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A new prototype of self-pressurizing fuel tank for micro and nano-satellites

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Abstract

To increase effective load, light-weight micro-propulsion system is necessary for micro-satellites. Traditional propulsion systems including large and heavy high-pressure vessels are difficult to be scaled down to fulfill the demand of micro-satellites. In this article, a novel self-pressurizing fuel tank without high-pressure gas vessel is proposed. When some liquid propellant is consumed, pressure is compensated with CO_2 released by heating NH_4HCO_3 powder in the fuel tank. Comparing with other types of self-pressurizing liquid fuel tank, a gas generator with special and simple structure was designed to stop or continue the NH_4HCO_3 decomposition reaction easily, and consumed a small amount of energy to heat the powder effectively. Performance tests showed that this new prototype is very suitable for micro-thrusters.

Keywords: Micro-propulsion system; Micro-satellite; Self-pressurizing; Liquid fuel tank

1. Introduction

Under the trend of space management strategy of "faster, better, cheaper", micro and nano-satellites have been severely investigated by space specialists in recent years. A compendium of small and micro-satellite launches by SSTL concluded that over 14 micro-satellites have been launched on average in each of the past 12 years. Micro and nano-satellites are being used to fulfill commercial, military, remote sensing, and science missions as well, even to achieve successful, high-value missions at lower overall cost and lower risk.

Micro or nano-satellites with propulsion and attitude control system can be used in formation flying, which embody a multitude of form and achieve a variety of objective: providing redundancy in case of failure, increasing capacity with more similar micro or nano-satellites, extending spatial coverage, overlapping service regions to produce enhanced products such as stereo or super-resolved images, etc. [1]

The volume and mass of micro or nano-satellites are strictly confined. While most of the electronic components and others such as micro-thrusters and valves can be downscaled by MEMS technology correspondingly, propulsion system, however, cannot be downscaled easily as other counterparts of satellites. In addition, the weight of fuel tank usually takes a significant fraction of a micro or nano-satellite, about 30%. Therefore, it is critical for a small spacecraft to equip with a light-weight fuel tank.

Traditional fuel tanks for large satellites include high pressure gas bottles such as nitrogen or helium. Because

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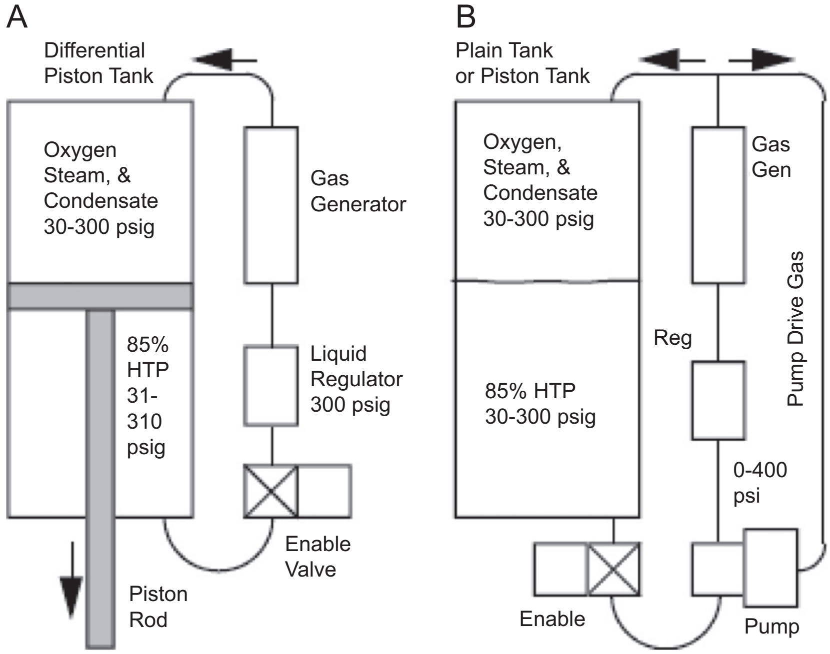


Fig. 1. A kind of self-pressurizing liquid tanks [2].

of high pressure, the wall of the bottle is thick, and thus the weight of it. Furthermore, a relief valve, which is hard to be micro-miniaturized, is needed to relieve pressure to fuel tank. In a word, it is difficult to downscale a traditional propulsion system to fulfill the need of a micro or nano-satellite.

