Discharge Characteristics of a Gas-fed Short-pulse Plasma Thruster

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Abstract: Studies on gas-fed PPTs have been conducted from the late 1950's. The research includes coaxial, parallel-plate, z-pinch and hybrid geometries using ambient fill or pulsed gas injection techniques with hydrogen, nitrogen, argon, and xenon propellants. In this study, discharge characteristics and plasma (electron and ions) acceleration characteristics of high-peak power short-pulse discharges were investigated. Thrust performance was also examined for various cases with a target pendulum thrust stand in a vacuum chamber. From the results, thrusts increase with frequency for each mass flow late case. The maximum thrust is 1.4 mN at *f* = 1 kHz, *m* = 1 sccm. Specific impulses and thrust efficiencies become significantly high at the smallest mass flow rate of 1sccm. The maximum specific impulse and thrust efficiency were 4700 sec, and 3.5 %, respectively, at *f* = 1 kHz, *m* = 1 sccm

Nomenclature

h	=	channel gap
l	=	channel length
w	=	channel width
L_C	=	charging inductor
R	=	discharge resistor
m	=	mass flow late
f	=	operating frequency
C_2	=	peaking capacitor
L_1	=	parasitic inductor
C_1	=	storage capacitor

I. Introduction

Pulsed-plasma thrusters, PPTs, utilizing a solid propellant usually PTFE (Teflon®), have attracted a growing interest for their system simplicity and advantages on miniaturization and mass reduction for the use of attitude or orbit control thrusters for small-sized spacecrafts, despite their low efficiency[1-4]. In their operations, short pulse discharges with several-microsecond duration are induced across an exposed propellant surface between electrodes, vaporizing and ionizing the surface, and also inducing a pressure force. Then an interaction of the discharge current (tens of kA) and its self-induced magnetic field results as the electromagnetic force, or Lorentz force, acting on the plasma and inducing a directed plasma beam exhaust, or thrust. In this electromagnetic acceleration process, it is necessary to complete phase changes of the propellant, such as vaporization and ionization,

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and the electromagnetic acceleration at the same time within a short duration of a pulse discharge. Improvements of the thrust performance can be expected with shorter pulse duration cases, since it is capable of higher current per unit time or higher power input, namely higher thrust, and of reducing loads on electrodes. However, it is difficult to complete the process including the phase changes and electromagnetic acceleration simultaneously during the discharge pulse, because there is a delay in the phase change of the solid-propellant after the pulse discharge initiation. The surface of the propellant will continue to evaporate long after completion of the discharge pulse, providing mass that cannot experience acceleration to high speeds by the electromagnetic and gasdynamic forces. The various masses including low-speed macroparticles can have quite different velocities. Since the residual vapor or plasma from the late-time evaporation of the propellant surface remains in the discharge channel due to the delay after the pulse discharge completion, which cannot contribute significantly to the impulse bit, it has been difficult for the thruster of this type to improve this mass loss of the propellant and thrust efficiency[1-4].

In order to improve the mass loss and thrust efficiency of PPTs, utilization various propellants in various phases, such as gas[5], liquid[6], powder[7], and laser ablation plasma[8-10] fed to the thrusters were investigated.

Studies on gas-fed PPTs have been conducted from the late 1950's. The research includes coaxial, parallel-plate, z-pinch and hybrid geometries using ambient fill or pulsed gas injection techniques with hydrogen, nitrogen, argon, and xenon propellants[5].

Until recently the gas-fed PPTs suffered from low propellant utilization efficiency due to the fact that the fastest available space-qualified gas valve with long enough life (> 10^7 pulses) has an open time not shorter than 1 ms. As the time to fill the discharge chamber is only the on the order of 0.1 ms, much of the propellant could not utilized effectively over the life of the device. Recent work has resulted in a complete solution[11, 12] to this problem by using state-of-the-art pulse power technology raising the propellant utilization efficiency to well above 90%. This solution relies on using modern pulsed-power conditioning technology to adjust the period between pulses to a length very close to the time it takes for the cold injected gas to fill the thruster chamber. This typically corresponds to pulse frequencies of a few kHz during the burst[12]. Depending on the available bus power and mission requirements, sets of such pulses can be produced such that each lasts a period that is at least as long as the response of a space-qualified valve (e.g. 1 ms) thus making sure that practically all injected propellant is utilized.

