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Technical Notes

Performance of ThO_2-W, Y_2O_3-W, and La_2O_3-W Cathodes in Quasi-Steady Magnetoplasmadynamic Thrusters

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Nomenclature

J = discharge current
$\dot{m}$ = mass flow rate
V = discharge voltage

I. Introduction

THORIATED tungsten (ThO_2-W) has been widely used as a cathode material for dc arcjets, magnetoplasmadynamic thrusters (MPDTs), and gas tungsten arc (GTA) welding for a long time, because of its high durability and electron emissivity. However, manufacturers are concerned about the radiological doses that users are exposed to when sharpening or grinding thoriated tungsten [1,2]. Yttriated and lanthanated tungsten (Y_2O_3-W and La_2O_3-W) electrodes have been proposed as alternatives to thoriated tungsten. Because these nonradioactive electrodes have superior durabilities and electron emissivities to conventional ThO_2-W in arc welding [3–5], they have replaced ThO_2-W electrodes.

The purpose of this study is to evaluate the operational characteristics of an MPDT with these alternative sintered tungsten cathodes. To our knowledge, no experimental data have been published for MPDTs with Y_2O_3-W or La_2O_3-W cathodes; data are available only for dc arcjets [6–8]. In quasi-steady operation, the cathode body temperature is typically low, and spotty arc attachment occurs. This increases the local temperature of thermionic electron emission, resulting in a much higher erosion rate [9] and higher discharge voltage than steady-state operation. Such cold-cathode conditions also occur during the startup phase of steady-state operation, until the surface temperature becomes sufficiently high for thermionic electron emission. Although our study focuses only on the quasi-steady mode, the results are also pertinent for the startup phase of steady-state operation.

II. Experimental Apparatus

The experimental apparatus and the procedure adopted in this study are similar to those used in our previous MPDT studies [10,11]. Figure 1 shows a schematic of the thruster. In this configuration, the arc current is considered to strike the lateral surface of the cathode, especially near the base of the cathode [12]. The cylindrical anode is made of phosphor bronze and has inner and outer diameters of 28 and 80 mm, respectively. Sintered tungsten cathodes (2% ThO_2-W, 2% Y_2O_3-W, 2% La_2O_3-W, length 42 mm, and diameter 8 mm) with hemispherical tips are pressed into the phosphor bronze holder.

The thruster is set in a stainless steel vacuum tank, which is 2.0 m long and 0.92 m in diameter. The tank pressure is less than 7 mPa prior to each firing. Gaseous argon propellant is injected through the eight choke orifices of fast-acting valves, producing a rectangular waveform that is 5 ms in duration. The mass flow rate at their steady-state values is 0.8 g/s, with a shot-to-shot variation of 5%. The discharge current is generated by a pulse-forming network, with an energy storage capacity of 25 kJ. It has a rectangular waveform that is 0.45 ms in duration, up to $J = 22$ kA. An ignition plug is not used; instead, discharge is initiated by high-voltage breakdown between the cathode and the anode. The discharge current is measured using a Rogowski coil, and the discharge voltage is monitored by sensing the small current through a high-impedance shunt resistor connected between the anode and the cathode. The signal is isolated, by a photocoupler, from the main discharge circuit. The discharge current and the discharge voltage are measured to an accuracy of less than 1%; the accuracy is mainly limited by the resolution limit of the data logger. In this study, the onset of the arc instability is defined at the point where the dispersion of the voltage hash amplitudes exceeds 5% of the mean voltage on the flat-topped region of the voltage waveform.

The thrust is measured by the parallelogram-pendulum method [10,11]. The impulse of the thruster is obtained from the amplitude of the swinging thrust stand, after the cold-gas impulse has been subtracted. The net thrust is obtained by dividing the resulting impulse by the quasi-steady-state pulse duration (0.45 ms).

Cathode erosion is measured at a discharge current of 9.6 kA (below the onset of arc instability) and at a mass flow rate of 0.8 g/s. After repeated firings (one–two shots per minute), the cathode mass loss was measured using an electronic microbalance to within an accuracy of 0.1 mg. The mass losses of the anode and the insulator were also measured, but they were found to be negligible compared with the cathode mass loss.

III. Experimental Results

Figures 2 and 3 show the operational characteristics of the MPDT. Each data point represents the average of five shots at a fixed operational condition. The error bars represent the shot-to-shot deviations. The discharge voltage curves of the three cathode materials differ considerably. In contrast, the thrust characteristics are independent of the cathode material. Similar tendencies were obtained using a converging–diverging anode. The maximum difference in the discharge voltages for the three cathodes was observed at about $J = 9$ kA; the differences decrease at higher currents. The onset of the arc instability was recognized above $J = 11$ kA for ThO_2-W cathode, and $J = 13$ kA for Y_2O_3-W and La_2O_3-W cathodes.

