank is used to achieve the same function. Similar principle is also used in the Giove-A satellite[13] of SSTL.

As shown in Figure 6, the isolation valve opens and closes under a certain cycle (for example, opening for 70ms and then closing for 1000ms). Because the opening time of the isolation valve is shorter than the closing time, the pressure in the steam storage tank can't be as high as the pressure in the propellant tank and the pressure reducing is achieved. A simple control loop can also be achieved. When the pressure is higher than the set value, the opening time in a cycle will be reduced or increased in the opposite case.

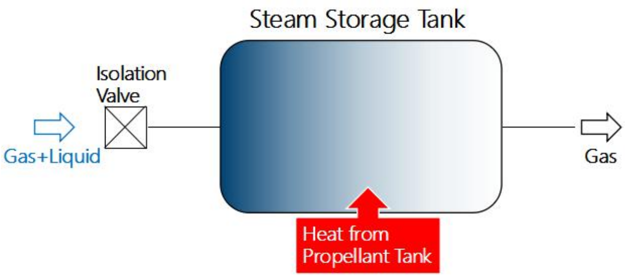

Figure 6: Operational Principle of the Steam Storage Tank

There's another benefit to this layout: if the residual liquid propellant gets into the steam storage tank from the propellant tank, it will evaporate at a lower pressure, resulting in decreasing of temperature in the steam storage tank. Then the outer surface of the steam storage tank contacting with the propellant tank will provide heat for continuous vaporization of residual liquid. The same "contacting to provide heat" principle is also used in Britain's X-4 satellite[2] and the similar propulsion system[14] developed by Beijing University of Aeronautics and Astronautics (BUAA).

Tests of this method have been performed on the prototype system, as shown in the rest of this paper.

Commercial Off-The-Shelf Valves

The vacuum environment and dramatically changing temperatures are both challenges to the reliability of the valves. For a cold gas propulsion system using liquefied gas propellant (HEC-134a), the evaporation of the propellant may cause a sharp drop in valve temperature and a sharp rise in pressure, which is dangerous to some valves whose tolerance to pressure and temperature is not strong.

Table 2: Valve Specially Designed for Cold Gas Propulsion vs COTS Valves

	Special Valves Used in Former BUAA's System[14]	GEMS-GH2012	GEMS-A2011
Mass(g)	33.5[15]	75	125.5
Envelope(mm³)	Φ18×20	Φ22×45	Φ26×50
Power(W)	—	2	6
Different Turn-On and Holding Voltage	√	×	×
Integrated Nozzle	√	×	×

On the other hand, COTS valves are usually designed for general uses, which don't have strict constraints on mass, volume, power and response time. Table 2 shows the difference between special astronautics valves and COTS valves, and the different turn-on and holding time is usually to reduce the response time of valves.

However, if the mass and power constraints are not strict, COTS valves are also acceptable in a propulsion system. At present, propulsion systems developed by other universities in China are also using COTS valves[16], and additional valve heating measures are sometimes necessary.

3D-PRINTED TANK: BENEFITS AND LIMITS

Additive Manufacturing has been used for tank production in several researches[17], including large titanium alloy tanks by Sciaky Inc. and tanks for CubeSats by Aerojet[18]. But in this paper, only commercially available manufacturing service is considered. There are several advantages of additive manufactured tanks for universities and private companies:

- Simplified design, manufacturing and testing process without welding and nondestructive testing. Customers may make it by themselves.
- Greatly reduce production time of tanks.

As an attempt, the steam storage tank was chosen as the 3D-printed component in this system because it does not normally require direct contact with the propellant liquid. Special-shape contact surfaces with the tank are designed to enhance the heat transfer between them and vaporize the residual liquid in the steam storage tank. The manufacturing is carried out on the EOSINT M280 commercial printer and the material is EOS Aluminum AlSi10Mg. Table 3 shows the comparison between traditional manufacturing and commercial additive manufacturing service (Selective Laser Melting, SLM) provided by the manufacturer (EJDY.Corp). Figure 7 shows the simple reinforcement design in the steam storage tank because of the application of additive manufacturing.