In this study, to develop novel gas-fed pulse plasma thrusters, which can be operated in a continuous mode, discharge characteristics and plasma (electron and ions) acceleration characteristics of high-peak power short-pulse discharges were investigated. The acceleration regime of plasma through the interaction of short-pulse discharges with matter clearly differs from the conventional acceleration regimes.

Recent rapid progress of pulse power generation technologies associated with recent development of power sources for photolithography of next-generation semiconductors has brought high-peak power sort-pulse drivers for extreme ultraviolet (EUV) and X-ray sources, particle accelerators, etc.[13-14] With this regime, a wide range of plasma densities, or acceleration regimes, from electrostatic acceleration to electromagnetic acceleration, can be expected, namely achieving either high-specific impulse accelerator or high-impulse accelerator depending on the mission requirement, which can possibly realize a highly robust propulsion system for future spacecraft. The primary objective of this study is to demonstrate these significant characteristics.

Authors have been investigating laser-assisted pulsed plasma thrusters (LAPPTs) and have demonstrated their high specific impulse characteristics[8-10].

In this study, as the next step, reducing the discharge short pulse width using newly developed pulse power source with smaller capacitances with higher peak voltages and currents, high-peak power discharges were demonstrated and their characteristics were investigated

II. Gas-Fed Pulsed Plasma Thruster

A schematic of the rectangular gas-fed pulsed plasma thruster is illustrated in Figure 1. At a time when a voltage between electrodes exceeds a breakdown potential, a discharge current flows through electrodes. When the current between the electrodes increases, the plasma can be heated and further ionized through joule heating. Thus, the electrothermal acceleration effect will be significant. With larger current exceeding more than one thousand amperes, the electromagnetic acceleration effect becomes significant. With the interaction of the current and a self-induced magnetic field, a streamwise acceleration of the plasma will be provided.

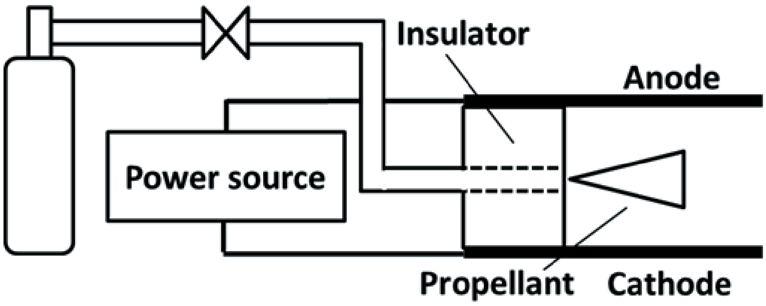

Figure 1. Schematic of a gas-fed pulsed plasma thruster

III. Power source

Figure 2 shows a schematic of the power source. The discharge circuit consists of a simple thyratron-switched capacitor-transfer scheme consisting of storage C_1 and peaking C_2 capacitors, parasitic L_1 inductance, charge L_C inductance, and discharge resistor *R*. The circuit operates as follows; when a voltage is applied to C_1, then the thyratron switch turns on and then C_2 will be charged. When the charge voltage of C_2 reaches the breakdown voltages, a pulse discharge through C_2,L_1 and R will be induced. Depending on capabilities of a DC power source and a thyratron switch, repetition frequencies of pulse discharges can be determined. In this apparatus, the maximum repetition frequency is limited up to 2 kHz, with the maximum voltage applied to the electrodes of 20 kV.

