ELEMENTARY SCALING LAWS FOR THE DESIGN OF LOW AND HIGH POWER HALL EFFECT THRUSTERS

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Sizing methods can be used to get a first estimate of the required Hall thruster dimensions and operating conditions for a given input power and a corresponding thrust level. In this work, an approach that considers the three characteristic thruster dimensions, i.e. the channel length, the channel width and the channel mean diameter as well as the magnetic field, is introduced and discussed. This approach is based on analytical laws deduced from the physical principles that govern the properties of a Hall effect thruster, relying on a list of simplifying assumptions. In addition, constraints on the propellant atom density inside the channel as well as on the channel wall temperature are taken into account. The proportionality coefficients of the scaling laws are determined using a vast database that comprises 33 single-stage Hall effect thrusters covering a power range from 10 W to 50 kW. Finally the sizing method is employed to obtain a preliminary geometry for a20 kW-class Hall effect thruster able to deliver a thrust of 1 N.

Notations

B	magnetic field strength
C_B	proportionality coefficient for B
C_h	proportionality coefficient for h
C_{Isp}	proportionality coefficient for I_{sp}
C_L	proportionality coefficient for L
$C_{T1,2,3}$	proportionality coefficient for T
d, d_{ext}, d_{int}	mean, external and internal channel diameter
h	channel width
I_d	discharge current
I_{sp}	specific impulse
k_B	Boltzmann constant
L	channel length
m_n, m_i	propellant atom mass, ion mass
$\dot{m}$, $\dot{m}_i$	propellant mass flow rate through the anode, ion mass flow rate
n_n	atom number density
P	input power
r_{Le}, r_{Li}	electron and ion Larmor radius
T	thrust
T_{max}, T_{ext}, T_{int}	maximum, external, internal wall temperature
T_e	electron temperature
U_d	discharge voltage
v_n, v_e, v_i	thermal velocity of atoms, electrons and ions
α	propellant conversion efficiency
β	ratio between ionization mean free path and channel length
η	thrust efficiency
λ_i	Ionization mean free path
ν_{ce}	electron gyrofrequency
ν_{en}	electron-atom collision frequency
σ_i, σ_{en}	cross-section for ionization and electron-atom momentum exchange
τ_{ce}	gyroperiod
τ_{en}	electron-atom collision time

1. INTRODUCTION

It is well known that chemical systems store their energy in the propellant. They are said to be "energy limited" as the chemical reactants have a fixed amount of energy per unit mass, which limits the achievable exhaust velocity or specific impulse. In contrast, the rate at which energy can be supplied to the propellant is independent of the mass of propellant, so very high power and thrust levels can be achieved. Electric propulsion systems are not energy limited. Neglecting component lifetime considerations, an arbitrarily large amount of energy can be delivered from solar arrays or a nuclear battery to a given mass of propellant so that the specific impulse can be much larger than that available from a chemical engine. Therefore, electric thrusters offer an attractive way to save propellant mass thanks to a much faster propellant ejection speed. Electric propulsion systems are termed "power limited" because the rate at which energy from the external source is supplied to the propellant is limited by the mass available for the power system. This has the result of limiting the thrust of the electric propulsion system for a given spacecraft mass. As a consequence electric propulsion devices tend to be low thrust-to-mass ratio – therefore low acceleration – devices. Although electric thrusters have low thrust-to-mass ratios, they can have a larger amount of impulse in comparison with chemical rocket jets. The total impulse corresponds to the product of specific impulse and propellant mass, i.e. the total change of momentum. So even though a chemical engine offers a high thrust-to-mass ratio, the propellant is expended in a short time at low specific impulse. On the contrary, a low thrust to mass ratio electric thrusters can be operated for periods ranging from hours to years and build up a larger total impulse.

