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The Physics and Limitations of Efficiency in Electrospray Thrusters

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Passively-fed Porous-media Electrospray Efficiency

Ionization Efficiency: $\eta_i = \frac{\dot{m}_i}{\dot{m}} \approx 1$

Total Efficiency: $\eta_T = \eta_i \, \eta_{tr}^2 \, \eta_\theta \, \eta_\epsilon \, \eta_p$

Specific Impulse: $I_{sp} = \frac{T}{\dot{m}\, g}$

Propulsion Efficiency: $\eta_{prop} = \frac{T^2}{2\, \dot{m}\, P_{in}}$

T, g and $P = I_{em} V_{em}$ known, however for passively-fed, porous-media electrosprays $\dot{m}$ is more complicated:

For example AFET-2 using EMI-BF4 should in theory have the following efficiencies

Emission Mode	η_i	η_{tr}	η_θ	η_ϵ	η_p	η_T
Positive Emission	100 (assumed)	99.3 %	71.6 %	94.5 %	93.8 %	**62.6 %**
Negative Emission	100 (assumed)	99.6 %	72.6 %	96.8 %	91.9 %	**64.1 %**
Overall Emission	100 (assumed)	99.5 %	72.1 %	95.7 %	92.9 %	**63.5 %**

Methods of Estimating Mass Flow Rate

Three primary methods of estimating the mass flow rate found in the literature:

Emission Current (EC)

$$\dot{m}_{EC} = \frac{I_{em}}{q} \sum_n m_n f_n$$

- allows fast in-situ measurement
- assumes all mass flow in the form of ion current

Time-of-Flight Current (ToF)

$$\dot{m}_{ToF} = \frac{4\, V_{em}}{D_f^2} \int_0^{\infty} I(t)\, t\, dt$$

$$T_{ToF} = \frac{2\, V_{em}}{D_f} \int_0^{\infty} I(t)\, dt$$

Thruster Mass Loss (TML)

$$\langle \dot{m} \rangle_{TML} = \frac{\Delta m}{\Delta t}$$

- only allows average to be calculated
- requires removing thruster from vacuum

For AFET-2 using EMI-BF4

Calculation Method	$\dot{m}$	I_{sp}	η_{prop}
Multiplied Efficiencies	-	-	63.5 %
Emission Current	0.58 µg/s	3439 s	66.8 %
Time-of-Flight Current	0.51 µg/s	3135 s	48.5 %
Thruster Mass Loss	1.42 µg/s	1436 s	24.3 %

$\eta_i = 1$ assumed

Efficiency Discrepancy Problem

Problem:

- Recent tests suggest the presence of an anomalous mass loss mechanism during thruster operation

$$\dot{m}_a = \dot{m} - \dot{m}_i - \dot{m}_v$$

- $\dot{m}_v$: Mass flow due to finite vapor pressure; Obtained from thruster outgassing tests
- $\dot{m}_i$: Mass flow due to ion emission; Obtained from Time-of-flight data
- $\dot{m}$: Total mass flow; Obtained from thruster mass change during test campaign
- $\dot{m}_a$: Mass flow due to anomalous process which occurs only during firing

$$\langle \dot{m} \rangle = \frac{\Delta m}{\Delta t}$$

$$\dot{m}_i \approx \frac{4\, V_{em}}{D_f^2} \int_0^{\infty} I(t)\, t\, dt$$

where $\dot{m}_v + \dot{m}_a > 0$ → reduced mass utilization efficiency, $\eta_m = \frac{\dot{m}_i}{\dot{m}}$