

High-Entropy Ceramic Cathode for Strong Applied-Field MPD Thruster

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Abstract: In this study, high-entropy material was focused on as cathode materials due to its oxidation resistance and applied to Applied-Field MPD thruster for operational testing. As a first step, argon was used as propellant. Compared to the conventional cathode material, thoriated tungsten, the concentration of the plume along the thruster's central axis, a decrease in discharge voltage, and improved thrust and thrust performance under strong magnetic fields were observed. These results are considered to be attributed to the low thermal conductivity of the high-entropy material, which causes the tip to become particularly hot, concentrating the current at the tip.

Nomenclature

$A_{Richardson}$	=	Richardson-Dushman constant
a	=	volume ratio between acceleration region to channel (decided by azimuthal current distribution)
B	=	magnetic field strength
e	=	elementary charge
F	=	thrust
I_{sp}	=	specific impulse
j_i	=	current density of element i
J_d	=	discharge current
k	=	Boltzmann constant
l	=	axial length of anode
$\dot{m}$	=	propellant mass flow rate

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Q_i	=	heat input of element i
R	=	resistance to thermal shock
R_a	=	anode radius
R_i	=	electrical resistance of element i
$S_{cross,i}$	=	cross-sectional area of element i
$S_{surf,i}$	=	surface area of element i
T_i	=	surface temperature of element i
u_{ex}	=	exhaust velocity
V_d	=	discharge voltage
V_0	=	fitting parameter for discharge voltage
W	=	work function
Δx	=	width of elements
$-$	=	representative value
α	=	coefficient of thermal expansion
β, γ	=	fitting parameters
ε	=	emissivity
η	=	thrust efficiency
κ	=	thermal conductivity of cathode material
ν	=	Poisson's ratio
σ	=	Stefan-Boltzmann constant
σ_e	=	electrical conductivity
σ_f	=	fracture stress of materials
ϕ	=	ratio between radial and axial magnetic field
ψ/ψ_c	=	characteristic parameter

I. Introduction

While xenon has been used in electric propulsion due to its advantages such as large atomic weight, low ionization energy, and chemical stability, its annual production is reported to be only 53 tons¹. However, with the clustering of satellites and other developments, the annual consumption is expected to increase several times², making research on alternative propellants an urgent problem. Among the candidates, oxygen-containing molecules such as carbon dioxide and water are also examined^{3,4,5,6}, but conventional cathode materials like thoriated tungsten and LaB6 have poor oxidation resistance⁷. For the application of these alternative propellants, cathode materials with superior oxidation resistance are needed.

In this study, we focus on high-entropy materials. Unlike conventional solid solutions where 1-2 base elements are typically doped with trace components of less than 1%, high-entropy materials are solid solutions containing approximately equal amounts of five or more elements⁸. There is a theory suggesting that these materials stabilize due to reduced Gibbs free energy resulting from higher configuration entropy, and experimental evidence has demonstrated improved oxidation resistance compared to conventional solid solutions⁹. Whereas applying cathodes using RF discharge¹⁰ without relying on thermionic emission is also a candidate for oxidizing environments, this approach faces challenges in achieving stable high-current operation¹¹. Therefore, in this study, we applied high-entropy material cathodes to Magneto-Plasma-Dynamic (MPD) thrusters, which require high-current discharge due to their acceleration mechanism and conducted operational experiments with argon propellant to evaluate the performance of high-entropy materials as cathode materials.

II. Experimental setup

A. Thruster head

Figure 1 shows a schematic diagram of the thruster used in this study. It is an axisymmetric, Applied-Field MPD thruster with an anode exit diameter of 40 mm. In this study, we conducted operations with three different configurations by replacing the cathode tip positioned on the central axis with



Table 1. Operation parameters.

