Modelling of Colloid Thrusters for Mission Analysis

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Abstract: The development of Colloid Thrusters requires adequate techniques to assess the capabilities of a given propulsive system. In the present paper we introduce methods to model thrusters either containing *N* different deterministic beam species, beams with specific charge probabilistic distribution or a combination of both.

These models are used to obtain the propulsive parameters of two different electrospray sources, one single source operating at high ion fraction regimes and a thruster head of 64 microfabricated emitters with a droplet dominated regime.

Nomenclature

α_i	=	fraction of beam current carried by specie *i*
η_θ	=	angular efficiency
η_Φ	=	acceleration efficiency
η_p	=	polydispersive efficiency
η_T	=	thrust efficiency
θ	=	beam half angle
ξ	=	specific charge
$\langle\xi\rangle$	=	average specific charge
Φ_A	=	accelerating voltage
Φ_{deff}	=	accelerating voltage loss
ϱ	=	specific mass
c_v	=	coefficient of variance (relative standard deviation)
f	=	probability density distribution
g	=	gravity
I_b	=	beam current
k	=	power to thrust ratio
$\dot{m}$	=	mass flow rate
SI	=	specific impulse
T	=	thrust

I. Introduction

The rapid increase in market share for SmallSats[1,2] and the future deployment of large constellations (OneWeb, SpaceX)[3,4] have made the development of propulsive systems capable of providing a thrust at both high SI and efficiency but at low cost whilst operating at low power crucial.

Amongst the several competing technologies trying to deliver these requirements including micro ion thrust[5] or FEET[6], the Colloid Thruster (CT)is a clear candidate to achieve this goal. Different Colloid Thruster concepts are

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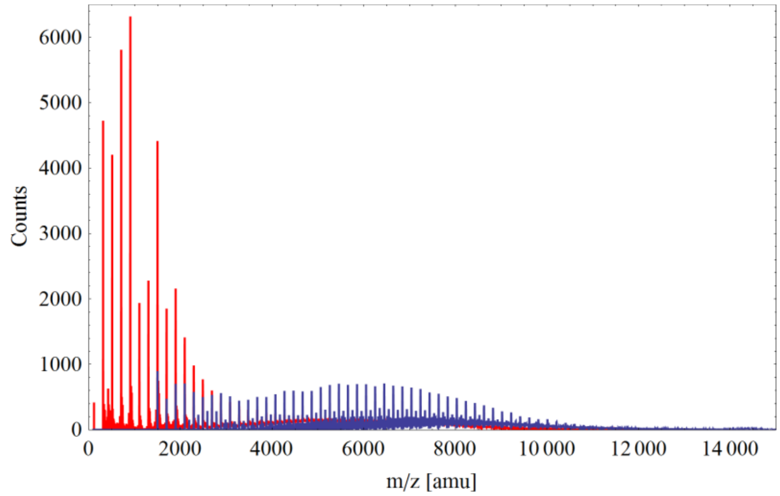

Figure 1. Specific mass spectra.
Two specific charges spectra for beams electrosprayed at 1225V (blue) and 1350V (red).

being developed on both sides of the Atlantic by Busek[7] and Accion Systems[8] in the US and the HiperLoc[9] consortium in Europe.

However, the behaviour of Colloid Thrusters is far from being fully understood and in consequence the analysis of how to tune the propulsive system to adapt to a specific mission is at best inconclusive. Some fundamental work has already been published modelling how the presence of different species in the electrospray beam have an impact on the total thruster efficiency. Whilst such models are helpful for quick estimates they greatly simplify the characteristics of the beam, by considering only the case of two species. The present work presents tools to model multispecies beams and apply the results to map potential mission parameters such as *SI* and the power to thrust ratio *k*.