There are three different types of electric propulsion systems, categorised according to the method used to accelerate the propellant, as electrothermal, electrostatic and electromagnetic. Electrothermal propulsion systems accelerate the propellant using heating. There are different subtypes: resistojets, arcjets and inductively or radiatively heated systems. Electromagnetic propulsion uses orthogonal electric and magnetic fields to apply a Lorentz body force to ionized propellant atoms, accelerating them out of the plume of the crossed fields. The electromagnetic propulsion techniques currently in use or being investigated include pulsed plasma thrusters and magnetplasmadynamic thrusters. Electrostatic propulsion systems accelerate the ionized propellant by means of an electric field. The principal techniques are field effect electrostatic propulsion, colloidal thrusters and gridded ion accelerators. Hall effect thrusters have been classed as both electrostatic and electromagnetic propulsion systems. An electrostatic field accelerates the ions in the propellant stream but that field is, to a large extend, produced by the actions of plasma electrons interacting with a magnetic field, giving both classes a claim to the technique.

Hall Effect Thrusters (HET), also called Stationary Plasma Thrusters or closed electron drift thrusters, are currently recognized as attractive propulsion means for long duration missions and for maneuvers that require a large velocity increment. They are advanced propulsion devices that use an electric discharge with magnetized electrons to ionize and accelerate a propellant gas [1,2,3]. Due to interesting features in terms of propellant ejection speed, efficiency, thrust-to-power ratio and lifetime, HET are now employed for missions like geosynchronous communication satellite orbit correction and station keeping. Moreover HETs appear as good candidates to be used as primary propulsion engine for space probes during interplanetary journeys, as demonstrated by the successful SMART-1 Moon flyby solar-powered mission of the European Space Agency [4].

In a Hall thruster, acceleration of heavy atomic ions to high velocity occurs within the core of the plasma where ions are produced, which implies the use of a magnetized plasma enable to sustain internal electric fields. A schematic of a Hall effect thruster is depicted in Figure 1. The basic physics of a HET therefore consists of a magnetic barrier in a low pressure DC discharge generated between an external hollow cathode and an anode. The anode, which also serves as gas injector, is located at the upstream end of a coaxial annular dielectric channel that confines the discharge. Xenon is generally used as propellant gas for its specific properties in terms of atomic mass and low ionization energy.

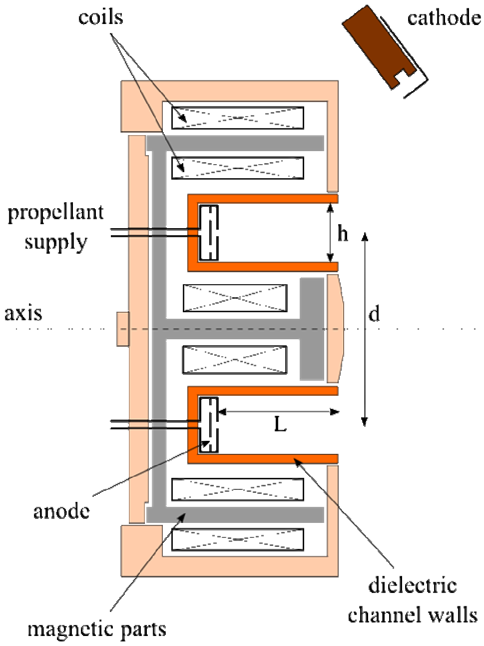

Figure 1: Schematic of a Hall thruster. The three characteristic dimensions *L*, *h* and *d* are also shown.

