Design and Validation of a Low-Power Hall Thruster for CubeSats: A Scaling Laws Approach

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With the advent of small spacecraft, such as cubesats, existing propulsion technologies need to scale down for the low powers involved. This study delves into the application of Hall thrusters scaling laws to low power thrusters. These laws are applied to rapidly estimate specifications for a low-power Hall thruster and validated using Hallis software [1]. Despite scaling law discrepancies, the study provides a preliminary specification for a 20W thruster, with concerns for efficiency estimation.

For the preliminary specification of a 20W thruster, the laws utilized in this work are retrieved from [2]. The performance, size, and electrical parameters of thrusters are derived from established databases, not publicly available. The databases also contain low-power thrusters [2]. In [2], two methodologies based on high and low assumptions based on plasma physics are presented. Low assumptions differ from high assumptions in that they assume phenomena as the plume divergence, multiply charged ions, and voltage losses. However, in [3], it is demonstrated that the difference between high and low assumptions yielded minimal improvement in accuracy, indicating that the high assumptions are adequate for obtaining a preliminary estimate of the geometry and operating conditions of a Hall Thruster [2] [3]. The equations and model considered, provide a thruster geometry and performance with input power and voltage (V_d). From these inputs, one could retrieve mean channel diameter (D), channel thickness (H), channel length (L), discharge current, thrust and I_{sp}. Figure 1 illustrates the detailed geometry of the Hall Thruster, highlighting all pertinent parameters.

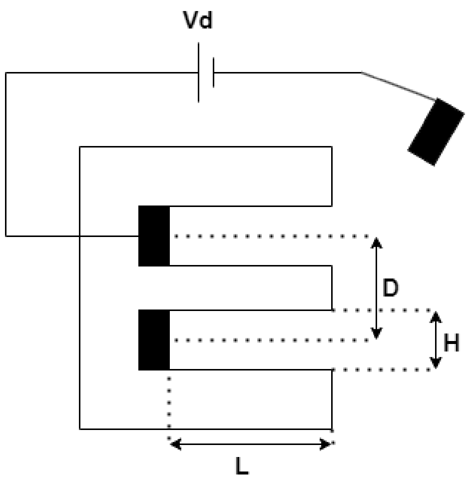

Figure 1 Detailed geometry of a Hall Thruster, showcasing its critical design parameters.

In this study, we begin by evaluating the accuracy of scaling laws against the SPT100 Hall thruster as a benchmark. By applying the SPT100's specifications—1350W power rating and 300V operation—through the scaling laws, we aim to assess the precision of these laws. This process yields estimated performance metrics and geometrical dimensions, which are then compared with the actual specifications of the SPT100 for validation. To ascertain the relevance of scaling laws for low-power Hall thrusters, we utilized the one-dimensional model provided by Hallis software [3]. To validate the applicability of scaling laws within low-power Hall thrusters, the 1D model of Hallis software is employed. [3] Throughout all simulations, consistency was maintained in terms of voltage, channel length, and magnetic field profile. Despite Hallis overestimating the power consumption, the overall performance aligns with the real performance of SPT100. The study reveals that scaling laws tend to overestimate the real performance of SPT100 by approximately 11%. When the geometry of the SPT100 is determined using scaling laws and then analysed using Hallis software, the scaling laws tend to overestimate the performance by approximately 14% in comparison to Hallis. For the designated 20W thruster, the scaling laws predict performance metrics that are 14.9% higher than expected, and also leading to an overestimation of efficiencies. The specifications derived from these scaling laws are summarized in the following table.

Thruster	Data	P [W]	V_d [V]	I_{sp} [s]	T [mN]	L [mm]	D [mm]	H [mm]	efficiency (%)
20W	Scaling Laws	20	300	1900	1.5	25	12	2	0.69
	Hallis	22.7	-	1637	1.29	-	-	-	0.45

Figure 2 Preliminary Specifications of a 20W Hall Thruster Derived from Scaling Laws.

Based on the observed errors between the scaling laws and Hallis software, one can conclude that the scaling laws method provides a reasonable approximation for initial performance estimation and does not seem to differentiate significantly between high and low power levels. However, the efficiency calculated in the simulation with the low-power thruster deviates from the literature. As mentioned in Reference [4], a 50W low-power thruster is reported to have an efficiency of 30%, whereas Hallis outputs an efficiency of approximately 45% for the 20W thruster. A potential explanation for this variance could be attributed to the fact that the Hallis software usually treats ion collisions with the walls as reflections after recombination or not included, as stated in the Hallis guide [1]. A potential explanation for this variance is that Hallis software typically models ion collisions with the walls as either reflections post-recombination or does not include them at all, as detailed in the Hallis guide [1]. In reality, sputtering affects a significant portion of the thruster wall, and the reduced area-to-volume ratio inherent to small thrusters leads to increased wall losses and efficiency decline. This in turn will influence performance. Employing practical measures like increasing channel thickness could help mitigate these losses, as recommended in [3].

In summary, this study examines the adaptation of scaling laws for low-power Hall thrusters. Through validation against empirical data and simulations via the Hallis software, we have formulated a preliminary design for a 20W thruster. This process underlines the critical role of scaling laws, alongside recognizing the constraints inherent in efficiency calculations.

[1] Hallis software page, Jan 2024. URL https://www.hallis-model.com/.

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