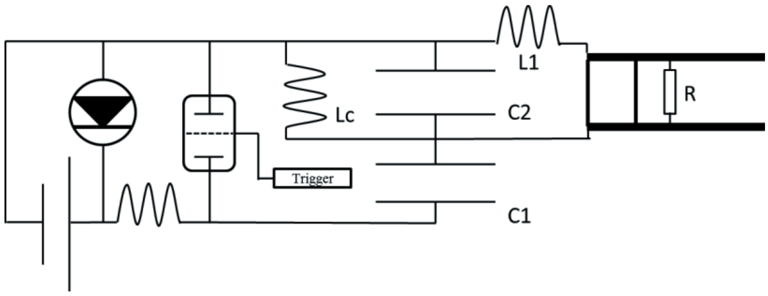

Figure 2. Discharge circuit of a power source

IV. Experiment setup

A. Impulse bit measurement

A photo of the thruster is shown in Figure 3, in which electrodes are made of copper and an insulator is made of PTFE. Configuration of the thruster is listed in Table 1. As shown in this figure, to enhance an electric field and namely to reduce required voltages to initiate discharge, a pair of parallel edges of rectangular solid electrodes were used for the acceleration channel.

To measure a thrust of a short-pulse Gas-fed PPT, the impulse bit measurement was conducted using a cylindrical target thrust stand shown schematically in Figure 4. In the thrust evaluation in this study, an impulse bit of 0.1 s duration, which is less than 10% of a natural frequency of the pendulum short enough to be assumed as a pulsed impulse, was measured to determine a steady (or average) thrust for the continuous pulses with the frequencies of 100 ~ 1 kHz. A plasma plume, generated from the thruster by an electrical discharge, comes into an entrance hole on the front plate. The bottom plate has a conical shape, and most rebounding gas particles from the bottom plate will leave radially from the target through the slits on the side of the cylinder. Figure 4 shows a schematic of the impulse bit measurement system. The thrust stand consisting of a cylindrical target pendulum measures a reaction force exerted from a plasma plume exhausted from a thruster during operation. The main body of the cylindrical target is made of a polyvinyl chloride (PVC) plate of 0.5 mm in thickness and a pendulum arm of 300 mm in length is made of aluminum. A thruster was installed in front of the target, and impulse bit was calculated from the displacement of the pendulum. Displacement of the pendulum was measured by an inductive displacement sensor (EMIC CORP., NPA-010, resolution: 0.5 µm, range: 0 ~ 1.0 mm, output voltage: 0 ~ 1.0 V), and output signals from the sensor were monitored and recorded by an oscilloscope (Tektronix, TDS3034B, band width: 300MHz, the best sampling rate: 2.5 GS/s).

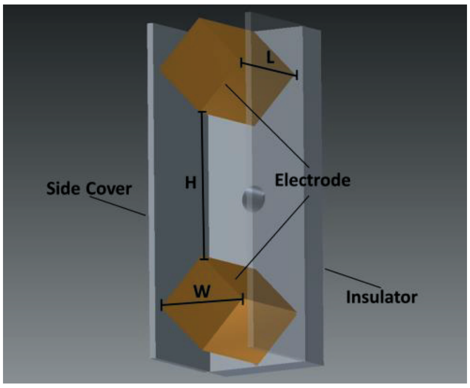

Figure 3. Illustration of thruster head

Table1. Configuration of Short Pulse Gas-fed PPT

Channel length:L	15 mm
Channel width:W	14 mm
Channel gap:H	20 mm
Electrode	Cu
Propellant	Ar
Insulator	PTFE
Side cover	Glass

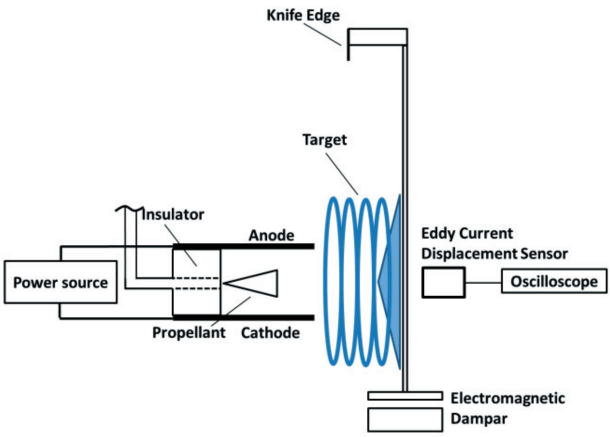

Figure 4. Schematic of an impulse bit measurement system.

