Voltage-Current Characteristics of Self-field Magnetoplasmadynamic Thrusters: Modeling and Application to Lithium Propellant

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A non-dimensional voltage-current (V–J) model for self-field magnetoplasmadynamic thrusters (SF-MPDTs) is developed and compared to experimental data from a lithium-fed 30 kW-class thruster. Starting from first principles and incorporating physical scaling for thrust and dissipative sinks, the model yields a closed-form expression for the non-dimensional voltage as a function of the MPDT electromagnetic scaling number, $\xi = J/J_{ci}$, where J_{ci} is the critical ionization current. The model accounts for ionization, thermal, and electrode losses, and predicts a universal $\widehat{V}(\xi)$ relationship valid across operating regimes with no free parameters. Validation using experimental data in the $\xi \leq 1$ regime demonstrates agreement down to $\xi \simeq 0.25$. This universal model enables predictive scaling of SF-MPDT performance and provides a foundation for future analytical and experimental studies, including forthcoming higher-power lithium MPDT testing.

Nomenclature

V = Voltage
J = Current
J_{ci} = Critical ionization current
T = Thrust
μ_0 = Magnetic permeability constant
ϵ = First ionization potential
k = Boltzmann constant
σ = Conductivity
M = Ion mass
r_a = Anode radius
r_c = Cathode radius
C_T = Thrust coefficient
$\dot{m}$ = Propellant mass flow rate
ξ = Ratio of discharge current to critical ionization current (MPDT scaling number)

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I. Introduction

THE voltage-current (V–J) characteristics of self-field magnetoplasmadynamic thrusters (SF-MPDTs) provide a direct reflection of device energetics, capturing the scaling and interplay of key energy sinks: acceleration (back EMF), heating, excitation, dissociation, ionization, and electrode-region dissipation. For molecular propellants, internal modes are also significant. An accurate, experimentally validated analytical V–J model, when coupled with a thrust production model, is essential for understanding SF-MPDT performance scaling and guiding design improvements. With growing interest in lithium-fed MPDTs, applying such models to lithium propellants is of both fundamental and practical value.

From a modeling perspective, prior work by Maecker,[2] Tikhonov,[3] and Choueiri[1,4] has advanced the predictive capabilities of SF-MPDT models. However, these efforts have yet to yield a fully non-dimensional model that robustly captures the scaling of energetic sinks across both high-current ($\xi > 1$) and low-current ($\xi < 1$) regimes.

In this work, experimental data obtained in our laboratory from a 30 kW lithium-fed SF-MPDT operated in the self-field mode below the critical ionization current are used to validate a proposed non-dimensional formulation of the voltage model. The model is designed to capture the relative scaling of major energy sinks with no reliance on empirical fitting parameters.

The paper begins by deriving the voltage model from first principles, then presents a non-dimensionalization framework using the MPDT scaling number ξ. We then compare the model to experimental data to determine the extent of its validity.

II. Voltage-Current Model of the SF-MPDT

Our objective is to develop a 0-D, non-dimensional V–J model that is both simple enough for insightful parametric exploration and sufficiently rigorous to retain the essential scaling behavior of the relevant energetic sinks. These are illustrated schematically in Fig. 1.

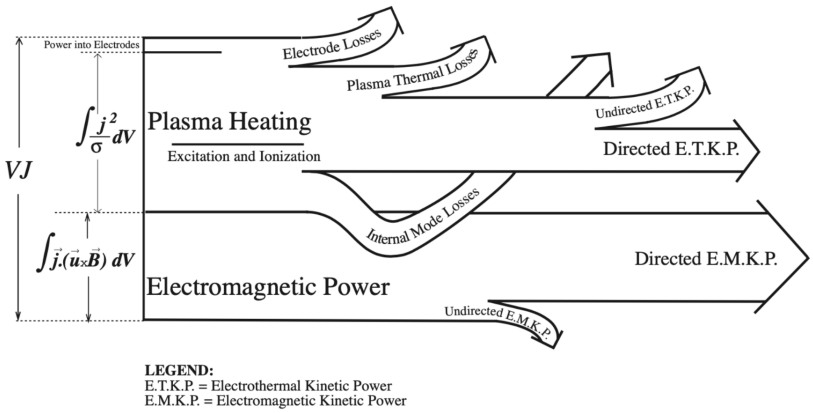


Figure 1: Arrow diagram showing the useful and dissipative energetics of a typical MPDT. From Ref.[7]

