A Performance Comparison of Solid Propellants in Surface Arc Thruster: Sulfur and Teflon

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A coaxial-type electrothermal Surface Arc Thruster (SAT) was prototyped and preliminary experimental results were reported in a previous paper. The aim of creating a thruster that can be mounted on small satellites was achieved, but propellant charring has been deteriorating its performance. The standard propellant, polytetrafluoroethylene (PTFE), contains carbon which contributes to carbonization. Consequently, a non-carbon sulfur propellant was proposed to overcome the charring phenomenon. In this paper, we experimented using solidified sulfur propellant, powdered sulfur propellant and PTFE. First, charring intensity on each propellant surface was experimentally investigated. Powdered sulfur propellant experienced the least intensity of charring in comparison with both solidified sulfur and PTFE. Second, we measured the delta pressure in the vacuum chamber, investigated the relationship between delta pressure and discharge time, and conducted a performance comparison of all propellants. It was shown that solid sulfur produced the maximum average pressure increase (1.9×10^{-3} Pa) in the vacuum chamber, whereas PTFE produced the minimum average delta pressure (0.43×10^{-3} Pa). Regardless of whether the propellant was sulfur or PTFE, delta pressure in the vacuum chamber gradually decreased as the shot numbers increased. It was also shown that the longest discharge caused the highest delta pressure in the vacuum chamber. Results suggest that charring may also be due to thermal decomposition (pyrolysis).

Nomenclature

C	= capacitance of a capacitor
E	= energy stored in capacitor
F	= axial thrust for the coaxial configuration
I	= current in the loop
Δp	= pressure increase in the vacuum chamber
r_i	= inner radius of SAT
r_o	= outer radius of SAT
μ_0	= vacuum permeability $= 4\pi \times 10^{-7} N/A^2$
V	= capacitor voltage

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I. Introduction

The development of small satellites has skyrocketed in the past decades. For instance, eighteen CubeSats have been developed and launched by Kyushu Institute of Technology (Kyutech) between May 5th, 2012 and June 17th, 2019. As the value of power limited CubeSats improves, the need for microthrusters to diversify their missions is increasing accordingly. For example, both HORYU-IV and AOBA VELOX-IV CubeSats had onboard microthruster missions. The HORYU-IV nanosatellite was launched to a 575 km altitude in 2016 with an onboard vacuum arc thruster system. An orbit descend microthruster was necessary for HORYU-IV in low Earth orbit (LEO) to re-enter the atmosphere within 25 years of ending its mission.[1] By deorbiting a nanosatellite which no longer serves a useful purpose, orbital debris in LEO can be proactively mitigated. Additionally, the primary mission of AOBA VELOX-IV, a 2U size CubeSat developed jointly by Kyutech and Nanyang Technological University, was to verify the performance of a Pulsed Plasma Thruster (PPT) on the Earth orbit. In fact, PPT was the only actuator for the momentum dumping of reaction wheels and orbit maintenance.[2] Recently, we prototyped a new microthruster (Fig. 1) that can be mounted on nanosatellites, namely Surface Arc Thruster (SAT). Preliminary experimental results using PTFE propellant indicated signs of charring. At the same time, we observed an inverse correlation between pressure increase and shot numbers (e.g. as the shot numbers increased, delta pressure in the vacuum chamber decreased). In this paper, we characterized the operation of SAT using both solid sulfur propellant and powdered sulfur propellant. Elemental sulfur was proposed to overcome the charring difficulties of PTFE at low current levels. Sulfur (S_8) is a chemical element without carbon, whereas PTFE is a fluorocarbon polymer with chemical formula (C_2F_4).