V. Result and discussion

A. Discharge current and voltage measurement

Figure 5 shows discharge current and voltage waveforms for single shot. The current reaches the positive peak value, 22kA, at 400 ns. Crossing zero at 300 ns, the current reaches the smallest (negative peak) value, -30kA, at 650 ns. A pulse width is about 100 ns. The voltage reaches the positive peak value, 20 kV, at 280 ns, and crossing zero at 400 ns. The voltage reaches the smallest (negative peak) value, -6 kV at 700 ns.

Figure 6 shows discharge current and voltage waveform for 1 kHz. The current reaches the positive peak value, 30 kA, at 250ns. Crossing zero at 180 ns, the current reaches the smallest (negative peak) value, -35 kA, at 550 ns. A pulse width is about 50 ns. The voltage reaches the positive peak value, 17 kV, at 170 ns. Crossing zero at 300 ns, the voltage reaches the smallest (negative peak) value, -5 kV at 550 ns.

The reduction of the pulse width and the peak voltage is probably due to the charged particles left in the acceleration channel between the electrodes.

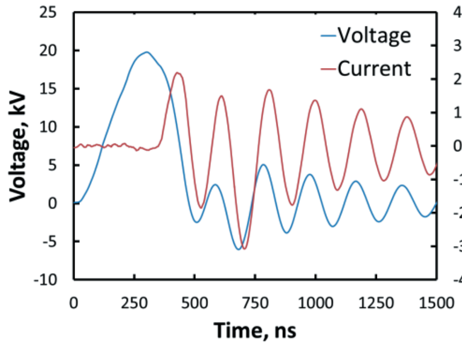

Figure 5. Discharge current and voltage waveform for single shot

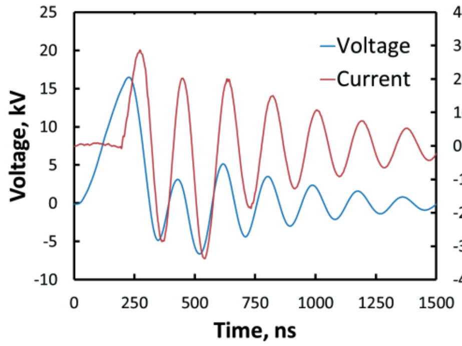

Figure 6. Discharge current and voltage waveform for *f* = 1 kHz

B. Thrust performance measurements

Some results of thrust of a short pulse gas-fed PPT (*m* = 1~10 sccm, *f* = 400~1000 Hz respectively) are shown in Figure 7. From this figure, it can be seen that thrusts increase with frequency for each mass flow late case. On the other hand, differences in thrusts among mass flow rates of 1 ~ 10 sccm are very small. The maximum thrust is 1.4 mN at *f* = 1 kHz, *m* = 1 sccm.

From the results, specific impulses and thrust efficiencies of the short pulse gas-fed PPT were estimated, and plotted in Figure 8 and 9, respectively. As shown in the figure, specific impulses and thrust efficiencies become significantly high at the smallest mass flow rate of 1 sccm. The maximum specific impulse and thrust efficiency were 4700 sec, and 3.5 %, respectively, at *f* = 1 kHz, *m* = 1 sccm