A. Derivation of the Dimensional Model

We begin with a first-principles derivation based on the generalized Ohm's law[6] for a conducting plasma in the MHD regime:

$$\boldsymbol{E}' = \frac{1}{\sigma}\left[\boldsymbol{j} + \Omega_e \frac{\boldsymbol{j}\times\boldsymbol{B}}{B} + s\frac{\boldsymbol{B}\times(\boldsymbol{j}\times\boldsymbol{B})}{B^2}\right], \tag{1}$$

where $\boldsymbol{E}' = \boldsymbol{E} + \boldsymbol{u}\times\boldsymbol{B}$ is the electric field in the electron rest frame. Here, $\sigma = n_e e^2/m_e\bar{\nu}_e$ is the scalar conductivity, $\Omega_s = \omega_{cs}/\bar{\nu}_s$ is the Hall parameter for species s, and $s = (\rho_n/\rho)^2\Omega_e\Omega_i$ is the ion slip factor. For the SF-MPDT, the plasma is typically highly collisional and sufficiently ionized that the ion slip term is negligible:[4]

$$\boldsymbol{j} = \sigma\boldsymbol{E}' - \Omega_e\frac{\boldsymbol{j}\times\boldsymbol{B}}{B}.$$

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Taking the dot product with $\boldsymbol{j}$, and using $\boldsymbol{j} \cdot (\boldsymbol{j} \times \boldsymbol{B}) = 0$:

$$\frac{j^2}{\sigma} = \boldsymbol{j} \cdot \boldsymbol{E}' = \boldsymbol{j} \cdot \boldsymbol{E} - \boldsymbol{u} \cdot (\boldsymbol{j} \times \boldsymbol{B}). \tag{2}$$

This gives a power balance between Ohmic dissipation and the electrical work done on the plasma.

Integrating over the discharge volume $\mathcal{V}$:

$$\int_{\mathcal{V}} \boldsymbol{j} \cdot \boldsymbol{E}\, d\mathcal{V} = \int_{\mathcal{V}} \boldsymbol{u} \cdot (\boldsymbol{j} \times \boldsymbol{B})\, d\mathcal{V} + \int_{\mathcal{V}} \frac{j^2}{\sigma}\, d\mathcal{V}. \tag{3}$$

The left-hand side represents total power input (excluding sheath drops), while the first term on the right corresponds to the Lorentz work that produces thrust, which we approximate as $T^2/2\dot{m}$, and the second term is Ohmic dissipation.

Including sheath effects, the power input becomes $J(V - V_e)$, where $V_e = V_c + V_a$ is the sum of cathode and anode sheath drops. This yields:

$$J(V - V_e) = \frac{T^2}{2\dot{m}} + \int_{\mathcal{V}} \frac{j^2}{\sigma}\, d\mathcal{V}. \tag{4}$$

Solving for V gives the general dimensional V–J model:

$$V = \underbrace{\frac{T^2}{2J\dot{m}}}_{\text{Thrust production}} + \underbrace{\frac{1}{\sigma}\int_{\mathcal{V}} j^2\, d\mathcal{V}}_{\text{Ohmic losses}} + V_e. \tag{5}$$

We next express the thrust T in terms of the current J using the thrust coefficient C_T:[1]

$$T = \frac{\mu_0}{4\pi} C_T J^2, \tag{6}$$

where C_T includes contributions from pinching, blowing, and electrothermal effects.