For satellites using liquid fuel, such as high test peroxide, or hydrazine, a kind of self-pressurizing propulsion system without gas storage vessels was proposed [2] by Whitehead et al. As shown in Fig. 1, a pump boosts the pressure of a small fraction of the hydrogen peroxide, so that reacted propellant can controllably pressurize its own source tank.

This kind of self-pressurizing fuel tanks gets rid of the large and heavy gas vessel. Maybe it is a good choice for small satellites but for micro or nano-satellites, it is too complex to micro-miniature further, because it needs a piston, a pump and valve to control the system.

SSTL has fabricated several kinds of propulsion system for micro or nano-satellites, such as micro-satellite gas propulsion system and SNAP-1 propulsion system, etc. Micro-satellite gas propulsion system comprises four cool gas generators. These have the capability to re-fill the tank with a certain amount of gaseous nitrogen at near ambient temperature. The nitrogen is generated from a Sodium azide based solid charge which generates the nitrogen when pyrotechnically initiated on demand. For SNAP-1 propulsion system, butane propellant is stored in a liquid state. It forms a self pressurizing system, which means no regulation system is required. The liquid is vaporized, then fed to the central thruster. The two kinds of propulsion system can self-pressurizing itself, but both of them use gas as propellant directly. Comparing with liquid chemical fuel, such as HTP or hydrazine, this gas cannot release any chemical energy to improve specific impulse.

In this article, a new prototype of self-pressurizing liquid fuel tank is proposed. Pressurant gas is "stored" as solid powder in the tank. When some liquid fuel is consumed and pressure drops in the tank, the solid powder will be heated and release some appropriate amount of gas to turn pressure back to a given level. Therefore the fuel tank can keep a stable pressure during its life time.

2. Choose of the solid chemical powder

To benefit micro-satellites, the ideal chemical powder should be of characteristics as followed:

(a) High ratio of releasing gas volume to chemical powder mass;
(b) Gas releasing reaction must be easily controlled, that is, the reaction can be easily started or stopped on demand;
(c) Gas releasing reaction must consume little energy;

(d) The chemical powder must be stable during a micro-satellite's life time.

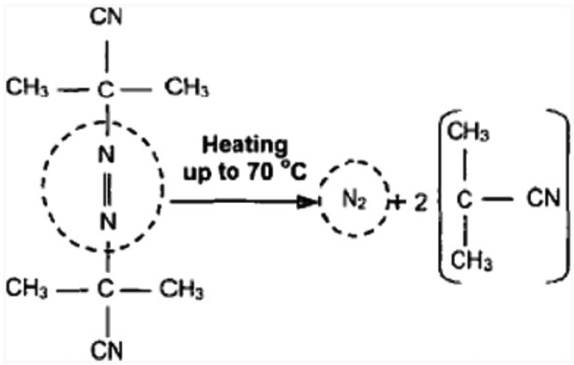
To select appropriate chemical powder, we have investigated several kinds of candidates:

(1) Sodium acid carbonate

$$2NaHCO_3 \xrightarrow{heat} Na_2CO_3 + H_2O + CO_2 \uparrow$$

$NaHCO_3$ will decompose at about 180 °C. 1 g $NaHCO_3$ releases 5.95×10^{-3} mol CO_2. Its products include solid residue Na_2CO_3 which cannot be separated from remainder reactant when reaction is stopped contemporarily.