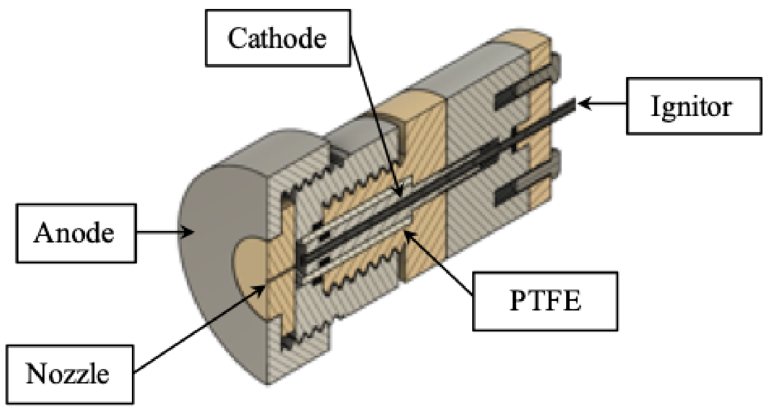


Figure 1: CAD rendering of coaxial type SAT.

II. SAT Principle

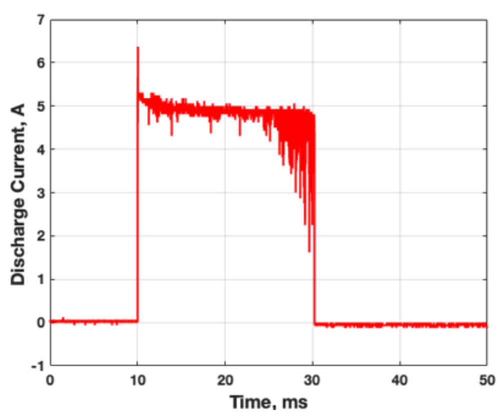
Figure 2 illustrates the experimental version of SAT: 42 mm long with a 20 mm body diameter. Notice that the coaxial anode has a 26 mm diameter. Fundamentally, the name "Surface Arc Thruster" implies the pulsed ablation and sublimation of solid propellant by surface arc discharge. SAT discharges the electric charges stored in the 2 mF rechargeable capacitor between the electrodes. The heat generated by the ignitor ionizes the resultant gas into the plasma. Because plasma consists of electrically charged particles[3], the plasma short-circuits the anode and cathode, thereby triggering the main discharge. Once the plasma is accelerated electrothermally, the nozzle provides an outgassing path, thereby exhausting the plasma and vapor from the plenum chamber by gas dynamic expansion capabilities. The nozzle resembles a de Laval nozzle to accelerate the exhaust to high velocities (thermal expansion) to generate the thrust. Although SAT operates like PPT, its discharge current is uniquely kept constant (5A) by current regulating diodes (CRD). Consequently, the duration of the discharge current pulse is several milliseconds to several tens of milliseconds.[4] The tungsten spark plug inside an alumina tube is housed inside the 2 mm aluminum cathode tube. The tubular PTFE propellant is sandwiched between the central cathode and the outer aluminum anode tube. Detailed information about the thruster can be found in the literature.[4,5]

Figure 2: Experimental version of SAT.

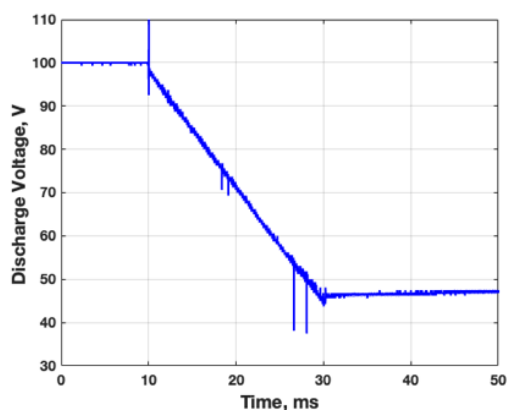
III. Experimental Results

A. SAT Main Discharge

To recreate as closely as possible the space pressure conditions, the experiments are performed in general-purpose vacuum chamber at Kyutech (0.45 m in diameter and 0.5 m in length). The maximum vacuum is 4.0×10^{-4} Pa and the achievement of 5.0×10^{-3} Pa takes about one hour. Figure 3 illustrates the typical discharge waveforms of SAT. We recorded the data with a commercial oscilloscope (LeCroy WJ314A) and measured the discharge current waveform in Fig. 3(a) using a current monitor (Pearson 5046). The discharge voltage waveform in Fig. 3(b) was measured using a Tektronix probe (TPP0201).