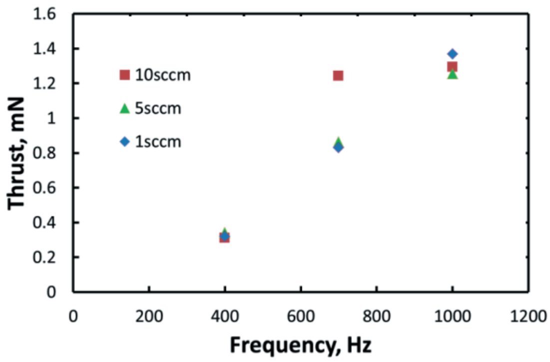

Figure 7. Impulse bit of a gas fed short-pulsed PPT

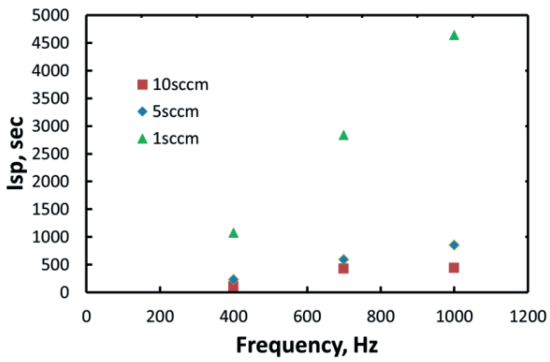

Figure 8. Specific impulse of a gas fed short-pulsed PPT

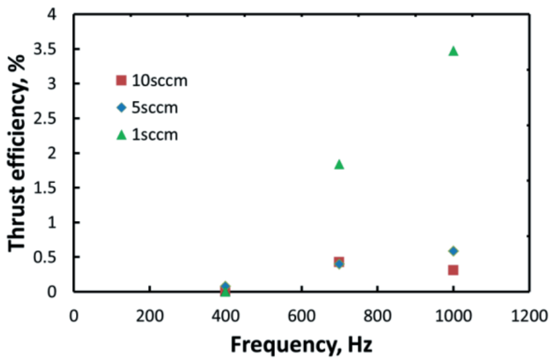

Figure 9. Thrust efficiency of a gas fed short-pulsed PPT

VI. Conclusion

In this study, discharge characteristics and plasma (electron and ions) acceleration characteristics of high-peak power short-pulse discharges were investigated. Thrust performance was also examined for various cases with a target pendulum thrust stand in a vacuum chamber. From the results of discharge voltage and current waveform, for single shots, discharge voltage is higher than 1 kHz, discharge peak current is lower than 1 kHz, and pulse width is longer than 1 kHz. The reduction of the pulse width and the peak voltage is probably due to the charged particles left in the acceleration channel between the electrodes.

References

[1]Jahn, R.G., *Physics of Electric Propulsion*, McGraw-Hill, 1968, pp. 198-316.

[2]Martinez-Sanchez, M., and Pollard, J. E., J. *Journal of Propulsion and Power*, Vol. 14, 1998, pp.688-699.

[3]Burton, R. L., and Turchi, P. J., *Journal of Propulsion and Power*, Vol. 14, 1998, pp.716-699.

[4]Micci, M. M., and Ketsdever, A. D. ed., “Micropropulsion for Small Spacecraft,” *AIAA Journal*, Vol. 187, 2000, pp.337-377.

[5]Ziemer, J., “Performance Scaling of Gas-Fed Pulsed Plasma Thrusters,” PhD Dissertation, Princeton U, 2001.

[6]Kakami, A. Koizumi, H., Komurasaki, K. Arakawa, Y., *ISTS*, b-15, 2002.

[7]Yokoyama, S., Horisawa, H. Funaki, I., Kuninaka, H., “Fundamental Experiment of Laser Micro Propulsion using Powdered-Propellant”, *ISTS* , s-10, 2006.

[8]Horisawa, H., et al., *Applied Physics*, A 81, 2005.

[9]Kishida, Y., et al., *Trans. JSASS*, Vol. 8, 2010.

[10]Y. Oigawa, et.al., AIAA, No. 3537, 2014.

[11]Ziemer, J. K., Cubbin, E. A. Choueiri, E. Y., Birx, D., ”Performance characterization of a high efficiency gas-fed pulsed plasma thruster,” AIAA, No. 2925, 1997.

[12]Ziemer, J. K., Choueiri, E. Y, Birx, D.,”Is the Gas-Fed PPT an Electromagnetic Accelerator? An Investigation using Measured Performance,” AIAA, No. 2289, 1999.

[13] W. Jiang, et al., *Proc. IEEE*, Vol. 92, pp.1180, 2004.

[14] K.Takayama, at al., Phys. Rev. Let., 98-054801, 2007.