II. Discrete multispecies beam

Perhaps the most fundamental parameter to assess for a new propulsive system is its propulsive efficiency (η). This can be defined as:

$$\eta_T = \frac{T^2}{2\dot{m}I_b\Phi_A} = \eta_p\eta_\Phi\eta_\theta \tag{1}$$

Thus the overall efficiency defined as the ratio between thrusting power and electric power, is found form the product of the following elemental efficiencies: the polydispersive efficiency η_P, the accelerating potential efficiency η_Φ (fraction of the accelerating voltage transferred to the beam) and the angular efficiency η_θ. The angular efficiency will depend on the angular distribution of the beam[10] but if one considers it to be a uniform flux within a beam angle θ it is equal[11] to:

$$\eta_\theta = \left(\cos\frac{\theta}{2}\right)^4 \tag{2}$$

The average accelerating voltage of the beam can be estimated by retarding potential analysis[12], and will depend on the propellant used in any particular system. Experimental results show that generally this efficiency η_Φ is very high.

We now wish though to consider in more detail the influence of the polydispersive efficiency as this typically may be the lowest component efficiency and hence the greatest effect upon the total thruster efficiency. Thus instead of considering the beam being formed by only two species as in most previous research[10,11,13] we now consider a beam formed by *N* different species. In doing so we obtain that the polydispersive efficiency to be:

$$\eta_p = \frac{\left(\sum_1^N \dot{m}_\iota\sqrt{\xi_i}\right)^2}{\dot{m}I_b} = \left[\sum_{i=1}^N \propto_i \sqrt{\frac{\langle\xi\rangle}{\xi_i}}\right]^2 = \left[\sum_{i=1}^N \propto_i \sqrt{\frac{\varrho_i}{\langle\varrho\rangle}}\right]^2 \tag{3}$$

Here α_i is the fraction of the current carried by each species i, with such species having specific charge ξ and its reciprocal value for specific mass ϱ (whilst the specific charge is more commonly used in this report we will use the specific mass as it simplifies some calculations). We note that using a simplified model that considers only 2 species, the efficiency is negatively impacted by the specific charge spread, thus beams containing very dissimilar species will have a lower efficiency than uniform beams.

The average specific charge and specific mass can be calculated from the total beam current and mass or from the intensity of each species in the following way:

$$\langle \xi \rangle = \frac{1}{\sum_1^N \frac{\alpha_i}{\xi_i}} \quad \& \quad \langle \varrho \rangle = \sum_{i=1}^N \alpha_i \, \varrho_i \tag{4\&5}$$

These results can be used to characterise more realistic beams, such as the ones shown in Figure 1 obtained with a 4 µm diameter emitter. These results were obtained with a mass spectrometer of exceptional resolution and reported in [14,15]. As one can also see in Figure 1 the current fraction carried by each species ion depends on the extracting voltage. This observation is especially relevant for CT systems which are passively fed and without a secondary accelerating grid. In such cases the beam properties become solely a function of the extracting voltage, since this now controls average specific charge, and hence *SI* and thus also the thrust efficiency . This is highlighted in Figure 2, which is a plot of the propulsive behaviour of the same electrospray source in Figure 1. As it can be seen over the extracting voltage range, the efficiency and the specific charge are negatively correlated and thus in order to increase the SI one has to sacrifice polydispersive efficiency. This case shows that the usual curves depicting the efficiency depending on just the beam ion fraction can be of little use once a thruster geometry has been adopted.

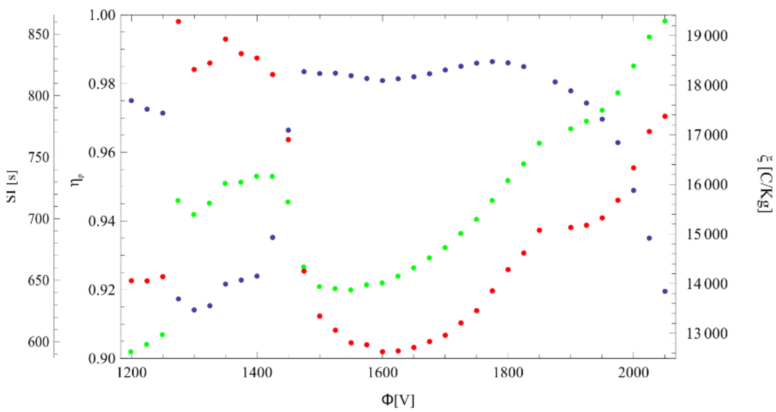

Figure 2. Propulsive parameters of a 4 µm emitter.
Evolution of specific impulse (green), polydispersive efficiency (blue) and specific charge (red) at increasing extracting voltages.