(a) Discharge current.



(b) Discharge voltage.

Figure 3: Typical discharge waveforms of SAT.

Unlike a typical PPT, the discharge current was kept constant at 5A by current limiting diodes. The duration of discharge was 10 ms and discharge current was non-oscillatory. A spike which occurred at 10 ms denotes the electromagnetic noise of the ignitor. Discharge stopped at around 46 V in Fig. 3(b) because discharges cannot be sustained at low voltage levels. Figure 4 confirms the operation of SAT as captured by a high-speed camera.

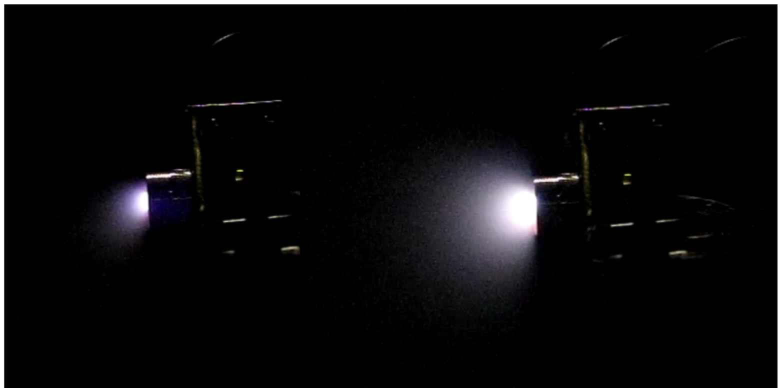


Figure 4: Operation of experimental SAT.

B. Propellant Charring

During firing tests, we observed an inverse correlation between shots and pressure increase (hereinafter called delta pressure) in the vacuum chamber resulting from the introduction of the thruster plume. A potential reason for this phenomenon can be propellant charring as indicated on the inner surface of PTFE tube in Fig. 5. Charring changes the chemical composition of PTFE and decreases the propellant utilization efficiency. Some researchers have proven that charring occurs due to a carbon back flux from the plasma.[7] This motivated us to investigate a noncarbon sulfur propellant and the particular use of sulfur as propellant took inspiration from the literature.[8]

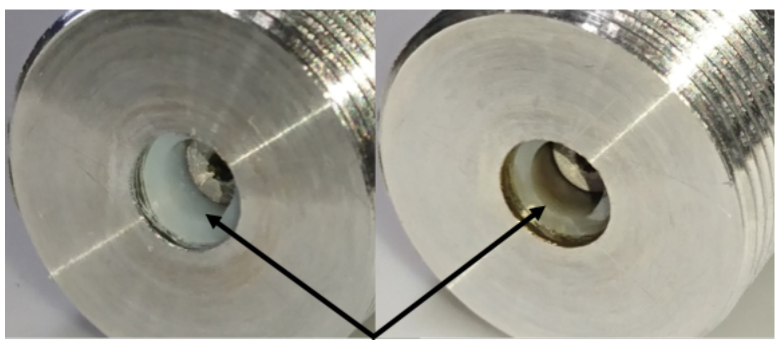


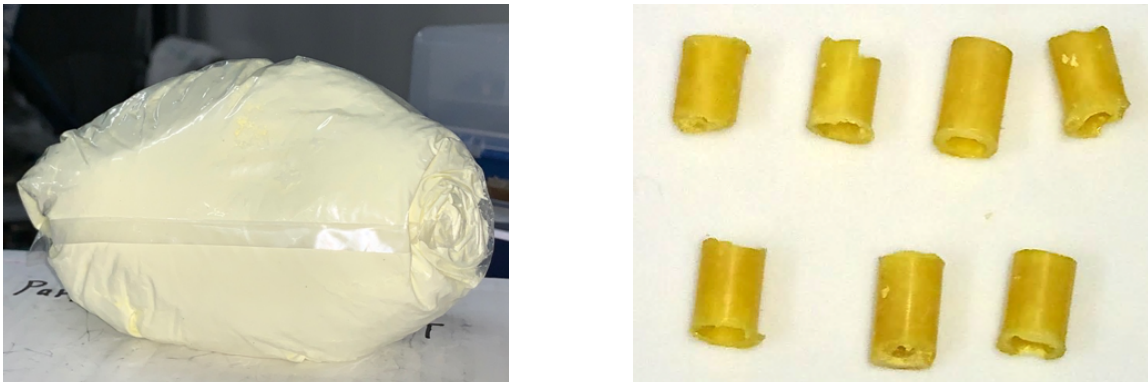
Figure 5: PTFE propellant before (left) and after (right) fifty consecutive shots.

