Limits on the Efficiency of a Helicon Plasma Thruster

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Abstract: A quasi two--dimensional analytical model for a helicon plasma source, that is an extension of a previously – published one-dimensional analytical model, is used to determine the conditions for minimizing radial wall losses. With the assumption of an ideal nozzle that converts all electron thermal energy to ion directed kinetic energy that provides thrust, the maximal efficiency of a helicon plasma thruster is found as a function of the energy per ion and for different values of electron heat conductivity. When radial wall losses are eliminated, the sources of inefficiency are the energy cost per ion generation and the energy flux into the back wall.

Nomenclature

ε_T	=	energy deposited per ion-electron creation
ε_c	=	energy cost for ionization
T	=	electron temperature
m	=	ion mass
m_e	=	electron mass
q	=	heat conductivity per electron
c	=	ion acoustic velocity
Γ_m	=	gas flow rate per unit area
η_m	=	propellant utilization
P_T	=	total deposited power

I. Introduction

THE Helicon Plasma Thruster (HPT) is being investigated intensively in recent years for space propulsion [1-29]. In space thrusters, the thrust equals the momentum per unit time carried by an ejected flow. The source of the kinetic energy of the ejected flow in the HPT is the thermal energy that the electrons acquire from helicon waves. Depositing electrical energy in the flow by electromagnetic waves is an advantage for space propulsion, since electrodes that are amenable to erosion are not immersed in the plasma. While in the HPT the helicon waves only deposit energy in the plasmas, there are other configurations in which, in order to increase the efficiency of the thruster, the helicon source is used as the first stage only, with a second stage of additional heating or acceleration mechanism. Additional energy is deposited in the flow exiting the helicon source in the second stage, through ion cyclotron waves (the VASIMR [11]), through rotating electric or magnetic field [16 - 17], or by including in the second stage a Hall thruster [19, 25], an ion thruster [20], or a magneto-dynamic plasmas thruster [23]. The Helicon Double Layer Thruster (HDLT) [1] relies on the excitation of a double layer at the exit of the helicon source [1 - 5].

In this paper, I discuss certain aspects of the HPT, which is based on a helicon source only, without any additional heating or acceleration mechanism. Also, no excitation of a double layer is assumed. If the ejected gas out of the HPT is mostly ionized, the momentum is carried by the ejected charged particles, the plasma. If, however, the gas is only weakly ionized, most of the momentum is carried not by the plasma but rather by the neutral gas that has acquired the momentum through collisions with the plasma [14, 29]. In this paper, the case of high ionization is addressed in which the momentum is carried by the ejected plasma. Part of the momentum is acquired by the plasma inside the helicon chamber itself and the thrust associated with that momentum is the force exerted by the plasma pressure on the helicon backwall. Another part of that momentum is delivered to the plasma in the magnetic nozzle at the helicon exit, and the associated thrust is the force exerted by the plasma, that carries a diamagnetic current, on the magnetic coils [6, 9, 10, 21, 24, 28].

In order to analyze the momentum delivery to the plasma in the HPT, I address separately the processes in the helicon chamber and in the magnetic nozzle. In a previous paper [13], I analyzed the momentum delivery to the plasma in the helicon chamber. Analytical expressions have been presented for the axial profiles of the plasma variables and for the propellant utilization at the limit of no wall losses. In addition, the specific impulse, thrust over power, and total efficiency, as a function of energy per particle have been calculated, due to the contribution to the thrust of the plasma in the helicon chamber only, without the contribution of the magnetic nozzle. Later, the same analytic expressions for axial profiles of the plasma variables in the helicon chamber were rederived, accounting also for wall losses, in a quasi-two-dimensional model [28]. Other models addressed numerically in various degrees of detail the performance of the HPT [21, 24, 28].