(2) 2,2′-Azobisisobutyronitrile [3]



2,2′-Azobisisobutyronitrile will decompose at about 70 °C. Thus a little energy is needed to start the chemical decomposition reaction. 1 g of it releases 5.95×10^{-3} mol N_2. But it is a radical reaction. Once the reaction start, it may explode severely and cannot be stopped.

(3) Sodium azide

$$2NaN_3 \rightarrow 2Na + 3N_2 \uparrow$$

Sodium azide must be ignited in high temperature to decompose. 1 g of it releases 23.07×10^{-3} mol N_2, a value much more than that of the two above. But similar with 2,2′-Azobisisobutyronitrile, it will explode and cannot stop easily. Further more, it is very toxic in the aquatic environment.

(4) Ammonium acid carbonate

$$NH_4HCO_3 \xrightarrow{heat} NH_3 \uparrow + H_2O + CO_2 \uparrow$$

NH_4HCO_3 decomposes at about 80 °C. 1 g NH_4HCO_3 releases 12.66×10^{-3} mol CO_2 and NH_3. This chemical decomposition reaction is mild and easy to be controlled with appropriate temperature. No solid residue is produced, then when reaction is stopped, the remainder powder is still pure, which is greatly convenient for us to design a simple reactor to control the reaction continuously. But NH_4HCO_3 also has its imperfect points that water is produced when decomposition and both NH_3 and NH_4HCO_3 are soluble. Then water may wet the remainder solid powder, which will cause more heat to be consumed when heating next time. Furthermore, whether NH_4HCO_3 is stable or not for a long period in the wet condition is unclear. Maybe desiccant should be added for a successful propulsion system using NH_4HCO_3 as pressurizing source.

Comparing the four kinds of chemical powder above, we consider that NH_4HCO_3 is the best choice of them because it consumes less energy to decompose, it decomposes mildly and no solid residue is left in its products. Based on these features of NH_4HCO_3, we design a self-pressurizing fuel tank with relative simple structure.

3. Structure of the new prototype of the self-pressurizing fuel tank

Fig. 2 shows the system components of the new prototype. This new prototype includes four primary parts: the vessel, the gas generator; the pressure sensor, and the pressure controller. When some of the liquid fuel in vessel is consumed, pressure drop in the vessel is sensed by the pressure sensor. Then the pressure dropping signal is transmitted into the pressure controller which controls the gas generator to heat chemical powder to release gas. Then the pressure rise again. When gas generator produces too much gas and pressure is higher than a certain value preset. Pressure controller shut down the power supply to the gas generator to stop heating the chemical powder. By this method, the vessel will sustain a certain pressure.

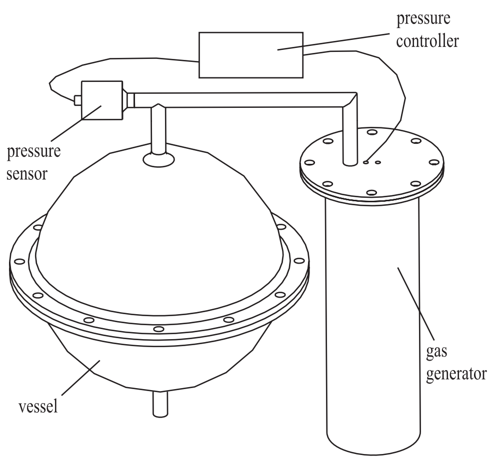


Fig. 2. System schematic of the self-pressurizing fuel tank.

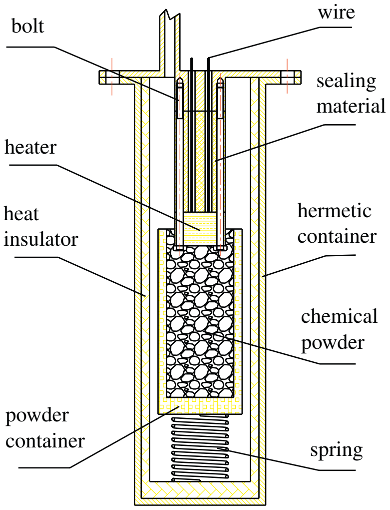


Fig. 3. Structure of the gas generator.