We define the dissipation integral as:

$$I_D \equiv \int_{\mathcal{V}} j^2\, d\mathcal{V},$$

which accounts for all losses not contributing to thrust, including ionization losses ($\dot{m}\epsilon_i/M$) and unrecaptured thermal energy (typically $\sim 2kT_e/e$). (The dissipation integral has been analyzed and discussed recently by Choueiri.[4]) This gives a dissipation-related voltage drop:

$$V_{\text{in}} = \frac{\dot{m}}{JM}\left(\epsilon_i + 2\frac{kT_e}{e}\right). \tag{7}$$

Finally, we add the electrode voltage drop:

$$V_e = V_c + V_a = \frac{2kT_e}{e} + \phi_{wfa} + \frac{2kT_{ea}}{e}, \tag{8}$$

where ϕ_{wfa} is the work function of the anode material (e.g., tungsten).

Substituting all components, we obtain the full dimensional voltage model:

$$V = \underbrace{\frac{\left(\frac{\mu_0}{4\pi}C_T\right)^2 J^3}{2\dot{m}}}_{\text{Thrust production}} + \underbrace{\frac{\dot{m}}{JM}\left(\epsilon_i + 2\frac{kT_e}{e}\right)}_{\text{Ionization and thermal losses}} + \underbrace{\frac{2kT_e}{e} + \phi_{wfa} + \frac{2kT_{ea}}{e}}_{\text{Electrode voltage}}. \tag{9}$$

III. The Electromagnetic Scaling Number

A central feature of SF-MPDT physics is the role of the non-dimensional scaling parameter ξ, known as the MPDT scaling number. Introduced by Choueiri,[1] this parameter captures key performance trends observed in experiments, including the scaling of thrust, voltage, ionization level, and discharge symmetry.

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The parameter ξ is tied to the concept of *nominal operation*, defined as the operating point at which the directed kinetic power in the exhaust equals the ionization power sink, assuming that the full mass flow rate is ionized to the first ionization potential ϵ_i:

$$\frac{1}{2}Tu_{ex} = \dot{m}\frac{\epsilon_i}{M}. \tag{10}$$

This equipartition is supported by prior work showing that ionization is a dominant energy sink, comparable to thrust power under nominal conditions.[8] Spectroscopy also indicates that less than 10% of ionization energy is recovered in the exhaust, with up to 85% of internal energy stored in ionization.[9]

Expressing this nominal condition in terms of the current yields:

$$\left(\frac{\mu_0}{4\pi}C_T\right)^2 J^4 = \dot{m}^2 u_{ci}^2, \tag{11}$$

where the critical ionization velocity u_{ci} is defined as:

$$u_{ci} \equiv \left(\frac{2\epsilon_i}{M}\right)^{1/2}. \tag{12}$$

For common propellants, u_{ci} is:

- Xenon: 4.22 km/s
- Krypton: 5.68 km/s
- Argon: 8.72 km/s
- Lithium: 12.24 km/s

The current at which nominal operation occurs is the *critical ionization current*, J_{ci}:

$$J_{ci} = \left(\frac{\dot{m}u_{ci}}{b}\right)^{1/2}, \tag{13}$$

where

$$b = \frac{\mu_0}{4\pi}C_T^*, \tag{14}$$

and C_T^* is the thrust coefficient evaluated at $J = J_{ci}$.

We define the MPDT scaling number ξ as:

$$\xi \equiv \frac{J}{J_{ci}}, \tag{15}$$

which, when written in terms of thruster parameters, becomes:

$$\xi = \frac{J}{\left[\dot{m}^{1/2}(2\epsilon_i/M)^{1/4} \,/\, \left(\frac{\mu_0}{4\pi}C_T^*\right)^{1/2}\right]}. \tag{16}$$

At $\xi = 1$, the thruster operates at nominal conditions with a nominal specific impulse $I_{sp} = u_{ci}/g_0$, independent of input power.

Choueiri[1] proposed a semi-empirical expression for $C_T(\xi)$ of the form:

$$C_T = \frac{\dot{m}_t/\dot{m}^*}{\xi^4} + \ln\left(\frac{r_a}{r_c} + \xi^2\right), \tag{17}$$

where $\dot{m}^*$ is a fitting parameter with units of mass flow rate, found to be approximately constant across operating conditions for noble gas propellants ($\dot{m}^* = 66$ mg/s for Ar, Kr, Xe).