A set of solenoids provides a radially directed magnetic field **B** of which the strength is maximum in the vicinity of the channel exhaust. The magnetic field is chosen strong enough to make the electron Larmor radius much smaller than the discharge chamber length, but weak enough not to affect ion trajectories. The electric potential drop is mostly concentrated in the final section of the channel owing to the low electron axial mobility in this restricted area. The corresponding induced local axial electric field **E** has two main effects. First, it drives a high electron azimuthal drift – the Hall current – that is responsible for the efficient ionization of the supplied gas. Second, it accelerates ions out of the channel, which generates thrust. The ion beam is neutralized by a fraction of electrons emitted from the hollow cathode. When operating near 1.5 kW, a HET ejects ions at 20 km/s and generates 100 mN of thrust with an overall efficiency of about 50 %.
New fields of application are nowadays envisaged for electric propulsion systems that require low and high power devices. Low power Hall thrusters (~ 100 W) are well suited for drag compensation of observation satellites that operate on a low-altitude orbit in the Earth atmosphere as well as for orbit corrections and orbit transfer of small platforms. The use of high power Hall thrusters (~ 5 kW) for orbit raising and orbit topping maneuvers of communication satellites would offer significant benefits in terms of launch mass, payload mass and operational life. In addition, orbit transfer of large platforms and journeys to far-off planets and asteroids with large and heavy robotic probes necessitates to build thrusters with an input power in the range of 10 – 100 kW. In view of this project demand, it appears necessary to expand the operating envelope of existing Hall effect thruster technology to achieve the required performance level. A non-trivial question then arises: How to extrapolate the design and architecture of currently existing Hall thrusters towards different scales and different operating conditions? In other words, what are the elementary scaling laws that connect Hall effect thruster characteristic dimensions with operating parameters like discharge voltage, propellant mass flow rate and magnetic field strength and performances in terms of thrust, specific impulse and overall efficiency?
Scaling laws that govern the physical properties, the acceleration ability as well as the propellant and energy consumption of Hall thrusters have been extensively investigated by numerous authors since the period of development of Hall thrusters in the 70's [1,5,6,7]. In spite of decades of research on this subject, the assessment of scaling laws is still a topic of great interest, with debates and controversies

as various methodologies and results exist. A detailed review of existing scaling laws and sizing methodologies has been presented in a previous article [8].

In this contribution we propose an original way to extrapolate Hall thruster geometry toward both the low and high power ranges. As we will see, the method is based on the combination of a set of scaling laws with a vast body of existing data. An approach, which considers the three characteristic thruster dimensions, i.e. the channel length; the channel width and the channel mean diameter as well as the magnetic field, is introduced. This approach is based on the analytical laws deduced from the physical principles that govern the properties of a Hall effect thrusters, relying on a list of simplifying assumptions. A constraint on the propellant atom density inside the channel is taken into account, which simplifies the developed scaling laws. The validity of the scaling laws is discussed in light of a vast database that comprises 33 single-stage Hall effect thrusters covering a power range from 10 W to 50 kW. This database is also used to determine the proportionality coefficients necessary for the sizing of a new thruster. The sizing method is employed to obtain a preliminary geometry and the magnetic field strength of a 20 kW Hall effect thruster able to deliver a thrust of 1N.

2. THEORETICAL APPROACH

A necessary first step in order to determine scaling laws for Hall effect thrusters does consist in finding some critical parameters as well as in defining the similarity criteria based on the current knowledge and understanding of the physics of Hall thrusters. The geometry of a Hall effect thruster is defined by three characteristic dimensions: the discharge channel length L, the mean diameter $d = ½ (d_{ext} + d_{int})$ and the channel width h, as well as by a set of operating parameters such as the magnetic field strength B, the discharge voltage U_d and the propellant mass flow rate $\dot{m}$.

To simplify the assessment of scaling laws, the following assumptions have been made throughout the entire paper:

- all quantities are steady in time,
- the electron temperature is constant and homogeneous whatever the operating conditions,
- the propellant gas has a uniform temperature all over the channel, hence a constant propellant velocity,
- the potential energy is fully converted into kinetic energy and all ions experience the whole potential drop, of which the magnitude is U_d,
- plasma-wall interactions are taken into account through heat load to the channel walls,
- the magnetic field is uniform; its value at the exit plane is solely considered,
- electron transport across the magnetic barrier is considered as classical: no anomalous transport is accounted for within the region of strong magnetic field [9],
- there are no multiply-charged ions in the plasma [10],
- a parallel monokinetic ion beam is produced, i.e. the plasma jet divergence is null.