C. Development of Sulfur Propellant

Sulfur (S_8) is a chemical element with atomic number 16. It has several types of allotropes, melts at 388.36 K, boils at 717.8 K, and sublimes easily.[9] In this paper, we experimented with powdered sulfur and solidified sulfur. To solidify sulfur, we heated powdered sulfur shown in Fig. 6(a) with a heating mantle. After melting at 388.36 K, we stopped the heating process, poured liquid sulfur in a special tube and let it cool down to form the tubes shown in Fig. 6(b). Table 1 lists the physical and chemical properties of sulfur.

Table 1: Physical and chemical properties of sulfur

Property	Value
Melting point	388.36 K
Density	2.07 g/cm^3
Molar heat capacity	22.75 J/(mol·K)
Heat of vaporization	45 kJ/mol



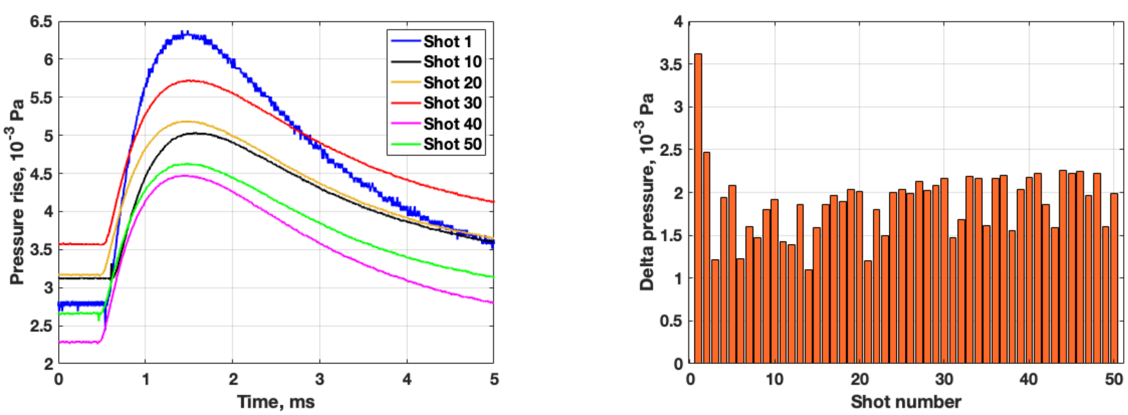
(a) Powdered sulfur. **(b)** Solidified sulfur.

Figure 6: Experimental sulfur investigated herein.