III. Continuous beams

As we just showed the ion/droplet model to assess the efficiency of a colloid thruster can be easily expanded to consider several deterministic species. However, if one observes the Time of Flight (TOF) traces of commonly used ionic liquids, it is apparent that the spectra obtained are formed by populations of ions and droplets with specific charge variation across the droplets and/or clusters making up the colloid beam. This identifies the need for the use of specific charge probability distributions to inform a more realistic model behaviour for colloid thruster systems.

Consider the beam of a colloid thruster to be formed of n species, with each specie *i* carrying a fraction of the beam current (α_i). Each specie has a specific charge distribution (f_i). In this case the average specific mass $\langle \varrho \rangle$, is:

$$\langle \varrho \rangle = \sum_1^n \alpha_i \int_0^\infty f_i(\varrho)\,\varrho\, d\varrho = \sum_1^n \alpha_i \langle \varrho_i \rangle \tag{6}$$

Where $\langle \varrho_i \rangle$ is the average specific charge of each specie. The probability distribution can be easily found from the derivative with time of the current in a TOF trace. Figure 3 shows the fitting of a TOF trace for a colloid thruster having 64 emitters (HC-2)[16] using two lognormal distributions. Whilst a normal distribution function is probably the more readily selected option, we believe that either Weilbull or lognormal distributions are better choices to model ϱ since in these probability distributions negative values are zero. These distributions have previously been used to model successfully relevant particle sizes[17,18]. We extend this in our approach to consider several species size distributions,

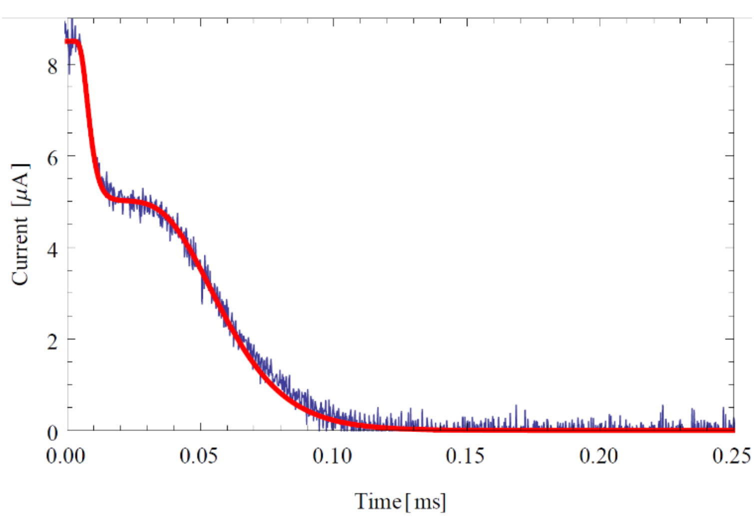

Figure 3. TOF fitting.
Fitting of a TOF trace using two LogNormal distributions containing ions and droplets.