Control parameter	Symbol	Value		
		ThW Rod	HE Rod	ThW Hollow
Magnetic field strength, T	B	0.24-0.48		
Discharge current, A	J_d	40, 50	30-50	50
Mass flow rate, mg/s	$\dot{m}$	3.0, 8.9	3.0	3.6, 4.8, 5.9

1. Thoriated tungsten rod cathode (ThW Rod)
2. High-entropy material ((HfZrTiTaNb)C+5%SiC) rod cathode (HE Rod)
3. Thoriated tungsten hollow cathode (ThW Hollow)

to compare operational performance of each configuration. The magnetic field was applied using a solenoid coil consisting of 200 turns of resistive copper wire cooled by a cryogenic cooling system described later.

Table 1 shows the operating conditions. The strength of the applied magnetic field B was defined as a representative value of the centerline of the anode. Discharge and coil current were supplied by commercial power suppliers (HX0300-50, Takasago Ltd. and PAT20-400T, Kikusui Electronics Co., Ltd., respectively). Argon was used as propellant. The flow rate was controlled by mass flow controller (3660 series, Kofloc, Inc.) The uncertainty of the mass flow rate was less than ± 0.03 mg/s (3.0 mg/s) or ± 0.4 mg/s (3.6 mg/s or more). For hollow cathode operation, the total mass flow rate was defined as the sum of the anode flow rate and cathode flow rate, with the ratio of anode flow rate to cathode flow rate fixed at 7:1, which yielded relatively high performance and stable operation. The lower limits of propellant mass flow rate and discharge current correspond to the minimum values at which steady-state discharge was achieved for each thruster configuration. For each configuration, measurements were taken three times at representative operating points, and their standard errors were defined as the representative errors for each configuration.

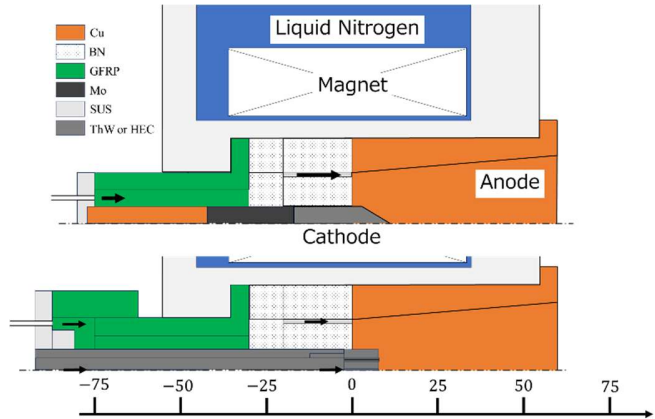


Figure 1. Schematic of the thrusters with rod (upper) and hollow (lower) cathode.

B. Vacuum Facility and Coil Cooling System

All experiments were conducted in a nonmagnetic stainless steel (ISO:4301-304-00-I) vacuum chamber with a diameter of 2.0 m and length of 4.0 m. During the experiments, the chamber was evacuated by two turbomolecular pumps (3203LM and 4304LM, Shimadzu Co. with pumping speeds of 3600 L/s and 4050 L/s, respectively), maintaining background pressure in the order of 10^{-2} Pa during thruster operation under all conditions. Additionally, liquid nitrogen for coil cooling was supplied through feedthroughs in the chamber wall.

Thrust measurements were performed using a pendulum-type thrust stand¹² consisting of a stand arm supported by two bearings, which was introduced into the chamber via vacuum bellows.

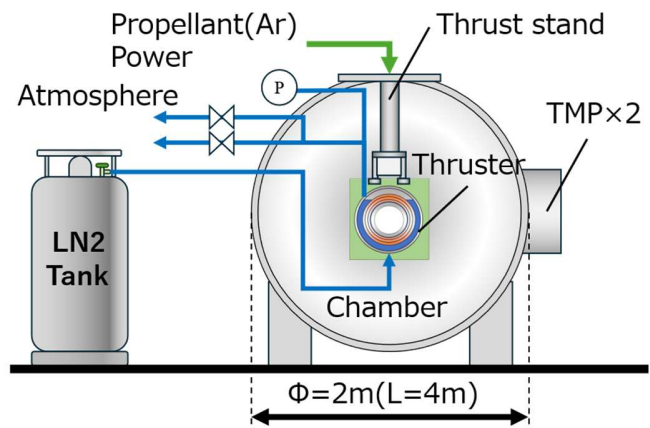


Figure 2. Schematic of the coil cooling system¹³.



