Ion Beam Diagnostics at a 5-kW Hall Thruster on Kr-Ar Mixture

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Abstract: Thruster performance and ion beam properties were analyzed at Kr-Ar mixture 5 kW-class P5 Hall thruster by conventional plasma diagnostics, a Faraday probe and an E×B probe. The discharge voltage and power of the thruster were fixed at 386 V and approximately 4.1 kW, respectively, while two different ratios of volumetric flow rates of Kr and Ar, 0% and 26%, were tested. Despite the higher ionization energy and lower mass of Ar than Kr, it was found that the performance parameters did not degrade even when mixing Ar by 26%, exhibiting similar levels of thrust, 103 mN and 102 mN, at the two operating setpoints, respectively. The measured ion properties, such as ion beam current density, and current and divergence utilization, were also similar between the two operating setpoints.

Nomenclature

T	=	Thrust
$\dot{m}_a$	=	Anode mass flow rate
V_d	=	Discharge voltage
I_{sp}	=	Specific impulse, $T/\dot{m}_a g$
I_d	=	Discharge current
I_b	=	Ion beam current
P_d	=	Discharge power, $V_d I_d$
η_a	=	Anode efficiency, $T^2/2\dot{m}_a P_d$
η_b	=	Beam current utilization, I_b/I_d
θ_m	=	Momentum-weighted plume angle
η_θ	=	Divergence utilization, $\cos^2\theta_m$

I. Introduction

UTILIZING alternative propellants is of great importance in Hall thruster-based missions due to the rising price of the conventional propellant, Xe gas. Kr is a popular replacement for Xe due to its relatively lower price while still providing decent performances [1–4]. Ar is another potential alternative propellant owing to its even lower price than that of Kr [5]. Despite the lower cost, using pure alternative inert-gas propellants inevitably faces lower performance due to their relatively higher ionization energy and lighter mass when compared to Xe gas [2,3]. Therefore, mixing two propellants may mitigate such a problem to a certain extent

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by leveraging the higher mass and lower ionization energy of the primary species to generate sufficient performance at a low total cost by mixing relatively inexpensive propellants.

In this study, we investigate 5-kW Hall thruster plasmas on a Kr-Ar mixture to understand the ion beam properties and thrust performance on propellant mixtures. Due to the different mass and ionization energy, the ionization inside the channel will be significantly varied as the fraction of the Ar mass flow rate is changed. We aim to understand the fundamental ion plume properties in Kr-Ar mixture plasmas by using ion beam diagnostics and measuring thrust at different Ar fractions across Kr. In this paper, we present the measured performances and ion properties at a fixed discharge voltage at two particular Kr-Ar mixture fractions, 0% and 26%-Ar case. Further in-depth analysis on wider range of the operating setpoints on Kr-Ar mixture is detailed on our recent publication [6].

II. Experimental setup

A 5 kW-class P5 Hall thruster, developed by the University of Michigan and Air Force Research Laboratory, was used to investigate Kr-Ar mixture plasmas [7]. The EPL HCPEE 500 hollow cathode was used to operate the thruster. The fraction between Ar and Kr was defined as the volumetric flow rate of Ar to the total anode volume flow rates, and the flow rates were controlled by two MKS GE50A controllers. Two different volumetric flow rate fractions were injected through the anode, and 0% or pure Kr and 26%-Ar cases were investigated. A small planum was used to mix Kr and Ar gases before being injected toward the anode. The test was conducted in Vacuum Test Facility (VTF) 1 at Georgia Tech, where the operating pressure of approximately 2.4×10^{-5} Torr-Kr was maintained at 79.7 sccm Kr. The cathode maintained pure Kr of 6.5 sccm.

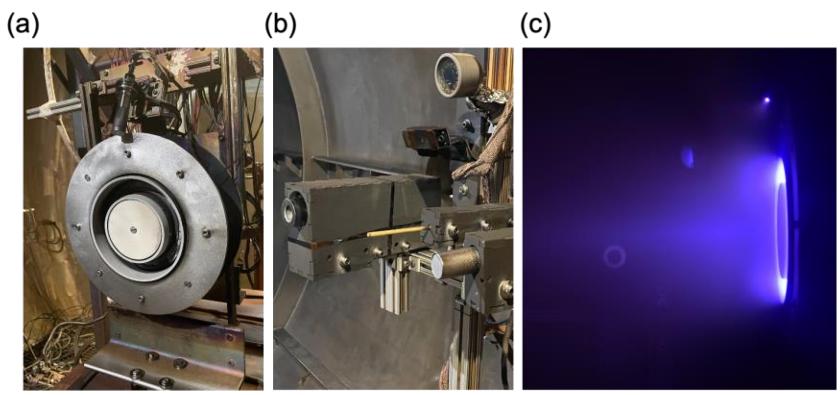

Fig. 1 (a) P5 Hall thruster mounted on the inverted pendulum thrust stand and (b) ion plume diagnostics. (c) Thruster operation at 26% Ar-case.

Subsequently, an E×B probe and a Faraday probe were utilized to measure the multiply charged ions and ion beam current density, respectively. The probe measurements were taken 1 m downstream of the thruster exit plane. A null-type, inverted pendulum thrust stand was used to measure the thrust [8], from which the specific impulse and anode efficiency were calculated. The average thrust was derived by three measurements at the same operating setpoints at different operations. Figure 1 shows the P5 Hall thruster and plasma diagnostics in VTF 1.