Table 3: Commercial Additive Manufacturing and Traditional Manufacturing on the Steam Tank

	Commercial Additive Manufacturing(SLM)	Traditional Tank Manufacturing
Material	EOS AlSi10Mg[19]	Aluminum 5083
Yield Strength (Rp0.2)	230MPa	110MPa
Elongation at Break	11%	12%
Smallest Wall Thickness	0.4mm	1mm (for low cost process[20])
Envelops Constrain	250×250×325mm (EOS M280[21])	None
Price for Steam Tank Production	¥12600	Vary by manufacturers
Time for Steam Tank Production	8 days	Months
Simple Reinforcement Design	√	×
Special Shape Manufacture	Easy	Hard
Welds Nondestructive Testing	Not need	Need

There are still some limitations in commercial additive manufacturing. For example, if the inclination angle of the structure is too large, supporting structure will be needed. The max inclination angle α recommended by the manufacturer is 48°. As shown in Figure 8, two ends of the steam storage tank are designed to have different inclinations, to avoid adding support inside the tank.

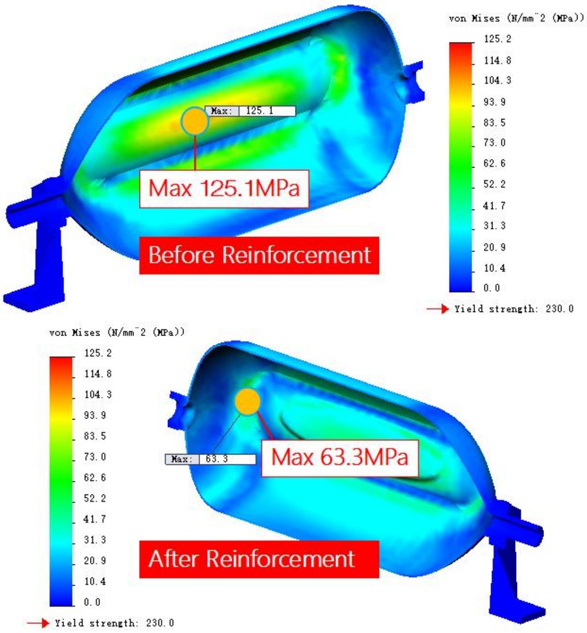

Figure 7: Simple Reinforcement Design

Figure 8: 1:1 Profile Model of the Steam Storage Tank in a Fused Deposition Modeling (FDM) Printer

On the other hand, the bottom of the tank which attaches the support should be properly thickened, otherwise the bottom may be broken when cutting the support from it. Smaller aluminum tanks with thickness of 1.5mm have been manufactured firstly. The first tank was destroyed during the removal of the support but the second was manufactured successfully and completed a stress test under 1MPa, as shown in Figure 9 and 10.

Although the simulation showed that the maximum value of Von Mises stress of the small tank(11MPa) under the 1MPa gas pressure was far less than the yield stress of the material(230MPa), strain hardening was still observed during the experiment. So more tests are still needed to be performed on commercial additive manufactured tanks.

