Section 8: Electromagnetic Propulsion

AE435

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6 Pulsed Plasma Thruster (PPT)

Contents

6.1 Pulsed Plasma Thruster

In 1964 Russians decided to avoid problems with tanks, valves, regulators, by using a solid propellant. The first propellant tried was Teflon, and although many others have been tried, Teflon (C_2F_4) remains the best choice. It has a density almost twice that of Lexan (2.2 g/cm3). It does not have a liquid phase, and evaporates from solid to vapor.

PPT was first flown in 1964 (Zond 2) and in 1968 (LES-6). The classic schematic is:

Figure 9: PPT Diagram

Parallel plate design. JxB acceleration.

Stored energy is:

$$\frac{1}{2}CV_o^2 \qquad [J] \tag{8.64}$$

For a pulse rate f, then the average power is

$$P_{\text{avg}} = f\,E_o \qquad [W] \tag{8.65}$$

Typically $f \sim 1 - 5Hz$.

Each pulse creates thrust, and evaporates mass, m.

Figure 10: Thrust to Propulsion Time

Impulse bit is:

$$\int T\,\mathrm{d}t = I_{\text{bit}} \tag{8.66}$$

Specific impulse is then:

$$I_{SP} = \frac{I_{\text{bit}}}{g_o\,m} \tag{8.67}$$

Average thrust:

$$\bar{T} \text{ or } T_{\text{avg}} = f\,I_{\text{bit}} \qquad\qquad P_{\text{avg}} = f\,E_o \tag{8.68}$$

The arc heats the Teflon to $\sim 600 - 700K$, so it ablates. This ablation continues to occur after the pulsed power is applied. And the ablation that occurs after the initial pulse is referred to as ”late time ablation”.

Figure 11: Late Time Ablation Illustration

6.2 Efficiency

The efficiency is calculated from a simple circuit model:

Figure 11: Efficiency Circuit Model

Assume a matched PFN:

$$R_L + Z_L = Z_o \tag{8.69}$$

Thus the voltage drop across the load is equal to that across Z_o, that is: $\frac{V_o}{2}$

Thus the current is:

$$J = \frac{\frac{V_o}{2}}{Z_o} = \frac{\frac{V_o}{2}}{R_L + Z_L} \tag{8.70}$$

Then the charge is

$$Q_o = C_o V_o$$

And the length of the pulse is

$$\frac{Q_o}{J} = \frac{C_o V_o}{(V_o/2)/Z_o} = 2\, C_o\, Z_o = t_p \tag{8.71}$$

Since $Z_o = \sqrt{\frac{L}{C}}$ where L, C are per section of the PFN, and

$$C_o = N\,C$$

Where N is the number of sections in the PFN number. We assume each section has the same capacitance

Then

$$t_p = 2\,N\sqrt{L\,C} \tag{8.72}$$

Recognize that for cases where Electromagnetic energy does work on a mass:

$$\text{Thrust} = F_{em} = \frac{1}{2}\,L'\,J^2$$

and the resulting power

$$P = \frac{1}{2}\,F\,u_e = J^2\,Z_o = \frac{1}{2}\left(\frac{1}{2}\,L'\,J^2\right)u_e$$

which means the impedance is

$$Z_o = \frac{1}{4}\,L'\,u_e$$

Also, for coaxial electrodes, Maecker (8.22) with (8.53) is:

$$F = \frac{\mu\,J^2}{4\,\pi}\left(\ln\left(\frac{r_a}{r_c}\right) + \frac{3}{4}\right) = \frac{1}{2}\,L'\,J^2$$

$$L' = \frac{2\,\mu}{4\,\pi}\left(\ln\left(\frac{r_a}{r_c}\right) + \frac{3}{4}\right) \tag{8.73}$$

Returning to efficiency, R_L represents losses in capacitors, switches, electrodes, etc., so let the efficiency:

$$\eta = \frac{Z_L}{R_L + Z_L} = \frac{1}{\frac{R_L}{Z_L} + 1} \tag{8.74}$$

so

$$Z_L = \frac{1}{4}\,L'\,u_e = \frac{1}{2}\,\frac{\mu}{4\,\pi}\left(\ln\left(\frac{r_a}{r_c}\right) + \frac{3}{4}\right)u_e \tag{8.75}$$

Equation 8.75 is the electromagnetic impedance for coaxial electrodes. The electromagnetic impedance for parallel plate electrodes is somewhere in our notes.