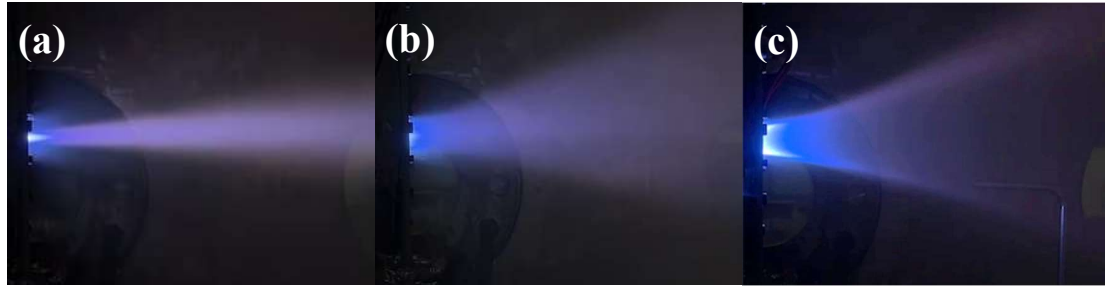


Figure 3. Images of plumes during discharge; HE rod(a), ThW rod(b) and ThW hollow(c).

The displacement of the thrust stand was amplified by a 1.1 m aluminum arm mounted outside the chamber and measured using a linear variable differential transformer (LVDT1301-2, Shinko Electron Co., Ltd.) installed at the tip of the arm. Copper pipes were positioned within the stand arm to supply discharge current, coil current, and propellant.

Figure 2 shows a schematic of the coil cooling system¹³. For steady-state operation with 0.4 T application using a water-cooled copper wire coil, a high-pressure water-cooling line is required, and errors of ± 350 mN originating from this cooling system have been reported¹⁴. However, by implementing cryogenic cooling using liquid nitrogen for the resistive copper wire coil, the resistivity is reduced to approximately 1/10 of that at room temperature. This reduction in Joule heating minimizes noise originating from the cooling system, enabling steady-state operation at 0.48 T and achieving an experimental system capable of thrust measurements in the order of 10 mN.

III. Result and Discussion

A. Thruster performances

Figure 3 shows the discharge images for each cathode. Compared to both the ThW rod and hollow cathodes, operation with the HE material rod cathode demonstrated a concentrated plume at the center of the thruster.

Figure 4 shows the obtained voltage characteristics. Since the operable experimental conditions differ for each configuration because of the difference in plasma ignitability, we have organized the results by plotting $J_d B^2 / \dot{m}$ on the horizontal axis, based on Fradkin's discharge voltage model¹⁵, which assumes that the discharge voltage is linearly determined by the Hall voltage generated by plasma rotation in a magnetic field:

Table 2. Fitting results of discharge voltage to Equation (1).