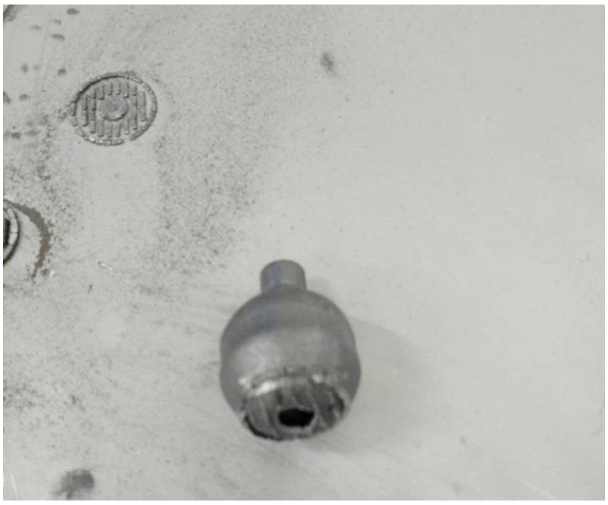

Figure 9: Destroyed Additive Manufactured Tank after the Removal of the Support

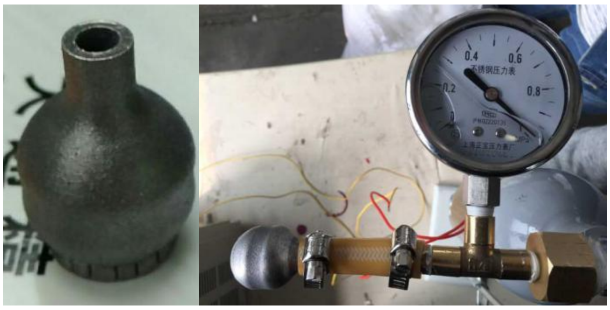

Figure 10: Second Tank for Stress Validation

PROTOTYPE PERFORMANCE

Simply Equipped Measurement of Thrust

BUAA has made several kinds of thrust stand[22] to measures micro thrust, but for mN-level thrust measurement of liquefied gas propulsion systems, a simple method of thrust measurement without any specially designed structure is recommended in this paper.

With the development of sensor technology, commercially available electronic scale has reached 30kg range and 0.1g resolution with a very low price (¥185, for example). At the same time, the mass of most of liquefied gas propulsion systems (or the whole satellite sometimes) is lower than 30kg. So the whole propulsion system, including tank, pipe, sensor and valves can be placed on the electronic scale to measure the thrust. Photograph of the experimental prototype and typical readings changing process during a thrust are shown in Figure 11 and 12.

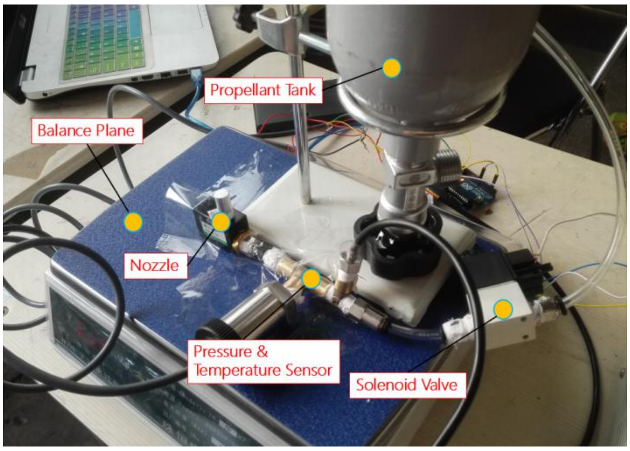

Figure 11: Photograph of Experimental Prototype

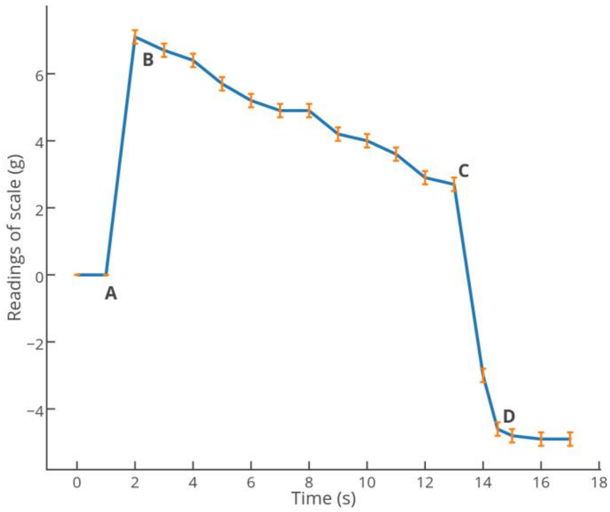

Figure 12: Typical Changes of the Scale Readings during a Thrust

The reading was set zero before measurement, and the difference between A and B or C and D can both be considered as the thrust value. The uncertainty is ±1mN. Figure 13 shows the measurement results at the atmospheric pressure.