The analysis contains two parts. First, I readdress the processes in the helicon chamber taking into account wall losses. The derived quasi-two-dimensional model is an extension of the one-dimensional (1D) analysis in my previous paper [13]. The wall losses are modelled in more detail than in [28], including three types of electron collisions that lead to cross-field transport. Because of shortage of space, this part of the analysis will be presented in a subsequent paper. The second part of the analysis is presented here. In this part of the analysis I estimate the maximal efficiency of the HPT. With the assumption of an ideal nozzle that converts all electron thermal energy to ion directed kinetic energy that provides thrust, the maximal efficiency of a helicon plasma thruster is found as a function of the energy per ion and for different values of electron heat conductivity. The electron heat conductivity is addressed through imposing a polytropic equation of state for the electrons [26]. When radial wall losses are eliminated, the sources of inefficiency are the energy cost per ion generation and the energy flux into the back wall.

II. Power Balance

The energy $\varepsilon_T(T)$ deposited in an ion-electron pair of the plasma flow into a sheath near a wall is different from that deposited in an ion-electron pair of the plasma flow at an open boundary. At a backwall, that energy is expressed as in Chapter 10 in [30]

$$\varepsilon_{Ts} = \varepsilon_c + 2T + 0.5T\left[1 + \ln\left(\frac{1}{2\pi}\frac{m}{m_e}\right)\right],$$

where m_e is the electron mass. The first term, ε_c, is the energy cost for ionization, $2T$ is the average energy flux for an electron, and the last term is the energy deposited in the ions, $0.5T$ in the presheath and the rest while they are accelerated in the sheath. The total energy deposited in an ion-electron pair that crosses the sonic plane at an open boundary, however, is written as

$$\varepsilon_{Te} = \varepsilon_c + 2.5T + 0.5T + q.$$

The first term on the RHS is the same energy cost for ionization as in the expression for ε_{Ts}, the second term is the electron enthalpy carried by an electron, and the third term is the kinetic energy of an ion $mc^2/2 = T/2$. This expression corrects the expression in my paper [13]. The correct form appears in our previous papers [31 - 33], and also in [21] 28. Here, q is the heat flux per electron flux. The importance of heat flux in the HPT has been pointed out recently [21, 26].

A detailed calculation of the energy cost for ionization $\varepsilon_c(T)$ in Ar, H_2 and H discharges, based on a large number of atomic cross-sections, is given in [34, 35]. We approximate the calculated $\varepsilon_c(T)$ for argon, as shown in

Fig. 1 in [35], by the expression

$$\varepsilon_c(T) = 13.47\,\mathrm{eV} + 7.085\,\mathrm{eV}\exp\left(\frac{5.408\,\mathrm{eV}}{T}\right).$$

The outward plasma particle flux at each of the two sides of the helicon is $\eta_m \Gamma_m$. Therefore, if radial wall losses are eliminated, H_1, the energy invested for an ion-electron pair that exits the plasma (which we coin the energy per ion) is the sum of the energies expressed in the equations deposited in the two pairs. The total power deposited in the plasma, P_T, is

$$P_T = \eta_m \Gamma_m H_1, \quad H_1 = \varepsilon_{Ts} + \varepsilon_{Te} = 2\varepsilon_c + 5.5T + q + 0.5T\ln\left(\frac{1}{2\pi}\frac{m}{m_e}\right).$$

The equations can be solved for η_m and T. The equations can be modified to also account for radial wall losses.

For a thruster, there are two sources of inefficiency, the energy cost for ionization, ε_c, and the energy lost at the backwall, ε_{Ts}. It is appealing to try eliminating the backwall losses, for example by constructing a magnetic mirror configuration at the backwall side of the helicon. The consequences of eliminating these losses for the thruster performance are also examined here. If backwall losses are so avoided, the energy per ion in this case, denoted as H_2 (= ε_{Te}), is smaller than H_1, and is expressed as

$$H_2 \equiv \varepsilon_{Te} = \varepsilon_c + 3T + q.$$

In the next subsection, we introduce a particular form for the heat flux.