D. A Performance Comparison between PTFE and Sulfur

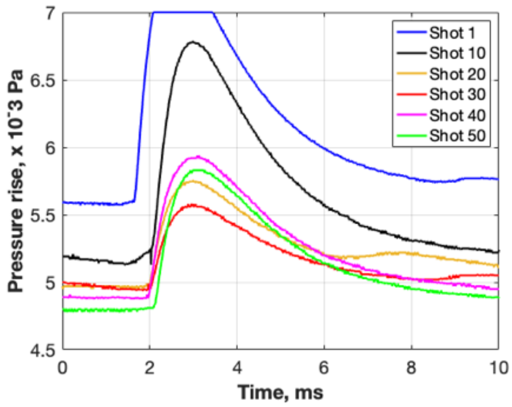
Figures 7 shows the delta pressure (Δp) of SAT with solidified sulfur as propellant, conducted under a base pressure of 10^{-3} Pa using a rotary pump and a turbo molecular pump. In Fig. 7(a), the first shot produced the maximum Δp, but the last shot did not necessarily produce the minimum Δp. Figure 7(b) shows a bar chart of the relationship between Δp and shot numbers and it is shown that the Δp waveform was slightly prone to shot-to-shot variations as the shot numbers increased. Figures 8 shows Δp in the vacuum chamber (10^{-3} Pa) resulting from the firing of SAT with powdered sulfur as propellant. In Fig. 8(a), the first shot is saturated because the resultant Δp significantly exceeded the estimated range of the oscilloscope. Figure 8(b) shows that the Δp waveform varied significantly as shot numbers increased. Additionally, Δp of the sixth shot was zero because SAT misfired.

Figures 9 shows Δp resulting from the introduction of SAT plume after the sublimation of PTFE. Compared with sulfur, the Δp waveform experienced severe shot-to-shot variations. In fact, Δp was very low that only 18% of the shots produced Δp greater than 0.5×10^{-3} Pa. Figure 10 shows a collective performance comparison of all propellants tested herein. The mean Δp of solidified sulfur, powdered sulfur and PTFE are 1.9×10^{-3} Pa, 0.94×10^{-3} Pa and 0.43×10^{-3} Pa, respectively. The reason why PTFE comparatively underperformed can be due to a high melting point (600 K) in comparison to sulfur (388.36 K). Ref. 10 has shown that a PPT's specific thrust can be increased with non-plastic fuels; in particular, fuels which included sulfur. This is attributed to sulfur's low melting and boiling point, low enthalpy of sublimation, and low ionization energies.[10]

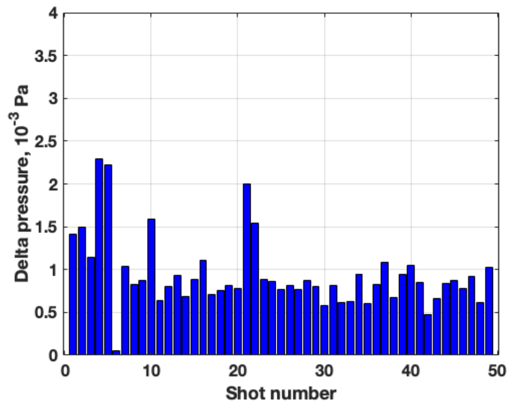


(a) Pressure rise. **(b)** Delta pressure as a function of shots.

Figure 7: Delta pressure results of solidified sulfur.

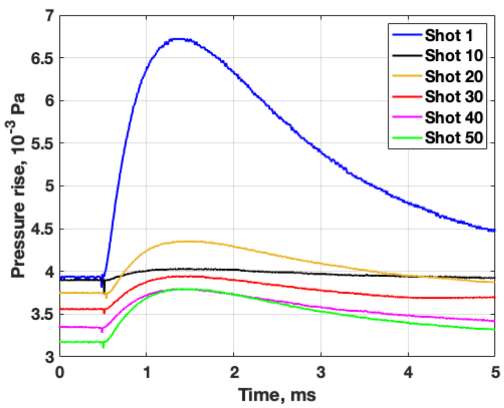


(a) Pressure rise.

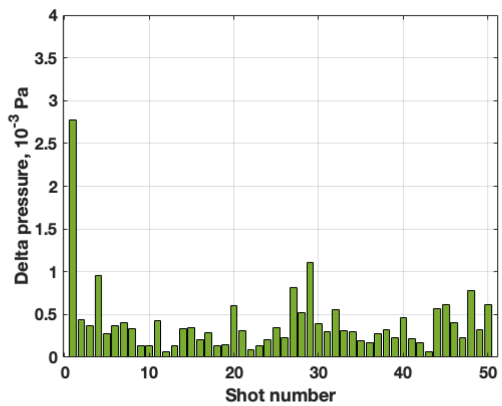


(b) Delta pressure as a function of shots.