To ensure a sufficient ionization of the gas the ionization mean free path λ_i must be much smaller than the channel length L. This is the so called Melikov-Morozov criterion:

$$\lambda_i = \frac{v_n}{n_n \sigma_i v_e} << L \quad \text{and} \quad \frac{\lambda_i}{L} = \beta \tag{2.1}$$

where v_n is the thermal velocity of the atoms, n_n the atom number density, σ_i the ionization cross section, v_e the thermal velocity of the electrons.

The electrons must be efficiently trapped inside the magnetic field in order to ensure a good ionization and an intensive electric field for the acceleration of the ions. On the other hand the ions should not be affected by the magnetic field. This leads to the following relations:

$$r_{Le} = \frac{m_e v_e}{eB} << L \quad \text{and} \quad r_{Li} = \frac{m_i v_i}{eB} >> L\,, \tag{2.2}$$

$$\frac{\tau_{en}}{\tau_{ce}} = \frac{\nu_{ce}}{\nu_{en}} = \frac{eB}{m_e n_n \sigma_{en} v_e} >> 1, \quad (2.3)$$

where r_L is the Larmor radius, τ_{en} the electron-atom collision time, τ_{ce} the gyroperiod of the electrons and σ_{en} the electron-atom momentum exchange cross-section.
Combining the three relations (1, 2, 3) and the previously cited assumptions, one finds:

$$T = C_{T1}\dot{m}\sqrt{U_d} \quad (2.4)$$

$$T = C_{T2}\frac{1}{L}\sqrt{U_d}\,hd \quad (2.5)$$

$$I_{sp} = C_{Isp}\sqrt{U_d} \quad (2.6)$$

$$L = C_L\frac{1}{n_n} \quad (2.7)$$

$$B = C_B\frac{1}{hd} \quad (2.8)$$

A detailed description of the derivation of these equations is given in a previous article [8]. The proportionality coefficients *C* can be determined using a vast database, as explained in the remainder of the article.

3. DATABASE

A thorough open literature research using a wide range of resources combined with data-gathering performed within the French research program on electric propulsion, allowed us to create a large database on Hall effect thruster performances. The database contains information about thruster geometry as well as performances, notably the thrust *T*, the specific impulse I_{sp} and the efficiency η for a series of 33 different single-stage Hall thrusters. Moreover, the database includes information about the magnetic field strength *B*, the discharge channel wall materials and the propellant gas. The entire database covers a vast range of input power that stretches from 10 W up to 50 kW, and a large collection of data points in terms of applied discharge voltage and gas mass flow rate. A broad range of thrust level is certainly covered, going from 0.4 mN with a micro-Hall thruster up to 2.95 N, delivered by the high-power thruster developed at NASA.

A part of the collected data in terms of thrust level is displayed in Figure 2. For all thrusters, channel walls are made of BN-SiO_2 and the propellant gas is xenon. The thrusters used to construct the figure are the following: a 4 mm in diameter micro-Hall thruster operating at 10 – 40 W [11], a laboratory model of the low-power SPT20 thruster [12], a SPT50 thruster manufactured by the Kurchatov Institute [12], the 1.5 kW-class PPS1350 HET developed and manufactured by SNECMA [13], the 5 kW-class PPSX000 which is a laboratory version of the PPS5000 technology demonstrator developed by SNECMA [13], the 10 kW T220 designed and built by TWR and Space Power Inc. [14], as well as the 50 kW-class NASA-457M thruster [15].
The propellant conversion efficiency α is the ratio of the ion mass flow rate to the propellant mass flow rate. Therefore α is not constant but a function of the discharge voltage and the mass flow rate. The value of α can be determined using the database. Figure 3 shows the calculated values of α for three different thrusters as a function of the applied voltage U_d when only Xe^+ ions are taken into account. This figure indicates that α depends both on the thruster size and on the value of U_d. For an applied voltage above 300 V, the quantity α is commonly in the range of 0.8 - 0.9 and thus close to the value of 0.9 given in the literature.