	V_0 [V]	β [-]
HE rod	50.2	0.011
ThW rod	60.6	0.016
ThW hollow	59.3	0.018

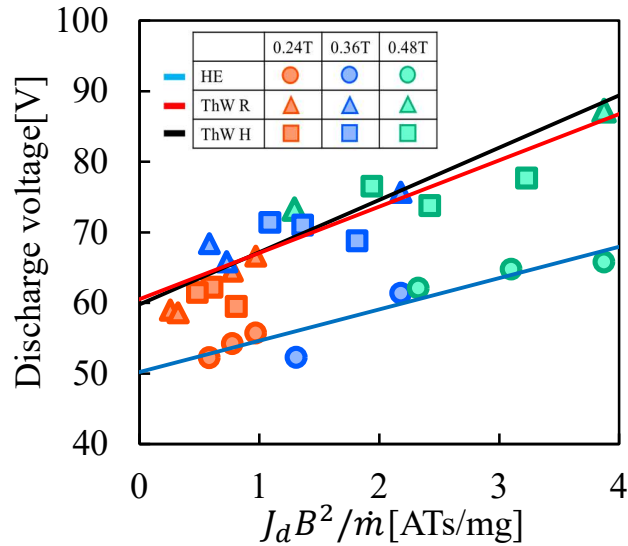


Figure 4. Discharge voltage characteristics.



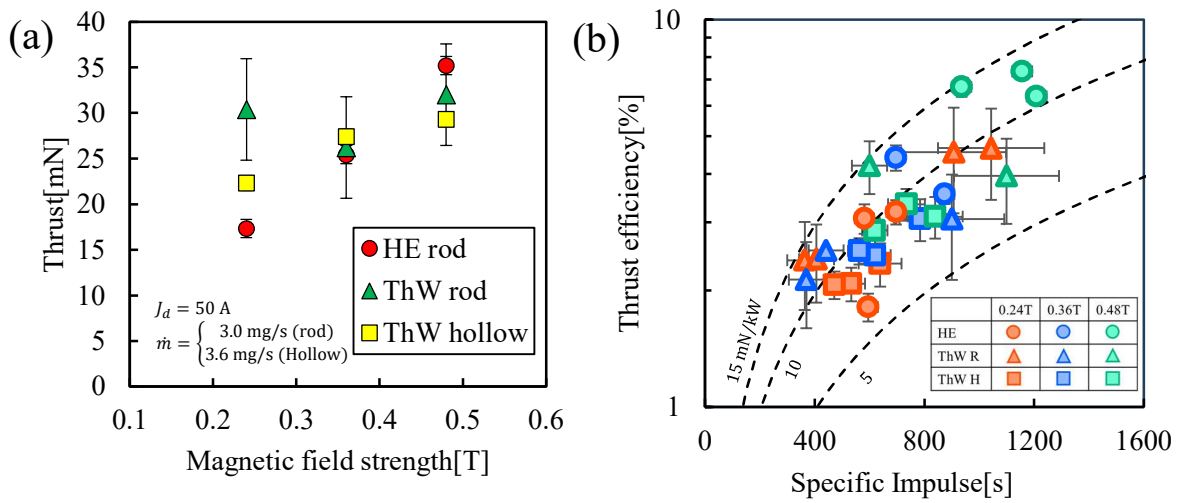


Figure 5. (a) Magnetic field strength dependence of thrust, (b) Thrust performance with different cathode materials.

$$V_d = V_0 + \beta \frac{J_d B^2 R_a^2}{\dot{m}} \quad (1)$$

The solid lines in the figure correspond to the predicted discharge voltages according to equation (1), obtained by liner regression for each configuration. The experimental results generally align with their respective regression lines. Whereas the ThW hollow cathode and rod cathode show relatively similar voltage characteristics, the HE material cathode demonstrated lower values for both V_0 (corresponding to the intercept) and β (corresponding to the slope) compared to the other configurations as shown in Table 2.

Figure 5a shows the thrust characteristics obtained with respect to the magnetic field. Since the same-condition operations for error evaluation are performed after the condition sweep, the errors include the influence of cathode damage, which will be described later. If we temporarily disregard the operation with the ThW rod cathode, which shows larger error compared to other operations, thrust is predicted to have a proportional relationship with the magnetic field based on simple $J_d B R_a$ models:

$$F = \gamma J_d B R_a \quad (2)$$

However, in the operation with the ThW hollow cathode, the gradient of thrust with respect to the magnetic field was observed to decrease with increasing magnetic field strength, whereas operation with the HE material rod cathode showed no such sensitivity decrease, exhibiting characteristics that followed the magnetic field more consistently.