For $\xi < 1$, the ξ^{-4} term dominates, highlighting the need for a physically motivated alternative to empirical fits, especially since thrust data for lithium-fed SF-MPDTs are limited. Furthermore, we seek a universal formulation independent of empirical parameters.

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Tikhonov[3] proposed a physical model for C_T based on cylindrical MHD flow in a plasma pinch, under assumptions of quasi-1D, isothermal, high magnetic Reynolds number flow. The thrust coefficient is given by:

$$C_T = \frac{1}{2\alpha_0^2} + \frac{\gamma+1}{2}, \tag{18}$$

where α_0 is a dimensionless parameter:

$$\alpha_0 = \frac{\gamma\mu_0}{8\pi a_0}\frac{J^2}{\dot{m}}, \tag{19}$$

with γ the specific heat ratio (5/3 for monatomic gases), and a_0 the ion acoustic speed upstream.

In the $\xi < 1$ regime, the α_0^{-2} term dominates, and we use it to replace the empirical ξ^{-4} scaling, giving:

$$C_T = \frac{1}{2\alpha_0^2} + \ln\left(\frac{r_a}{r_c} + \xi^2\right). \tag{20}$$

Next, we express α_0 in terms of ξ. Using $J = \xi J_{ci}$ and $J_{ci}^2 = \dot{m}_t u_{ci}/b$:

$$\frac{J^2}{\dot{m}_t} = \xi^2\frac{J_{ci}^2}{\dot{m}_t} = \xi^2\frac{u_{ci}}{b},$$

which gives:

$$\alpha_0 = \frac{\gamma\mu_0}{8\pi c_s}\xi^2\frac{u_{ci}}{b}.$$

Substituting $b = \frac{\mu_0}{4\pi}C_T^*$ yields:

$$\alpha_0 = \frac{\gamma}{2}\frac{u_{ci}}{c_s}\frac{\xi^2}{C_T^*}, \qquad \alpha_0^{-2} = \left(\frac{2}{\gamma}\right)^2\left(\frac{c_s}{u_{ci}}\right)^2\frac{C_T^{*2}}{\xi^4}.$$

Since $u_{ci}^2 = 2\epsilon_i/M$ and $c_s^2 = kT_e/M$, we obtain:

$$\frac{c_s^2}{u_{ci}^2} = \frac{kT_e/M}{2\epsilon_i/M} = \frac{kT_e}{2\epsilon_i}, \qquad \Rightarrow \alpha_0^{-2} = \frac{2}{\gamma^2}\frac{kT_e}{\epsilon_i}\frac{C_T^{*2}}{\xi^4}.$$

Thus, the final expression for the physically based thrust coefficient is:

$$C_T(\xi) = \frac{1}{\gamma^2}\frac{kT_e}{\epsilon_i}\frac{C_T^{*2}}{\xi^4} + \ln\left(\frac{r_a}{r_c} + \xi^2\right). \tag{21}$$

IV. Non-Dimensionalization of the Voltage Model

To construct a universal, parameter-free expression for the voltage, we now reformulate the dimensional model in Eq. (9) using the MPDT scaling number ξ and the physically derived expression for $C_T(\xi)$ from Eq. (21).

First, note that for $\xi < 1$, only a fraction of the total mass flow $\dot{m}_t$ is ionized and accelerated. Choueiri and Di Lauro[4] showed that this ionized fraction scales linearly with ξ, justifying the relation:

$$\dot{m} = \xi\dot{m}_t, \qquad (\xi \le 1). \tag{22}$$

Experimental evidence (presented in the next section) also shows that T_e and T_{ea} scale linearly with ξ in this regime. Thus, we adopt the forms:

$$T_e = \xi T_e^*, \qquad T_{ea} = \xi T_{ea}^*, \qquad (\xi \le 1), \tag{23}$$

where T_e^* and T_{ea}^* are the electron temperatures at nominal operation ($\xi = 1$).