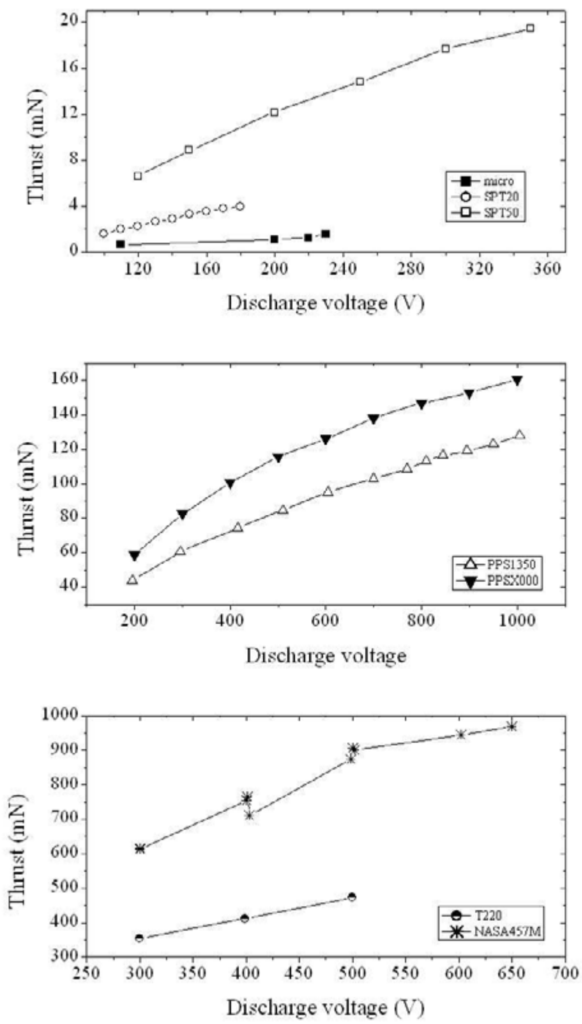

Figure 2: Thrust as a function of the discharge voltage for seven different thrusters: micro-thruster (0.2 mg/s), SPT20 (0.472 mg/s), SPT50 (1.0 mg/s), PPS1350 (3.5 mg/s), PPSX000 (5 mg/s), T220 (19.4 mg/s) and NASA-457M (35.2 mg/s).

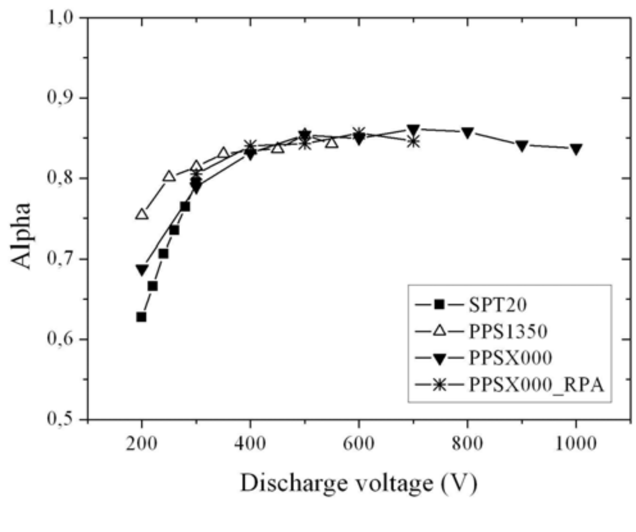

Figure 3: Propellant conversion efficiency α as a function of the discharge voltage for three types of Hall thrusters. The star symbol corresponds to values obtained for the PPSX000 thruster when the ion velocity is recorded by means of a RPA (Retarding Potential Analyzer).