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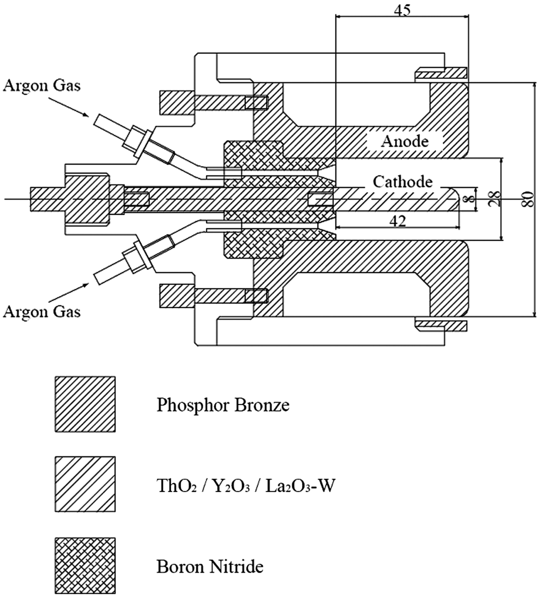

Fig. 1 Cross-sectional view of the coaxial MPDT.

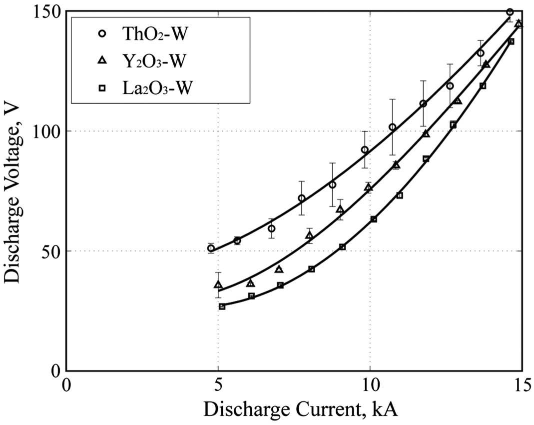

Fig. 2 Characteristics of discharge voltage vs discharge current (argon, $\dot{m} = 0.8\ \mathrm{g/s}$).

Y_2O_3-W and La_2O_3-W had small shot-to-shot deviations up to 15 kA, whereas the ThO_2-W cathode exhibited very large shot-to-shot deviations.

Table 1 shows the erosion measurement results. La_2O_3-W had the lowest erosion rate, followed by Y_2O_3-W and ThO_2-W (in that order). A moderate number of testing shots (between 100 and 200 shots [14]) were used, to avoid effects caused by impurities on the surface at the beginning of the experiment.

IV. Discussion

The voltage differences for these three cathodes are quite large. They cannot be explained just in terms of the cathode sheath potential (which is considered to be about 20 V for a ThO_2-W cathode [13]). In this section, we explain the voltage difference in terms of both the sheath drop and the voltage drop across the bulk plasma.

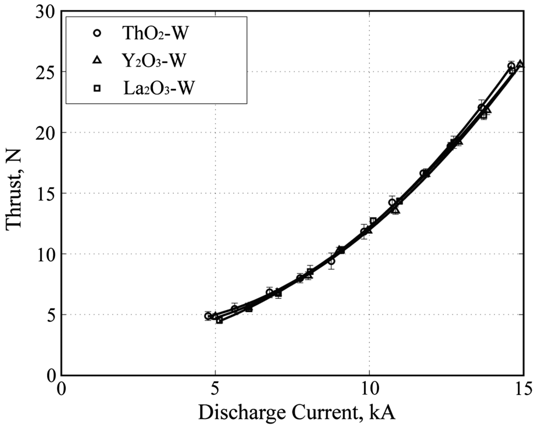

Fig. 3 Characteristics of thrust vs discharge current (argon, $\dot{m} = 0.8\ \mathrm{g/s}$).

Cathode sheath effects in quasi-steady MPDTs can generally be described by a cold-cathode model [15], that is, when many arc spots are generated on the cathode surface. They increase the local temperature, which causes significant amounts of thermal (partially field-enhanced) electrons to be emitted into the bulk plasma. The cathode material on an arc spot rapidly melts and evaporates. The cathode spot temperature is one of the most important parameters for determining the cathode sheath drop, but it is quite difficult to experimentally measure the instantaneous temperature of a local cathode spot during quasi-steady-state operation. Table 2 shows the melting and boiling points of the three rare-earth oxides used in the present experiment. The boiling points are those at atmospheric pressure, but the pressure within the spot is considered to be higher than the atmospheric pressure [15]. The boiling point of pure thorium is also included in Table 2, for the following reason. For the ThO_2-W cathode, pure thorium is considered to dissociate from ThO_2, and most of it diffuses to the cathode surface, where it forms a monolayer [5]. The electric dipole layer, formed by this electropositive atom on tungsten, facilitates the escape of electrons from the cathode surface. In the case of Y_2O_3-W or La_2O_3-W, the rare-earth oxide forms its tungstate or oxitungstate [5]. For example, $Y_2O_33WO_3$ or $La_2O_33WO_3$ is recognized on the cathode surface after arcing [5]. The melting points of these oxitungstates are typically lower than the original rare-earth oxides [5]. When we mention the work function of these cathode materials, the existence of dissociated thorium or the oxitungstate of rare-earth oxide has to be taken into consideration.