Substituting into Eq. (9) gives:

$$V = \underbrace{\frac{\left(\frac{\mu_0}{4\pi}C_T\right)^2 J^3}{2\dot{m}}}_{\text{Thrust term}} + \underbrace{\frac{\dot{m}}{JM}\left(\epsilon_i + 2\frac{kT_e}{e}\right)}_{\text{Ionization and thermal losses}} + \underbrace{\frac{2kT_e}{e} + \phi_w + \frac{2kT_{ea}}{e}}_{\text{Electrode voltage}}, \tag{24}$$

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where

$$C_T(\xi) = \frac{1}{\gamma^2}\frac{kT_e}{\epsilon_i}\frac{C_T^{*2}}{\xi^4} + \ln\left(\frac{r_a}{r_c} + \xi^2\right),$$
$$T_e = \xi T_e^*, \qquad T_{ea} = \xi T_{ea}^*,$$
$$J = \xi J_{ci}, \qquad \dot{m} = \xi \dot{m}_t.$$

The thrust term becomes:

$$V_{\text{Thrust}}(\xi) = \frac{1}{2}\left(\frac{\mu_0}{4\pi}\right)^2 \frac{J^3}{\dot{m}} C_T(\xi)^2 = \frac{1}{2}\left(\frac{\mu_0}{4\pi}\right)^2 \frac{J_{ci}^3}{\dot{m}_t}\xi^2 C_T(\xi)^2. \tag{25}$$

We define the reference voltage as the thrust voltage term evaluated at $\xi = 1$:

$$V_{\text{ref}} \equiv V_{\text{Thrust}}(1) = \frac{1}{2}\left(\frac{\mu_0}{4\pi}\right)^2 \frac{J_{ci}^3}{\dot{m}_t} C_T^{*2}. \tag{26}$$

We subtract the electrode voltage before normalizing:

$$V'(\xi) \equiv V(\xi) - V_{\text{el}} = V_{\text{Thrust}}(\xi) + \frac{\dot{m}}{JM}\left(\epsilon_i + 2\frac{kT_e}{e}\right), \tag{27}$$

$$V_{\text{el}} = \frac{2kT_e}{e} + \phi_w + \frac{2kT_{ea}}{e}. \tag{28}$$

Dividing by V_{ref} gives the normalized voltage:

$$\widehat{V}(\xi) \equiv \frac{V'(\xi)}{V_{\text{ref}}} = \xi^2\left(\frac{C_T(\xi)}{C_T^*}\right)^2 + \frac{\frac{\dot{m}}{JM}\left(\epsilon_i + 2\frac{kT_e}{e}\right)}{V_{\text{ref}}}. \tag{29}$$

Since $\dot{m}/J = \dot{m}_t/J_{ci}$ is independent of ξ:

$$\frac{\frac{\dot{m}}{JM}\left(\epsilon_i + 2\frac{kT_e}{e}\right)}{V_{\text{ref}}} = \left(1 + \frac{2kT_e}{e\epsilon_i}\right)\frac{\left(\frac{4\pi}{\mu_0}\right)^2 b^2}{C_T^{*2}}, \tag{30}$$

with $b = \frac{\mu_0}{4\pi}C_T^*$, which reduces the expression to:

$$\widehat{V}(\xi) = \xi^2\left(\frac{C_T(\xi)}{C_T^*}\right)^2 + \kappa, \tag{31}$$

where

$$\kappa \equiv 1 + \frac{2kT_e}{e\epsilon_i}. \tag{32}$$

This equation defines a universal, non-dimensional voltage model $\widehat{V}(\xi)$, fully specified by known physical constants and measurable quantities.

V. Comparison with Li-MPDT Experimental Data

At present, self-field MPDT voltage-current data are scarce, as most prior measurements were conducted with externally applied magnetic fields. While new experiments are underway at Princeton using a 30 kW-class lithium-fed MPDT, one useful data set already exists. It was acquired in our laboratory by Lev,[5] who tested the same thruster in the self-field mode at three different mass flow rates. Conveniently for this study, Lev also measured the anode voltage drop under the same conditions, allowing us to evaluate the electrode fall term in our model.