4. SCALING LAWS

It was shown in a previous paper that there is an optimum atomic number density n_n in order to keep the physical processes at work in a Hall thrusters unchanged, to warrant a high efficiency and to limit the thermal load as well as the wall wear [8]. According to the large amount of gathered data, the value that turns out to guarantee a satisfying operation is $n_n = 1.2\times10^{19}$ m^{-3}. This is also the value that is commonly found in literature [2].

Considering a constant optimum atomic number density, one can refine the scaling laws with respect to what was explained in a previous article [8]. For a constant number density n_n the channel width h must be proportional to the channel mean diameter d. This relation can be verified using the database. In Figure 4, the channel width in plotted as a function of the mean diameter for different thrusters covering a broad power range (units are arbitrary as this is sensitive information). As can be seen, the two dimensions h and d are indeed proportional. This then leads to the following equation:

$$h = C_h d \tag{4.1}$$

For a constant atomic number density and using relation (4.1), the thrust appears to be proportional to the product of the square of the diameter times the square root of the discharge voltage. In like manner, the input power depends on d^2 and U_d. Besides, the magnetic field strength is proportional to reciprocal of the square of the diameter. The Hall thruster scaling laws therefore read:

$$P = C_p d^2 U_d \tag{4.2}$$

$$T = C_{T3} d^2 \sqrt{U_d} \tag{4.3}$$

$$B = C_B \big/ d^2 \tag{4.4}$$

$$L = C_L \frac{1}{\beta} \tag{4.5}$$

This set of relations can again be verified using the aforementioned database. Figure 5 shows the thrust T as a function of $d^2\sqrt{U_d}$ for different thrusters. The dashed line represents a linear fit through all data points. For each thruster some values of T are chosen around the point of normal operation.

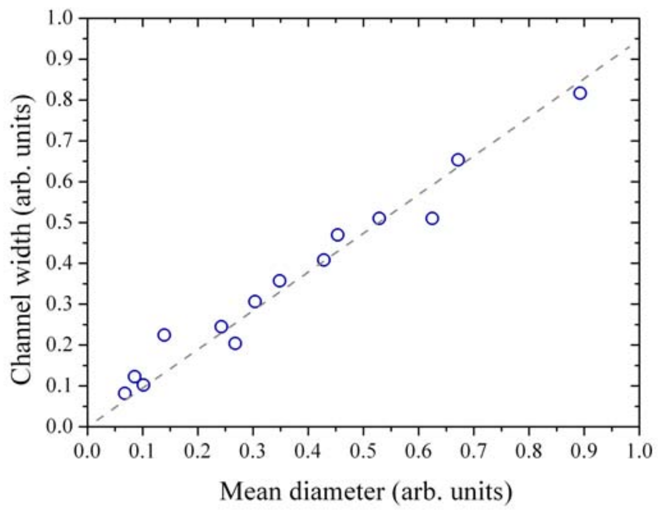

Figure 4: Channel width h as a function of the channel mean diameter d for a series of Hall effect thrusters (sizes are in arbitrary units as this represents sensitive information). The two dimensions d and h are proportional.