III. Efficiency and Heat Conductivity

The maximal efficiency (for propellant utilization that equals unity) is

$$\eta_1 = \frac{3T+q}{H_1} = 1 - \frac{\left[2\varepsilon_c + 2.5T + 0.5T\ln\left(m/2\pi m_e\right)\right]}{H_1}.$$

For writing the second equality, we used a previous expression. If the backwall losses are avoided, the maximal efficiency is

$$\eta_2 = \frac{3T+q}{H_2} = 1 - \frac{\varepsilon_c}{H_2}$$

IV. The Energy per Ion and Heat Conductivity

We write the heat conductivity per electron as $dq = de + pdV$, where $e = (3/2)T$ is the electron internal energy, p is the electron pressure and V is the volume. For a polytropic equation of state, the expression becomes $dq = (3/2)(3\gamma - 5)/(\gamma - 1)\,dT$. Assuming that the temperature at infinity is zero, the outward heat flux per electron at the helicon exit is

$$q = sT, \quad s \equiv \frac{1}{2}\left(\frac{5-3\gamma}{\gamma-1}\right),$$

where T is the electron temperature at the helicon exit. This form of heat flux at the helicon exit for a polytropic equation of state has been recently suggested in [26].

Because the plasma particle fluxes are equal at the two axial sides of the helicon, for each ion-electron pair that exits the helicon, there is an ion-electron pair that hits the backwall. Using the equation for the heat conductivity, we write the energy per ion for the two cases as

$$H_1 = 2\varepsilon_c + (5.5+s)T + 0.5T\ln\left(\frac{1}{2\pi}\frac{m}{m_e}\right),$$

and

$$H_2 = \varepsilon_c + (3+s)T.$$

V. Maximal Efficiency

The maximal efficiency (for propellant utilization that equals unity) is

$$\eta_1 = \frac{(3+s)T}{H_1} = 1 - \frac{\left[2\varepsilon_c + 2.5T + 0.5T\ln(m/2\pi m_e)\right]}{H_1}.$$

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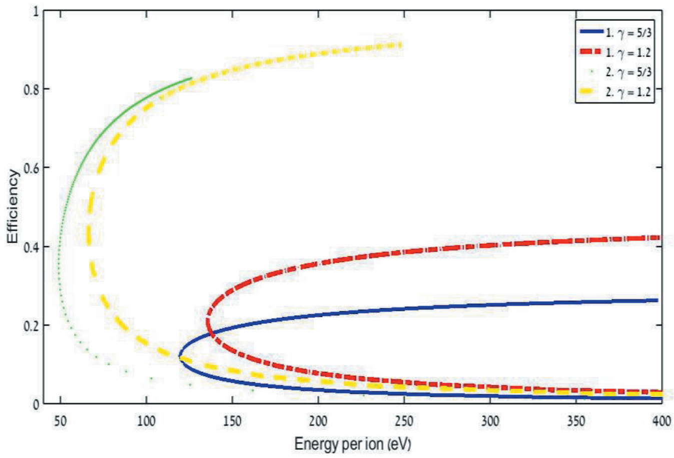

Figure 1. The maximal efficiency as a function of the energy per ion when there are backwall losses (blue and red) and when backwall losses are eliminated (green and yellow).

If the backwall losses are avoided, the maximal efficiency is

$$\eta_2 = \frac{(3+s)T}{H_2} = \frac{(3+s)T}{\varepsilon_c + (3+s)T} = \frac{H_2 - \varepsilon_c}{H_2} = 1 - \frac{\varepsilon_c}{H_2}$$

The maximal efficiency is determined by the heat conductivity and the temperature. Assuming that the heat conductivity is given (by s) then the maximal efficiency is determined by the energy per ion (either H_1 or H_2), where s and H_1 (or H_2) determine T. Figure 1 shows η_1 and η_2 as a function of H (either H_1 or H_2) for the two values of γ, one corresponding to adiabatic flow, $\gamma = 5/3$ ($s = 0$), and the other was $\gamma = 1.2$ ($s = 3.5$). For each H and s, the value of T is found either from the equation for calculating η_1 or from the equationfor calculating η_2. It is seen that η_2 is much larger than η_1, demonstrating the great advantage of eliminating backwall losses.

Heat conductivity affects the efficiency in two different ways. On one hand, a higher heat conductivity (a higher s) results in more energy flowing out with the electrons at the helicon exit, allowing a larger thrust. On the other hand, for specified power into the flow (a specified H), a higher heat conductivity results in a lower electron temperature T , making the thrust smaller.

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