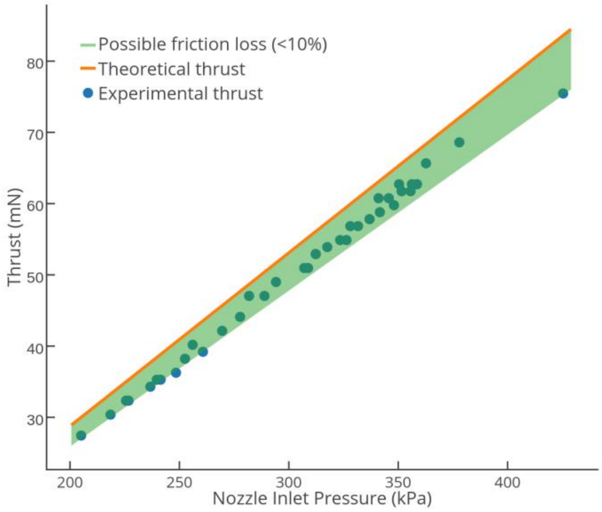

Figure 13: Thrust Measurement Results

Pressure Reducing Performance

The capacity of the steam storage tank is 0.53L, so a cylinder with similar capacity (0.51L) was used to validate the feasibility of the design. The pressure in the 0.51L tank was set at 250kPa at first and then changed to 200kPa, and the pressure in the propellant tank was around 340kPa. The closing time of the isolation valve was a constant value of 1000ms while the opening time would change according to pressure in the tank. Figure 14 shows the experiment results.

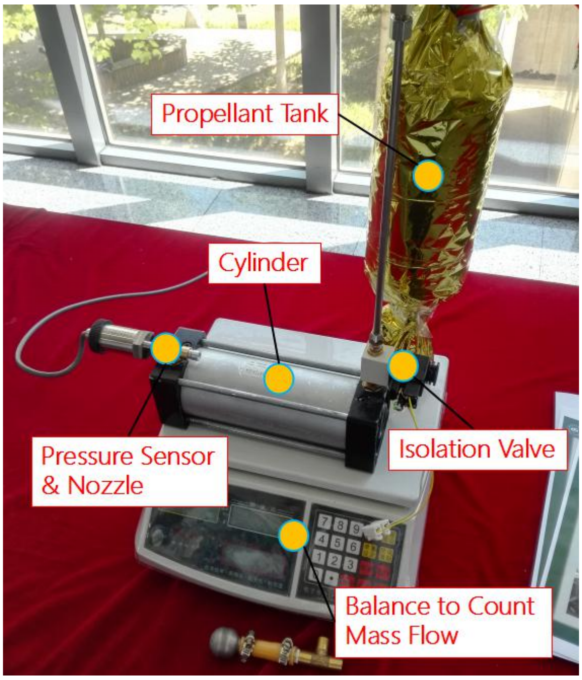

Figure 15: Pressure Reducing Test Setup

Endurance Test

To determine the total firing time of the propulsion system before the pressure in the propellant tank drops too low, the endurance test has been performed. Theoretical pressure drop can be calculated by