Figure 8: Delta pressure results of powdered sulfur.



(a) Pressure rise.



(b) Delta pressure as a function of shots.

Figure 9: Delta pressure results of PTFE.

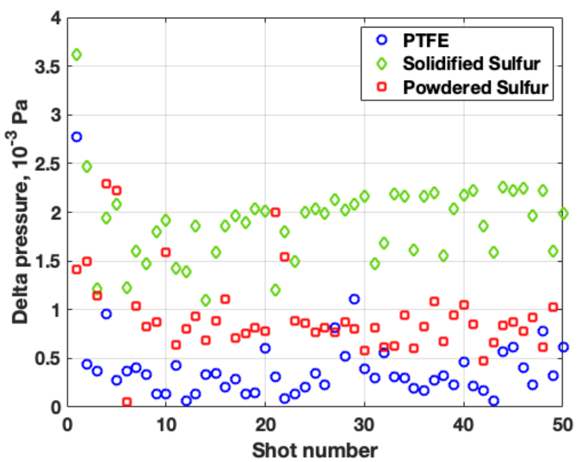


Figure 10: A performance comparison of solid propellants.

E. Relationship between Delta Pressure and Discharge Time

Figure 11 shows the relationship between discharge duration and delta pressure (Δp) for PTFE propellant. In the figure, each point corresponds to one discharge. The figure shows that the pressure increase was proportional to duration of the current waveform. In addition, the longest duration of discharge (20 ms) produced the maximum Δp (2.7×10^{-3} Pa). Similar results were obtained regardless of the material of the propellant. Furthermore, the discharge duration of 80% of the shots was less than 5 ms in case of PTFE. Consequently, the resultant Δp for 80% of the shots was below 0.5×10^{-3} Pa. This finding suggests that Δp depends on the duration of discharge and by sustaining the arc longer, the performance of SAT can be improved.

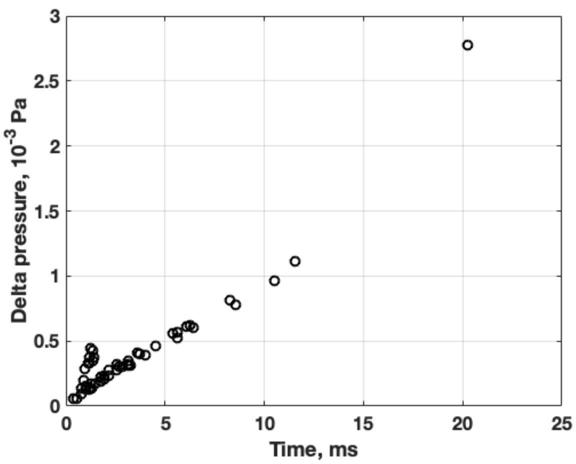
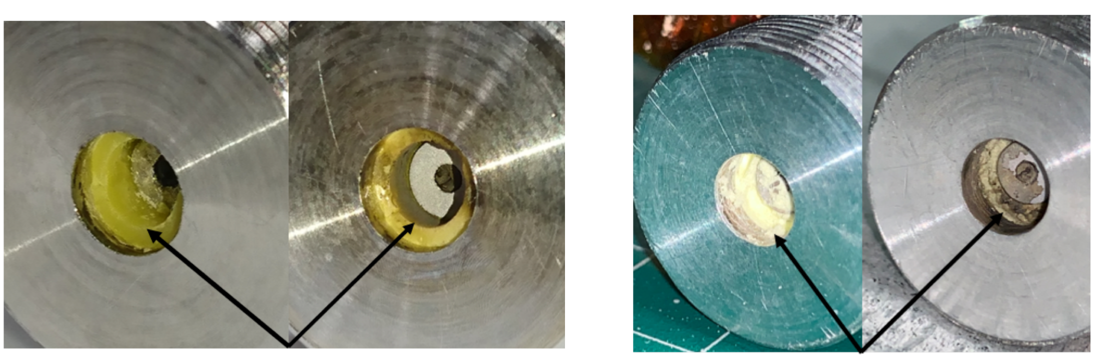


Figure 11: Relationship between delta pressure and discharge time for PTFE.