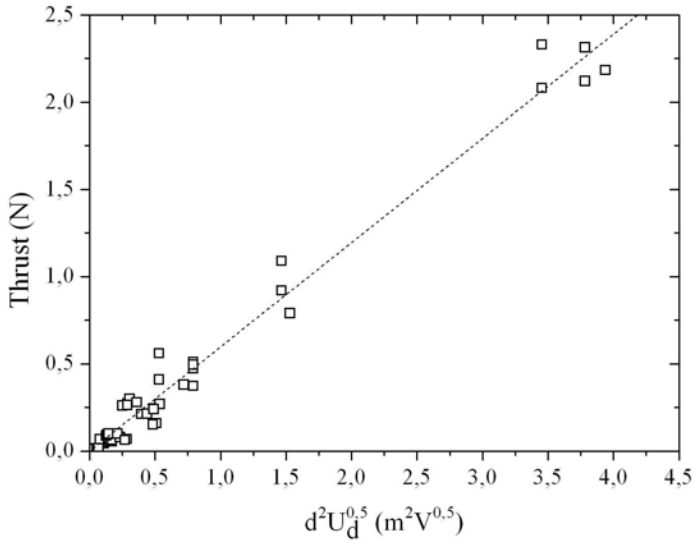

Figure 5: Thrust as function of $d^2U_d^{0.5}$ and the linear fit for different Hall effect thrusters (dashed line). For each thruster, some thrust values are chosen around the point of normal operation.

5. ASSESSMENT OF PROPORTIONALITY COEFFICIENTS

In order to assess the required thruster dimensions by way of a scaling method for an available input power, it is thus necessary to know the proportionality coefficients of the previously presented equations. These coefficients can be determined either empirically, using the database, or analytically from the developed scaling laws, as explained in detail in a previous paper [8].

The empirically determined proportionality coefficients used for sizing a Hall effect thruster are naturally not given in this contribution as it is sensitive information. Only the C_P and C_{T3} coefficients can be derived from outcomes of this study. Yet, they are available in an article previously published by R. Jankovsky and co-workers [16].

6. DESIGN OF A 20 kW HALL THRUSTER

High-power Hall effect thrusters in the range of 10-30 kW and able to deliver a thrust level around 1 N with a specific impulse of about 2500 s, are thought to be used as primary propulsion system for robotic space probes during interplanetary journeys [17,18,19]. Such high-power Hall thrusters may also be of interest for orbit transfer maneuvers of large satellites. Only a few high-power prototypes have been developed in the world so far and a significant research effort on this specific technology is now appearing within Europe. For this reason, the sizing method based on the aforementioned widely applicable scaling laws in combination with our large database is employed to design a 20 kW-class thruster with a thrust level of 1 N.
The discharge voltage is fixed to U_d = 500 V in order to limit the thermal charge and the secondary electron emission. Xenon is used as propellant gas. The thruster channel walls are assumed to be made of BN-SiO_2 ceramics. The wall losses are fixed to 4 % of the applied power and the ionization efficiency is fixed to 0.9.

The scaling process that consists in determining the thruster dimensions *L*, *h* and *d* as well as the magnetic field strength *B* must be carried out step by step. The standard procedure is the following:

1. The required mass flow rate is determined by means of equation (2.4).
2. The diameter d is obtained using equation (4.3).
3. The discharge current is given by: $I_d = \frac{\alpha}{0.8} \frac{e}{m_n} \dot{m}$.
4. The electric power reads: $P = I_d U_d$.
5. The h size is found using the relationship (4.1).
6. The channel length L is assessed with equation (4.5).
7. The magnetic field strength is obtained from the relation: $B = f(d^2)$.
8. At least, it should be verified that the number density n_n is close to 1.2×10^{19}. To do so, the proper equation is the following:

$$\dot{m} = n_n m_n v_n \pi \, hd \, .$$

The atom thermal speed is given by:

$$v_n = \sqrt{\frac{8k_B T_{wall}}{m_n \pi}} \, ,$$

where k_B is the Boltzmann constant.

The channel length is the dimension that is the most difficult to determine as the proportionality coefficient C_L strongly depends on the value of β. As has been shown previously [8], the ratio between l_i and L is not constant but it can vary considerably for different thruster geometry, gas mass flow rate and discharge voltages. The Melikov-Morozov criterion can however be used to get a first estimate of the channel length by using a mean value for β determined from the database. The value of L can then be adjusted using the thermal constraint.