In terms of the voltage drop across the bulk plasma, vaporized rare-earth metals are considered to reduce the amount of energy required to sustain arc discharge. The electrode mass loss per shot is much smaller than the propellant mass shot (400 μg) during quasi-steady-state firing (0.5 ms). However, even a small amount of impurities can significantly affect the electrical conductivity of bulk plasma [20,21], because evaporated metal atoms generally have low-energy excited states. Different kinds of metal vapor contamination give rise to different plasma temperatures and electrical conductivities in the argon arc plasma [22]. Since the electrical conductivity is strongly

Table 1 Cathode erosion after repeated shots at $J = 9.6\ \mathrm{kA}$ and $\dot{m} = 0.8\ \mathrm{g/s}$, with argon propellant; total mass loss is accurate to within 0.1 mg

Electrode type	Total mass loss	Mass loss per shot, $\mu g/\mathrm{shot}$	Mass loss per coulomb, $\mu g/C$
ThO_2-W	4.3 mg/150 shots	29	6.7
Y_2O_3-W	2.9 mg/146 shots	20	4.6
La_2O_3-W	2.7 mg/160 shots	17	3.7

Table 2 Thermodynamic properties of rare-earth metal oxides; melting and boiling points of oxides at atmospheric pressure are from [16–19]

	Melting point, K		Boiling point at 1 atm, K	
Rare-earth metal oxide	[16]	[17–19]	[16]	[17–19]
ThO_2	3493	3663	4673	4673
Y_2O_3	2683	2963	——	4573
La_2O_3	2580	2578	4473	4473
Th	2023	——	5063	——

related to the electron temperature, one might think if the electron temperature is changed the thermal part of the thrust should also be differed. However, the thrust characteristics do not change when different cathode materials are used. In this study, measured thrust is almost similar to the theoretical electromagnetic thrust calculated from Maecker's formula [11], so the contribution of the thermal part of the thrust is very small. The difference of the plasma temperature is considered not to affect the thrust. At any rate, electron temperature measurement is quite necessary to provide a better understanding.

The erosion rates obtained in this study (several micrograms per coulomb) are very similar to those reported for quasi-steady MPDTs [9,14,23]. In quasi-steady-state mode, the evaporation of the boiled cathode material, or the ejection of growing particles or droplets, is considered to be a dominant erosion component [15]. Our results reveal that Y_2O_3-W and La_2O_3-W are more durable than conventional ThO_2-W in this point.

Thus, the results confirm that Y_2O_3-W and La_2O_3-W are good alternatives to ThO_2-W as the cathode material for quasi-steady MPDTs. Although we do not have any experimental result for steady-state MPDTs, the feasibility of these alternative cathodes can be presumed from the results of GTA welding [3–5]. According to [5], the cathode tip temperatures of ThO_2-W and La_2O_3-W become 3613 and 2713 K, respectively, after 30 min of continuous arcing at 150 A in pure argon. Estimated work functions from the Richardson equation are considered to be 2.5 eV for ThO_2-W, and 2.0 eV for La_2O_3-W. These work functions are for the mixture of rare-earth oxide, their tungstate, and the dissociated material (as mentioned previously). Since the higher discharge current gives the higher cathode body temperature, the depletion rate of Y_2O_3 or La_2O_3 might be large at a kA-class steady-state operation.

V. Conclusions

The operational characteristics of self-field, quasi-steady MPDTs with ThO_2-W, Y_2O_3-W, and La_2O_3-W electrodes were experimentally measured. The following conclusions were obtained:

1) The cathode material had a large effect on the discharge voltage. The La_2O_3-W cathode exhibited the lowest voltage, and the ThO_2-W cathode showed the highest voltage, over a wide discharge current range. However, the differences in the voltage characteristics became smaller at higher currents.

2) The La_2O_3-W and Y_2O_3-W cathodes had lower erosion rates than a conventional ThO_2-W cathode. For pulsed arc discharge, erosion is caused by the evaporation or the ejection of the molten cathode material, due to the spotty arc attachment on the cathode surface. La_2O_3-W and Y_2O_3-W cathodes have high durability in this point.

3) In summary, La_2O_3-W and Y_2O_3-W cathodes are promising alternatives to conventional ThO_2-W cathodes, for quasi-steady MPDTs. In addition, they suffer less damage during the startup phase in steady-state MPDTs.

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