III. Experimental Results

For the tests at 0% and 26%-Ar cases, the discharge voltage was fixed as 386 V with discharge currents of 10.6 A and 10.8 A, respectively. Therefore, the discharge power was kept nearly constant at 4.1 kW and 4.2 kW in this study to investigate the impact of the Ar mixture. The magnetic field also maintained the same. The mass flow rate of the 0%-Ar case was 79.0 sccm Kr, while 61.9 sccm Kr and 22.3 sccm Ar were used in the 26%-Ar case. The details of the operating setpoints are shown in Table 1.

Table 1. Operating setpoints of P5 Hall thruster

Case	V_d (V)	I_d (A)	P_d (kW)	Kr (sccm)	Ar (sccm)	Ar %
1	386	10.6	4.1	79.0	0	0
2	386	10.8	4.2	61.9	22.3	26

The thruster was operated for a sufficient time to reach above 200°C of the thruster body before the measurement. The thrust, T, measured at the two Ar cases, manifested similar levels of 103 mN and 102 mN at the 0% and 26%-Ar cases, respectively. The specific impulse, $I_{sp} = T/\dot{m}g$, were 2120 s and 2280 s, and the anode efficiency, $\eta_a = T^2/2\dot{m}_a P_d$, of 26% and 27%, respectively, where $\dot{m}_a$ is the total anode mass flow rate and P_d is the discharge power. The thruster performances measured in this study were relatively lower than those in other studies of krypton at similar anode power. However, further optimization in terms of thruster performance could be made in future research while the discussion this study concentrates on, the impact of propellant mixtures, can still remain valid.

At each operating setpoint, the ion beam properties were measured. Figure 2 exhibits the measured E×B probe traces and angular profiles of the ion beam current density $j_b(\theta)$ in the two cases. The fraction of the multiply charged ion at the pure Kr, 0%-Ar case, was estimated by fitting two separate Gaussian curves on the trace, which resulted in approximately 20% of the Kr^{2+} ion current. The velocities of the Kr^{2+} and Ar^{+} ions lay almost the same when comparing the 0% and 26%-Ar cases. This can be also inferred from the fact that the ion velocity ratio of the two ion species mostly depends on the ratios of charge and mass, i.e., $v_{Kr^{2+}}/v_{Ar^{+}} \sim \sqrt{2M_{Ar}/M_{Kr}} \sim 0.97$ assuming an identical acceleration voltage. The mass of Kr is almost twice as heavy as the Ar mass, which provides similar velocities between the Kr^{2+} and Ar^{+} ions. The ion beam current and plume angles were derived from the angular profiles of the ion beam current density measured by the Faraday probe. The correction of the measured ion beam current was conducted considering the multiply charged ions and the thruster geometry deviating from a point source using the method suggested by Ref. [9]. Subsequently, the beam current utilization, $\eta_b = I_b/I_d$, and divergence utilization $\eta_\theta = \cos^2\theta$, were calculated. The results for 0% and 26%-Ar cases are summarized in Table 2.

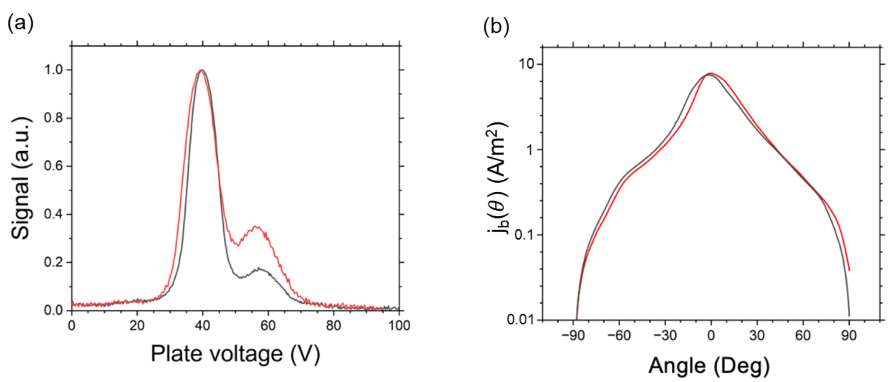

Fig. 2 (a) Measured E×B traces and (b) angular profiles of the ion beam current density $j_b(\theta)$ of the P5 Hall thruster at 4.2 kW. Black and red curves indicate the dataset at the 0% and 26%-Ar cases, respectively.

Table 2. Measured thrust performances and ion plume properties at the operating setpoints

Case	*T (mN)*	I_{sp} *(s)*	η_a	η_b	η_θ
1	103	2120	0.26	0.45	0.66
2	102	2280	0.27	0.46	0.65

Even though the Kr neutral particles were replaced by Ar with a volumetric fraction of 26%, the analyzed ion beam properties from the probes and measured thrust manifested negligible differences when compared to each other. The in-depth study in terms of ionization has been discussed in our recent paper [6], where most of the analysis was made on the lower discharge voltages to keep a wide range of Ar fractions at the same magnetic field.

IV. Conclusion

The ion beam properties and thrust performances of the 5 kW-class P5 Hall thruster operating on Kr-Ar mixture were investigated. The thrust at the 26%-Ar case was 102 mN, which was almost the same as that of the 0% case, 103 mN, even though the Kr was replaced by Ar which has a higher ionization energy and lower mass. The ion beam current and divergence were also similar. Further analysis based on various plume diagnostics will be conducted to figure out the cause of the similar thrust generated by two operating conditions.

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