Figure 5b shows the thrust performance under all operating conditions. Compared to other operations, the high-entropy material rod cathode operation at 0.48 T demonstrated higher thrust efficiency, achieving a maximum thrust efficiency of 7.4% at a specific impulse of 1157 s. At this point, the input power was 2.6 kW, with a thrust-to-power ratio of 13 mN/kW.

The difference between cathode characteristics observed in Figure 3 are presumed to originate from the cathode surface temperature distribution. Therefore, to qualitatively capture these differences, we conducted a one-dimensional heat transfer analysis that accounts for cross-sectional area changes to predict the temperature distribution. For simplicity, the following assumptions were made:

- Heat input, generation, and dissipation considered include ion-bombardment, Joule heating, and radiation
- Heat input due to ion bombardment is concentrated at the tip of the cathodes
- Secondary electron emission is neglected

Under these conditions, the current flowing from a differential element, temperature, and heat passing through that element can be determined using the Richardson-

Table 3. Properties used in the calculation.

	Work function[eV]	Thermal conductivity [W/(m · K)]
ThW	2.6	174
HE	4.3	13.8



Table 4. Result of thermal analysis.

	Heat input at cathode tip [W]
ThW rod	141.9
HE rod	45.9

Dushman equation¹⁶ for thermionic emission and values from the upstream differential element in the direction of current flow, as follows:

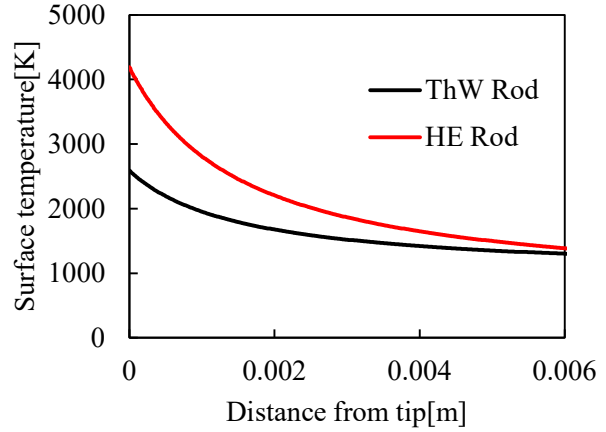


Figure 6. Expected axial temperature distribution.

$$j_i = S_{surf,i} A_{Richardson} T_i^2 \exp\left(-\frac{eW}{kT_i}\right) \quad (3)$$

$$T_i = T_{i+1} - Q_{i+1} \frac{\Delta x}{\kappa S_{cross,i}} \quad (4)$$

$$Q_i = Q_{i+1} - Q_{rad,i} + Q_{joule,i} \\ = Q_{i+1} - \varepsilon \sigma (T_i^4 - T_{out}^4) + R_i \sum_{k \geq i} j_k \quad (5)$$

The temperature distribution was determined by iteratively calculating the heat input at cathode tip that would match the sum of currents to the discharge current. The parameters used in the calculation are shown in Table 3.

Table 4 and Figure 6 show the analytical results obtained. The discharge current was set at 50 A. The high-entropy material cathode required less ion bombardment heat input compared to the thoriated tungsten cathode. Since this heating process requires acceleration of ions by biasing the cathode negatively relative to the space potential, the decrease in this bias voltage qualitatively explains the lower V_0 . Additionally, the high-entropy material cathode, with its lower thermal conductivity, exhibited higher temperatures at the tip with a steeper temperature gradient. Considering the Richardson-Dushman equation, this surface temperature trend is likely reflected in the current distribution as well, suggesting that the elevated temperature at the tip due to low thermal conductivity led to a plume concentrated near the central axis. Heat input is also considered to have a distribution; therefore, more detailed analysis requires measurement of cathode surface temperature distribution such as radiation temperature measurements.