F. Charring of Sulfur Propellant

Examination of sulfur propellant surface indicates signs of dark residues but we have not confirmed content of the element carbon. However, unlike PTFE carbonization, residues did not rub off the sulfur propellant surface when we scratched it. This finding implies a chemical change in case of sulfur and a physical change in case of PTFE. Perhaps the arc heated sulfur beyond its decomposition temperature, leading to a thermal decomposition. Figure 12(a) shows charring of solidified sulfur, whereas Fig. 12(b) shows charring of powdered sulfur. Powdered sulfur experienced the least intensity of charring. Assuming that charring is caused by excessive heat flux (pyrolysis) in an inert atmosphere, the spaces (grain boundary) between the particles potentially tend to decrease the thermal conductivity or heat transfer in propellant, thus the charring intensity was low in case of powdered sulfur.



(a) Solidified sulfur before (left) and after (right) firing **(b)** Powdered sulfur before (left) and after (right) firing.

Figure 12: Charring of propellant in SAT after fifty discharges.

G. Axial Thrust for Coaxial SAT

SAT is typically classified as electrothermal [4,5] because its a low power thruster. The capacitance of a capacitor bank is 2 mF charged to a potential of 100 V. Using Eq. (1), we calculated the energy stored in it.

$$E = \frac{1}{2}CV^2 = 10J \tag{1}$$

In a typical PPT, the amount of axial thrust for a coaxial configuration is calculated using Eq. (2).[11] Please note that calculating SAT's thrust using Eq. (2) assumes the thruster to be electromagnetic with a coaxial geometry.

$$F = \frac{1}{4}(\pi)\mu_0 I^2 ln\left(\frac{r_o}{r_i} + \frac{3}{4}\right) \tag{2}$$

Because the plasma is non-magnetic, the value of μ_0 remains the same as free space.[11] Plugging in the numbers (I = 5 A; $r_i = 0.001$ m; and $r_o = 0.013$ m), we obtained a thrust of $64.7\mu N$.

This thrust is two orders of magnitude less than the thrust previously calculated from pressure measurements in Ref. 4. This potentially confirm that Eq. (2) is not applicable to electrothermal thrusters with a coaxial configuration such as SAT.

IV. Conclusion

We successfully operated a surface arc thruster by using sulfur as propellant. We also compared the delta pressure in the vacuum chamber resulting from the introduction of SAT plume using two propellants: 1) PTFE and 2) sulfur. Both propellants experienced charring but the composition of the residues is not known. Powdered sulfur experienced the least intensity of charring, whereas solidified sulfur underwent severe charring. Particles have spaces (grain boundary) between them in powdered sulfur, whereas particles are closely packed in solidified sulfur. Additionally, the physical and chemical properties of solid sulfur are dependent on its temperature history.[9] Therefore, if charring is the thermal decomposition of propellant by excessive heat flux generated by the arc, then the spaces between the particles obviously decrease the thermal conductivity of propellant. Consequently, it decreases heat transfer and charring of powdered propellant. According to Ref. 9, the thermal conductivity of sulfur also decreases from 11 W/m·deg at 4.2 K to 0.29 W/m·deg at 0 ^{o}C, whereas at 100 ^{o}C it is 0.15 W/m·deg.[9] We then conclude that besides a carbon backflow from the plasma[7], charring may also be caused by pyrolysis. In terms of delta pressure, the shot-to-shot variation was greater when using powdered sulfur than solidified sulfur. Similar results were reported in Ref. 12 using PTFE powder. Similarly, we herein attribute the significant shot-to-shot variations to propellant losses because of high particulate emission in case of powdered propellant.[13] We further observed that delta pressure depends on duration of discharge and by sustaining the arc longer we can improve the impulse bit. Moving forward, we are planning to characterize the operation of SAT using the parallel-plate configuration with a nozzle. We will further conduct parametric research to investigate the impact of altering currently fixed parameters on the performance of SAT.

Acknowledgments

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