For the thermal constraint, a maximum wall temperature T_{max} is set in order to limit the thermal load on the channel walls. Knowing the thruster dimensions L, h and d, the wall temperatures T_{ext} and T_{int} can be computed as a function of the input power. The process of calculating the wall temperatures can be iterative: in case that the wall temperature is above T_{max}, the dimensions must be changed until the thermal constraint is satisfied. This constraint is described in detail in a previous paper [8].
In this work the maximum temperature is set to: T_{max} = 900 K. Since the value of d and h given by the scaling laws is quite reliable, it appears better to rather modify the channel length L than the mean diameter d or the channel width h in case an iterative loop is necessary to satisfy the thermal constraint.

The dimensions, the parameters and the estimated performances of a 20 kW-class Hall thruster are given in Table 1. The external wall temperature is T_{ext} = 640 K and the internal wall is T_{int} = 700 K.

100 kW class Hall thruster

The scaling methodology previousy described was also employed to determine the channel sizes of a 100 kW Hall thruster. Such a high-power thruster could be used as propulsion device for cargo missions to the Moon or to Mars and for exploration missions towards far-off planets and asteroids [20,21]. For a discharge voltage U_d = 500 V, one finds a mean diameter d of 660. The thruster would

Tab. 1: Dimensions, parameters and performances evaluated from scaling laws for a thruster delivering 1 N of thrust.

Hall effect thruster able to deliver 1 N of thrust			
Dimensions	Parameters	Parameters	Performances
d = 270 mm	U_d = 500 V	P = 17.2 kW	T = 1N
L = 70 mm	$\dot{m}$ = 41.5 mg/s	$n_n = 1.3\times10^{19}$ m^{-3}	I_{sp} = 2456 s
	I_d = 34.3 A	T_{wall} = 670 K	η = 70 %

then be able to deliver a thrust of 5.8 N with a xenon mass flow rate $\dot{m}$ = 242.2 mg/s (I_d = 200 A and $I_{Hall} \approx$ 600 A). Considering the calculated mass flow rate, 1 ton of xenon is then consumed within 1147 hours that means 47 days.
With such dimensions and power level, there are several constraints for thruster building and operation. On a technological viewpoint, building and assembling of ceramic rings may be difficult. In like manner, the magnetic circuit architecture must provide the required field over long distances. Heat evacuation as well as Hall current induced magnetic field have to be studied. Besides, power generation is also a critical issue. In order to produce 100 kW, one needs either very large solar panels or a nuclear battery onboard. Finally, another technical aspect to take into account is the size and the pumping capacity of the test facility for test campaigns and experimental investigations of such a large Hall thruster.

7. CONCLUSION

The Hall effect thrusters sizing method described in this article considers the three characteristic dimensions L, d, h, as well as the magnetic field strength B. The method relies on analytical laws that are established from the fundamental principles that govern the physics of a Hall thruster in the frame of simplifying assumptions. Besides, the thrusters must fulfil stringent criteria about atomic number density and channel wall temperature. A vast database that encompasses 33 single-stage Hall thrusters covering a power range between 10 W and 50 kW allows to check the validity of the developed scaling laws and to determine the values of the corresponding proportionality coefficients necessary to dimension a new thruster. The sizing approach was then employed to obtain a first estimate of the characteristic dimensions and of the magnetic field strength for a 20 kW-class Hall thruster capable of providing a thrust of 1 N.
Scaling laws developed here solely represent a first-order approach due to numerous simplifying assumptions on the physics at work in a Hall thruster. Nevertheless, for a given set of operating conditions they furnish a first estimate of the geometry and the magnetic field strength of a thruster, which permits to save time during the design and optimization process. One way to improve the accuracy of the scaling method is to reduce the number of assumptions. The evolution of the electron temperature, of the gas temperature and of the fraction of multiply-charged ion species as a function of the discharge voltage could for instance be taken into account. However, available data are scarce what anyway limits the gain. Finally, attempt to incorporate the magnetic field topology into scaling laws would represent a tremendous progress, since the latter is the most fundamental feature to ensure a successful operation.

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