Sasoh et al.¹⁷ theoretically demonstrated that the thrust of Applied-Field MPD thrusters is governed by a parameter:

$$\frac{\psi}{\psi_c} = \frac{\bar{\sigma}_e B^2 / \dot{m}}{1 / (2a\bar{\phi}^2 R_a^2 l)} = \frac{2a\bar{\phi}^2 R_a^2 l \bar{\sigma}_e B^2}{\dot{m}} \quad (6)$$

This parameter ψ/ψ_c can be considered as a ratio between Lorentz force due to the current generated by back electromotive force $\propto \bar{\sigma}_e(u_{ex}\bar{\phi}B)$ and thrust $\dot{m}u_{ex}$, and once this parameter exceeds a certain threshold, as the back electromotive force becomes significant, the thrust reaches a saturation point regardless of further increases in the magnetic field B . Additionally, it has been confirmed that azimuthal current (Hall current) is concentrated in regions of high plume luminosity and the acceleration region that determines a coincides with this high luminosity region. Thus, the enhanced performance of the HE material rod cathode in strong magnetic fields can be attributed to the reduction of a due to the concentration of azimuthal current near the thruster's central axis, as well as the maintenance of a low $\bar{\phi}$ (ratio between radial and axial magnetic field components), which decreases toward the central axis due to the divergent magnetic field configuration. These factors allowed ψ/ψ_c to remain below the threshold value even in strong magnetic field regions, thereby contributing to the observed performance improvement.



B. Cathode durability

Figure 7 shows ThW and HE ceramic cathodes after operations. In the ThW rod cathode, erosion was observed at the root of cathode protruding from the insulator, whereas in the HE material cathode, damage was seen in the form of tip collapse. In SF-MPD thrusters, it has been reported that discharge instability occurs in association with similar cathode root erosion, and Kuriki et al.¹⁸ have theoretically demonstrated that this is caused by the concentration of discharge current at the cathode root when the magnetic Reynolds number is excessively high. A similar phenomenon may also occur in AF-MPD under strong magnetic field operation.

The following parameter has been proposed for evaluating resistance to thermal shock R^{19} :

$$R = \frac{\sigma_f \kappa (1 - \nu)}{E \alpha} \quad (7)$$

As shown in Table 3, HE materials possess thermal conductivity κ an order of magnitude lower than ThW, resulting in a low value for this parameter. It is considered that the materials failed due to thermal shock during ignition when temperature gradients are particularly steep, indicating that durability represents a trade-off with thrust characteristics.

IV. Conclusion

In this study, we focused on high-entropy materials as cathode materials with excellent oxidation resistance and applied it to an AF-MPD thruster for operational experiments. Compared to thoriated tungsten, the conventional cathode material, we observed a plume concentrated along the thruster's central axis, reduced discharge voltage, and improved thrust and thrust performance in strong magnetic fields. These improvements are attributed to the low thermal conductivity of high-entropy materials, which resulted in particularly high temperatures at the tip, causing current concentration at this location. However, this temperature concentration is also linked to failure due to thermal shock, and for practical applications, it is necessary to identify the conditions under which both requirements can be satisfied.

Although the thrust efficiency obtained in this study is at maximum 7.4 %, operations using high-entropy materials demonstrated thrust and thrust performance improvements that responded consistently to magnetic field strength. This suggests that further performance enhancements can be expected with the application of stronger magnetic fields.

Acknowledgments

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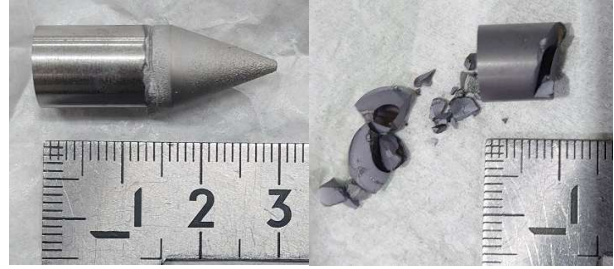


Figure 7. Appearance of cathodes after operations (left) thoriated tungsten, (right) HE material.



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