Figure 2 shows the measured total voltage as a function of discharge current for $\dot{m} = 5$, 8, and 20 mg/s.

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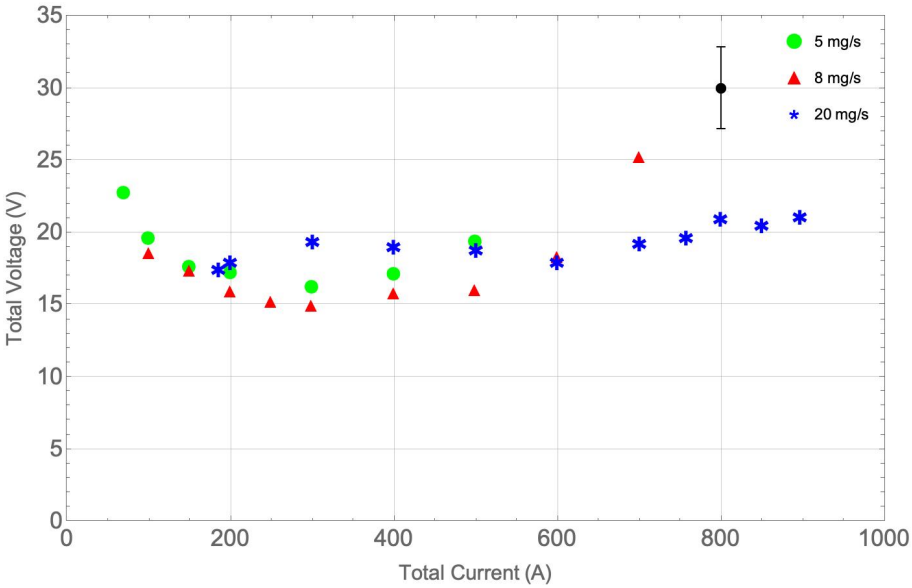


Figure 2: Measured total voltage vs. current for the Princeton 30 kW Li-MPDT at three values of the mass flow rate ($\dot{m} = 5, 8, 20$ mg/s). Adapted from Ref.[5]

Lev also performed emissive probe measurements to determine the anode voltage drop V_a, using a probe placed 1 mm from the anode surface. These data were used to extract the effective electron temperature near the anode, T_{ea}, assuming:

$$V_a = \phi_{wfa} + \frac{2kT_{ea}}{e}, \tag{33}$$

where $\phi_{wfa} = 4.53$ eV is the work function of tungsten. The linear fits of V_a as a function of ξ yield the following $T_{ea}(\xi)$ profiles:

- $T_{ea}(\xi) = 7.4\,\xi \pm 1.9$ eV at 5 mg/s,
- $T_{ea}(\xi) = 6.3\,\xi \pm 2.9$ eV at 8 mg/s,
- $T_{ea}(\xi) = 6.4\,\xi \pm 3.3$ eV at 20 mg/s.

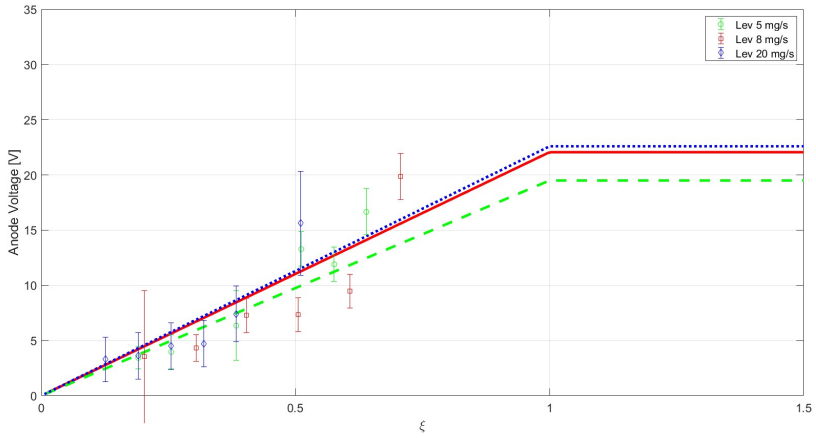


Figure 3: Linear fits of the emissive probe voltage 1 mm from the anode surface, used to determine T_{ea} as a function of ξ for $\dot{m} = 5, 8, 20$ mg/s.