$$Lmdt + [C_p(m_{p0} - mt) + C_t m_t]dT = Qdt \tag{11}$$

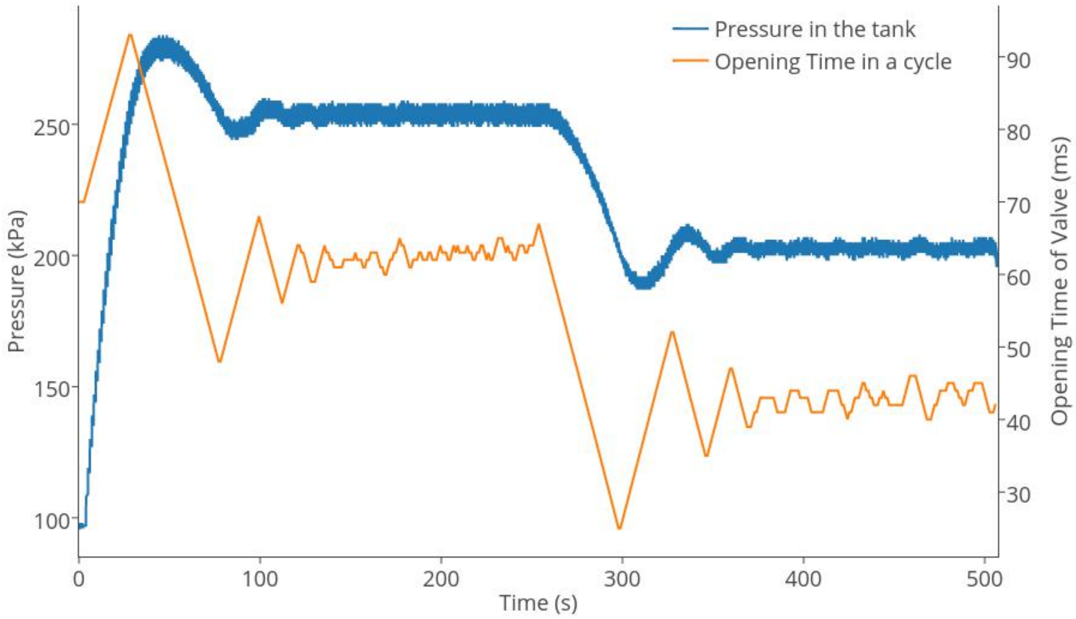

Figure 14: Pressure Reducing Experiment Result

Where L = vaporization heat, J/kg; C_p = specific heat at constant pressure; Q = heating power, W; and m, m_{p0} and m_t are the mass flow, initial propellant mass and tank mass. The theoretical and experimental values are shown in Figure 16.

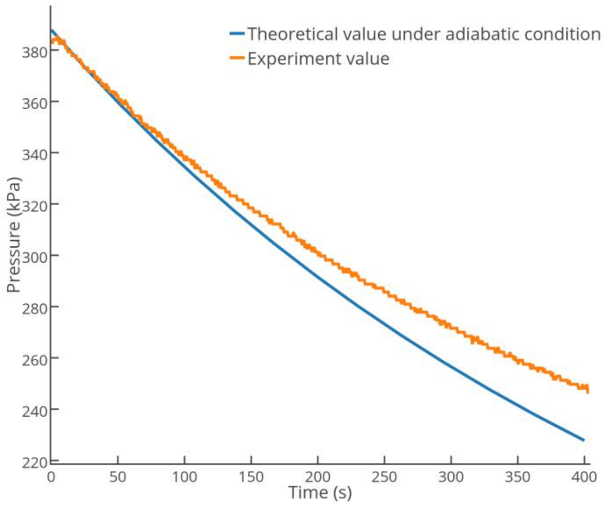

Figure 16: Endurance Test Result

SUMMARY AND PROSPECT

There are still many problems in the development of a micro propulsion system which are not involved in this paper, including sealing, choke and friction in the nozzle. However, simple gas extraction, pressure reducing and thrust measuring methods have been primarily validated that can solve the problems caused by lacking of astronautics grade components. And additive manufacturing is also helpful to reduce costs and production time.

Relying through their own efforts, more Chinese universities and private companies will enter the field of small satellites in the next 10 years. After they make the first propulsion systems by simple means, more work, including the development of both of their own teams and components, needs to be taken into consideration.

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