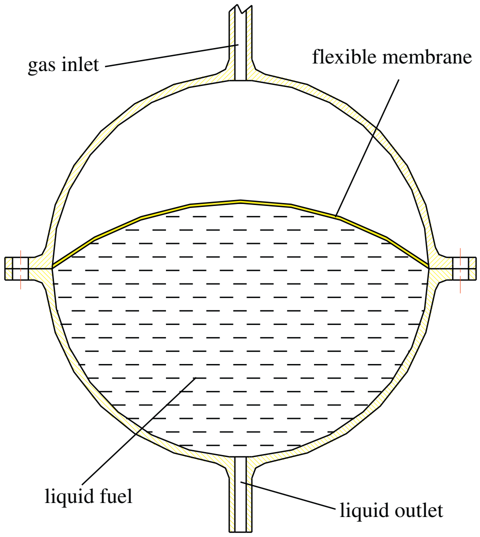


Fig. 4. Structure of the vessel.

Fig. 3 shows that a spring is used to lift the powder container up to keep the remainder powder contacting with the heater tightly. It is important to assure that the remainder powder always sticks to the surface of the heater, otherwise it will consume more heat energy to start the decomposition reaction and waste precious energy in micro-satellites. Because NH_4HCO_3 purchased in the market is very soft, it should be squeezed tightly when being filled in the container. Then powder container will hold more powder, and tight powder prevents the heater from miring down in powder under the spring force.

The heater is placed in the hermetic container. Wires supplying power to the heater have to cross the wall of the container but must keep the container from leaking. Therefore, a special structure must be adopted to fulfill this function: a piece of material, such as Teflon, which serves as both heat insulator and sealing material is set between the heater and the top of the container. A long screw bolt is used to connect and clamp the heater, sealing material and the cap of the container to keep hermetic. Convex part of the cap of the container is used to fabricate dead hole for the bolt, otherwise through hole may lead to leaking.

Inside the container a layer of heat insulator is set to prevent too much heat form diffusing out of the container. NH_4HCO_3 is slightly volatile when it is heated. After this new prototype running for a while, a little NH_4HCO_3 condenses on the surface of the heat insulator. So a gap must be left between the heat insulator and the powder container to ensure the latter moving smoothly.

The vessel containing liquid fuel can be a ball with a flexible membrane to separate gas and liquid phase as showed in Fig. 4 or a propellant management device of surface tension tanks.

In this experiment, pressure sensor and pressure controller are Setra pressure transmitter C206 and RKC CD901, respectively. But they are too bulky for nano-satellites, and could be replaced by smaller device such as MEMS silicon chip pressure sensor and other micro-electronic devices or on-board computer to make the propulsion system smaller and more compact. Other components such as heater, hermetic container, insulator, powder container, and spring etc. also can be reduced further.

4. Performance test of the self-pressurizing fuel tank

Performance of the new prototype was tested by pressurizing the fuel tank at first, and water in the tank being drained in a certain mass flow rate. As showed in Fig. 5, pressure keeps static when water in the tank is being drained. The smaller the mass flow rate, the more stable the pressure. As showed in Fig. 6, the temperature of mass flow rate = 0.0421 g/s, pressure = 3.92 bar raises more quickly and higher than that of mass flow rate = 0.0082 g/s, pressure = 3.41 bar because the former need more gas to compensate the pressure dropping. Higher temperature causes faster reaction rate.