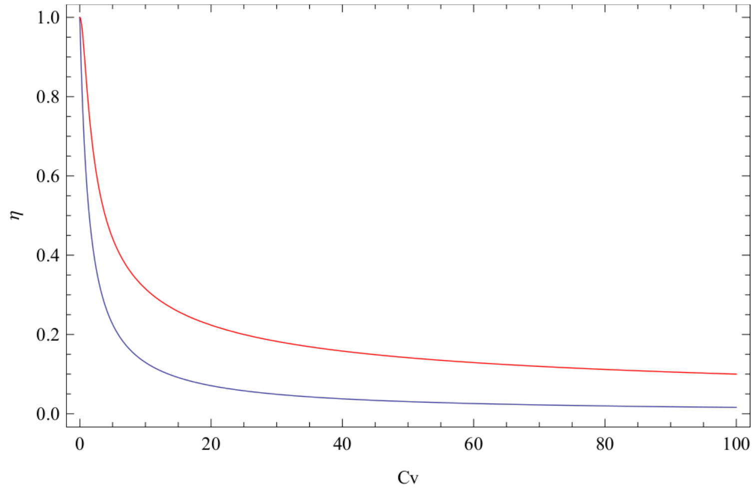

Figure 4. Polydispersive efficiency as a function of c_v. *Polydispersive efficiency dependence on the relative standard deviation for lognormal (blue) and Weilbull (red) distributions*

with each species identified by its charge state. Hence we can consider ρ as the size (or equivalently mass) of the droplet (or ion) divided by its charge. Clearly the charge state is quantized: 1, 2 …n representing each of the "n" species making up the total population. With these considerations the polydispersive efficiency is then:

$$\eta_p = \frac{\left[\sum_1^n \alpha_i \int_0^\infty f_i(\varrho)\sqrt{\varrho}d\varrho\right]^2}{\langle\varrho\rangle} \quad (7)$$

In the case of a beam formed by a single specie modelled using a lognormal distribution, the efficiency has a closed form:

$$\eta_{p_i} = \sqrt[4]{\frac{1}{1+c_v^2}} \quad (8)$$

Where c_v is the coefficient of variation or relative standard deviation (quotient between standard deviation and mean). Once again the efficiency is only a factor of the distribution shape, it is independent of the average specific mass, this holds true for any other distribution even those without a closed form (such as the Weilbull distribution). Unfortunately, but not surprisingly as can be seen in Figure 4, different assumed statistical distributions lead to a different values for efficiency, even if these distributions have the same coefficient of variation. Thus we still need to be able to identify the appropriate distribution function that properly models the beam, if we are to be able to determine the overall efficiency.

For a beam composed by different distributions it can be useful to have the efficiency as a function of each species polydispersive efficiency instead of using equation (7). In this case we can write the efficiency as:

$$\eta_p = \frac{\left[\sum_1^n \alpha_i \sqrt{\langle\varrho\rangle_i\, \eta_{p_i}}\right]^2}{\langle\varrho\rangle} \quad (9)$$

Figure 5 shows how equation 9 can be used, modelling an electrospray formed from only two species. One specie is the pure ion (non-solvated) with no variance. The second species has a distribution of droplets with a varying specific charge, with an average specific charge a factor of 100 below the pure ion. As expected the increase in the variance of the droplet distribution reduces the polydispersive efficiency. The curves are plotted at decreasing droplet variance at values of 400%, 200%, 100%, 50% and 25% relative deviation.

As we have noted however the system requirements to meet market opportunities are not only driven by the total efficiency of the propulsive system but it is also the specific impulse and the power to thrust ratio (k) that are critical system requirements underpinning a given mission. These factors must be mapped into operating point values of the thruster. In a typical case the total accelerating voltage, Φ_A, and the fraction of ions, α_{ion} require sensitivity analysis. .

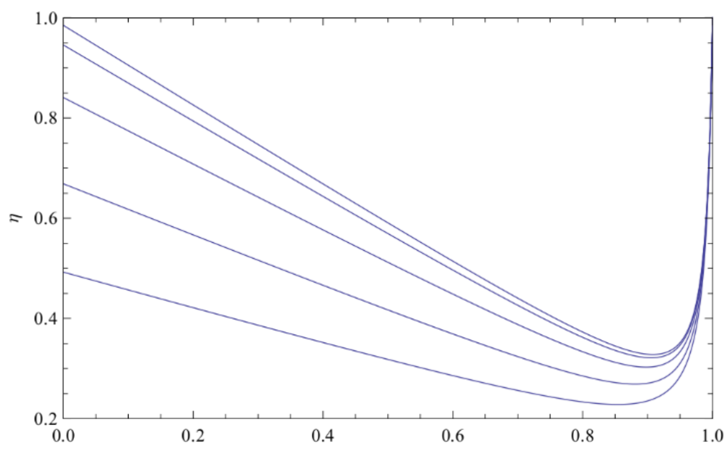

Figure 5. Multispecies beam efficiency. *Polydispersive efficiency for a beam with specific ions and a distribution of droplets for different current fractions and droplet variance.*