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To validate the universal voltage model of Eq. (31), we compute the normalized voltage $\widehat{V}(\xi)$ for each data point using:

$$\widehat{V}(\xi) = \frac{V(\xi) - V_{\text{el}}}{V_{\text{ref}}}, \tag{34}$$

where V_{ref} is defined in Eq. (26), and V_{el} includes both cathode and anode contributions:

$$V_{\text{el}} = \frac{2kT_e}{e} + \phi_{wfa} + \frac{2kT_{ea}}{e}. \tag{35}$$

For the comparison, we used the following parameter values consistent with the experimental configuration:

- $r_a/r_c = 2.99$,
- $\phi_{wfa} = 4.53$ eV,
- $T_e^* = 2$ eV,
- $\gamma = 5/3$,
- $\epsilon_i = 5.4$ eV (Li).

Figure 4 shows the non-dimensional experimental data overlaid with the universal model $\widehat{V}(\xi)$.

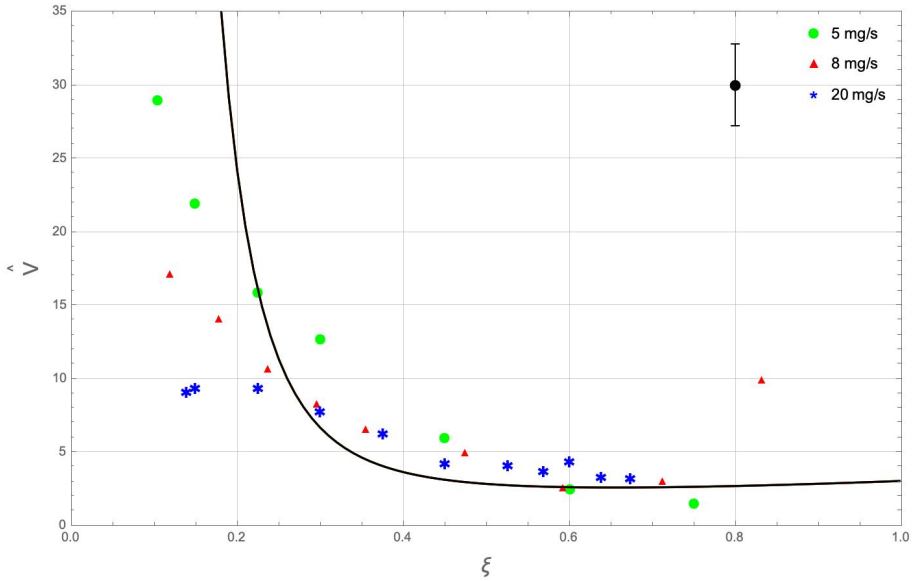


Figure 4: Comparison of the universal voltage model in Eq. (31) with non-dimensionalized experimental data for $\dot{m} = 5, 8, 20$ mg/s in the $\xi \leq 1$ regime.

The universal model, derived with no empirical fitting parameters, agrees with the experimental data within experimental error down to approximately $\xi \approx 0.25$. Below this threshold, deviations are expected due to the breakdown of assumptions underpinning the thrust coefficient model—specifically, the assumption of a confined pinch region (implicit in the derivation of the first term of the thrust coefficent in Eq. 21), which becomes less valid at low current.

These results lend confidence to the proposed universal model as a predictive tool for SF-MPDT behavior across sub-nominal conditions. Further experimental validation—especially in the $\xi \geq 1$ regime—is forthcoming from ongoing testing at Princeton (30 kW) and NASA-JPL (200 kW).

Acknowledgments

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