Lots of micro-thrusters' mass flow rates reported in literatures is much lower than that we have tested in the experiment. That is, the new prototype will be

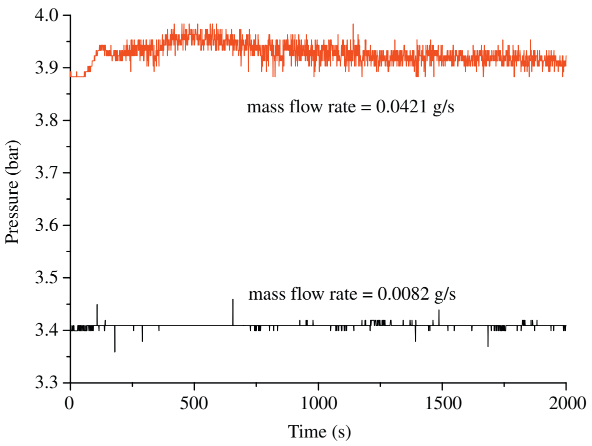


Fig. 5. Pressure profile in the performance testing of the prototype.

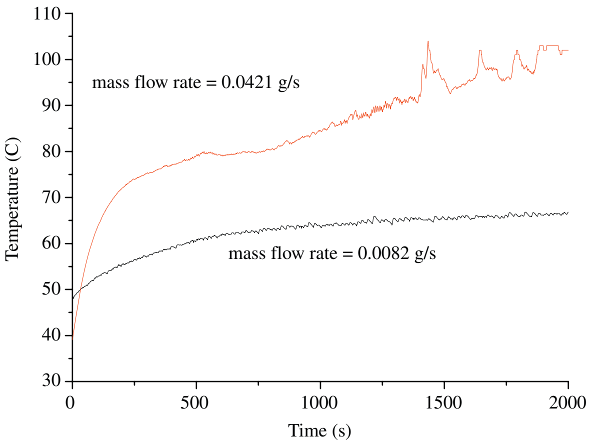


Fig. 6. Temperature profile in the performance testing of the prototype.

successful to supply liquid fuel to these thrusters. For example, Maurya et al. [4] reported a silicon MEMS vaporizing liquid micro-thruster (VLM). The VLM produce thrusts in the range of 5–12 μN at a water flow rate of 1.5 μl/s. A maximum thrust of 120 N was produced with a heater power of 2 w at water flow rate of 0.7 μl/s. Hitt et al. [5] investigated a MEMS-based hydrogen peroxide micro-propulsion with a mass flow rate of 390 μg/s. Ye et al. [6] test a vaporizing water micro-thruster with mass flow rate less than 0.04 mg/s.

5. Advantages of this new prototype for micro and nano-satellites

Compared with traditional fuel tanks which adopt high pressure nitrogen or helium tank as pressure source, and other kinds of self-pressurizing fuel tank, this new prototype has many advantages suitable for micro or nano-satellites.

(1) Pressurizing gas is "stored" in solid chemical powder. Its volume is much smaller than equivalent high pressure gas. Then the propulsion system can reduce its size greatly.
(2) It need not a heavy, bulky high-pressure bottle like traditional propulsion system. Therefore the weigh of it is reduced greatly.
(3) Since the high-pressure bottle is not necessary, and consequently a pressure-relief valve is not needed. Then more weight is reduced.
(4) No extremely initial high-pressure exit in this new prototype of self-pressurizing fuel tank. Therefore the wall thickness of the vessel is reduced.
(5) The same reason as (4) makes leakage relieved.
(6) The structure of the new prototype is relative simple, and it could be downscaled even into a silicon chip with MEMS technology to fit for pico-satellite.

6. Conclusion

A new prototype of self-pressurizing liquid fuel tank for micro-satellite is proposed in this article. When liquid fuel is consumed and pressure in the fuel tank drops, chemical powder in this system is heated and decomposed to release gas. Then pressure rise to a designated point again. A special structure of reactor should be designed to make it convenient to control the decomposition rate, start or stop. Compared with traditional fuel tank, this new prototype has many advantages for micro-satellites: no heavy high-pressure vessel and relief valve are needed; leakage was reduced; it can be scaled down to very small one. Experiments showed that within the flow rate of mN or μN micro-thrusters, this prototype can keep pressure of the tank very stable. Smaller satellite will make this new prototype better performance.

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