For a colloid thruster these two system factors can be defined by:

$$SI \leq \frac{1}{g}\sqrt{2\langle\xi\rangle\left(\Phi_A - \Phi_{deff}\right)} \tag{10}$$

$$k \leq \sqrt{\frac{2\left(\Phi_A - \Phi_{deff}\right)}{\langle\xi\rangle{\Phi_A}^2}} \tag{11}$$

In these model definitions both the voltage drop during the atomization of the spray (Φ_{deff}) and the specific charge must be assumed to be a function of the ion fraction.

For a specific mission the values of SI and k will be identified to meet system requirements. The mapping for the specific case of HC-2 can be seen in Figure 6; the voltage deficit Φ_{deff} has been estimated from the results obtained by Gamero for Emi-Im[12]. The specific charge is not only dependent on the ion fraction but also on how the specific charge for each species evolves with the selected operating point. Here this has been approximated by interpolating the results from different TOF traces. With these assumptions it is then possible to plot the dependence of the system performance as indicated in the figure and from this we can identify the target operating point for the thruster. Thus if we require an SI greater than some value (say 200s) the voltage applied must be greater than that seen as the line identifying an SI of 200s. If this SI is required with a thrust performance better than some value of power per unit thrust k (say k=1500W/N) then the voltage must be below the corresponding curve. Thus the valid operating zone for this requirement (ie >200s and <1500w/N) is the one between these two curves and in Figure 6 is here highlighted as the white zone: all points within this region will satisfy the set requirements).

IV. Conclusion

We have presented a method on how to expand the traditional deterministic ion/droplet beam efficiency model to a more realistic one containing numerous species. The results of modelling a single emitter suggest that the idea of being capable to tailor the ion fraction on a given thruster might be unrealistic.

In the case of modelling a Colloid Thruster with a continuous TOF trace we have suggested to use either Weibull or lognormal distributions to fit the results and how the relative standard deviation affects the polydispersive efficiency. Finally the thruster head HC-2 is analysed to obtain a map of operational values for different mission requirements.

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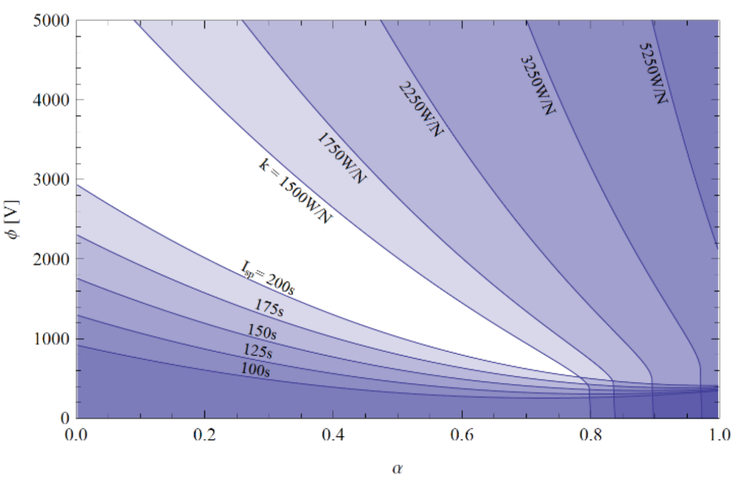

Figure 6. Validity regions.
Mapping of the valid operational regions (Φ_A,α) of the multiemitter colloid thruster HC-2 for different values of SI and k.

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