For Example:

6.3 Two Stream Model

The first complication is that Teflon (C_2F_4) is dissociated to $C+F+F$ and then is partially ionized (C^+, F^+). Because of pressure, neutrals are accelerates to lower velocity than ions. This leads to a two-stream model.

The PPT is partially ionized. Neutral and Ions. We have a situation in PPT where the pulse results in "fast" ions and "slow" neutrals coexisting in the same channel. "Two-Fluid" model.

Consider the situation shown here:

Figure 12: Two Fluid Model

Total ablated mass is the sum of the fast and slow species.

$$M = M_f + M_s \tag{8.76}$$

Impulse bit is then:

$$I_{\text{bit}} = m_f\, u_f + m_s\, u_s \tag{8.77}$$

Thus I_{SP} and efficiency are:

$$I_{SP} = \frac{I_{\text{bit}}}{m\, g_o} = \frac{m_f\, u_f + m_s\, u_s}{(m_f + m_s)\, g_o} \tag{8.78}$$

$$\eta = \frac{\frac{1}{2}\, I_{\text{bit}}^2}{m\, E_o} \tag{8.79}$$

Experimentally we can measure I_{bit}, m and $E_o = \frac{1}{2}\, C\, V_o^2$. But cannot know m_f, u_f, m_s, u_s. We can also calculate the Electromagnetic portion of I_{bit}:

$$I_{\text{bit}} = \int T_{ET}\,\mathrm{d}t + \int \frac{1}{2}\,L'\,J^2\,\mathrm{d}t \tag{8.80}$$

If we say

$$\int \frac{1}{2}\,L'\,J^2\,\mathrm{d}t = m_f\,u_f \tag{8.81}$$

Then from measured I_{bit}, we also know $m_s u_s$; solve Equation 8.80 for

$$\int T_{ET}\,\mathrm{d}t = m_s u_s$$

Now the problem is, what are m_f and m_s, or u_f and u_s?

We find the answer in Cosmology, more specifically a theory for the origin of the solar system by Hannes Alfven (Nobel Prize in Physics 1970). Alfven's paper "On the Origin of the Solar System" assumed the Sun and a magnetized dust cloud.

Alfven: When KE = ionization energy, particle falling in is ionized, losing all energy, so stops. In this way, atoms of H, He, Ne, etc. stop at different radii.

$$\frac{1}{2}\,m\,u_c^2 = e\,\varepsilon_i \tag{8.82}$$

So for the PPT it is assumed that u_f cannot exceed u_s by more than u_c:

$$u_f - u_s = u_c \tag{8.83}$$

What is u_c for Teflon (CF_2)?Carbon: $u_c = 13\,[km/s]$ Fluorine: $u_c = 13\,[km/s]$

Example, assume

Conclusion: Most efficient PPT has highest degree of ionization, which minimizes ms and raises Isp.

6.4 More Advanced PPT Modeling

More advanced PPT models use an ablation model connected with an electrothermal or electromagnetic (i.e., electromechanical) acceleration model connected with a plume model.

6.4.1 Ablation Model:

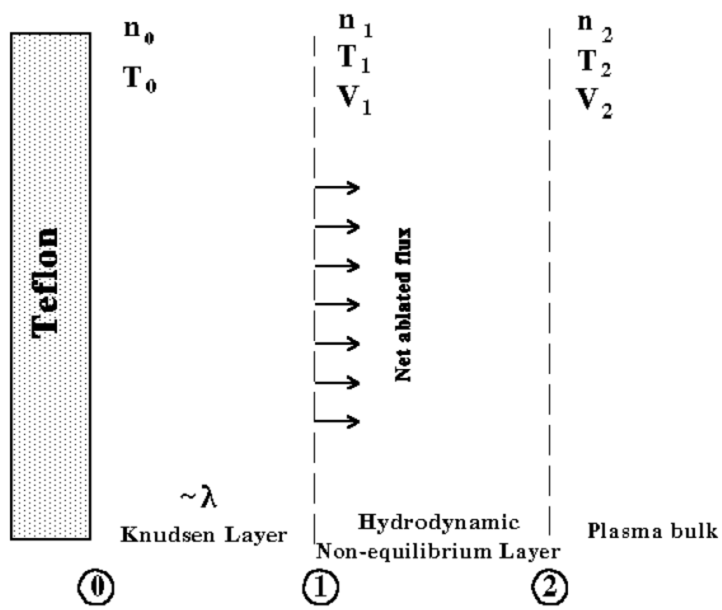
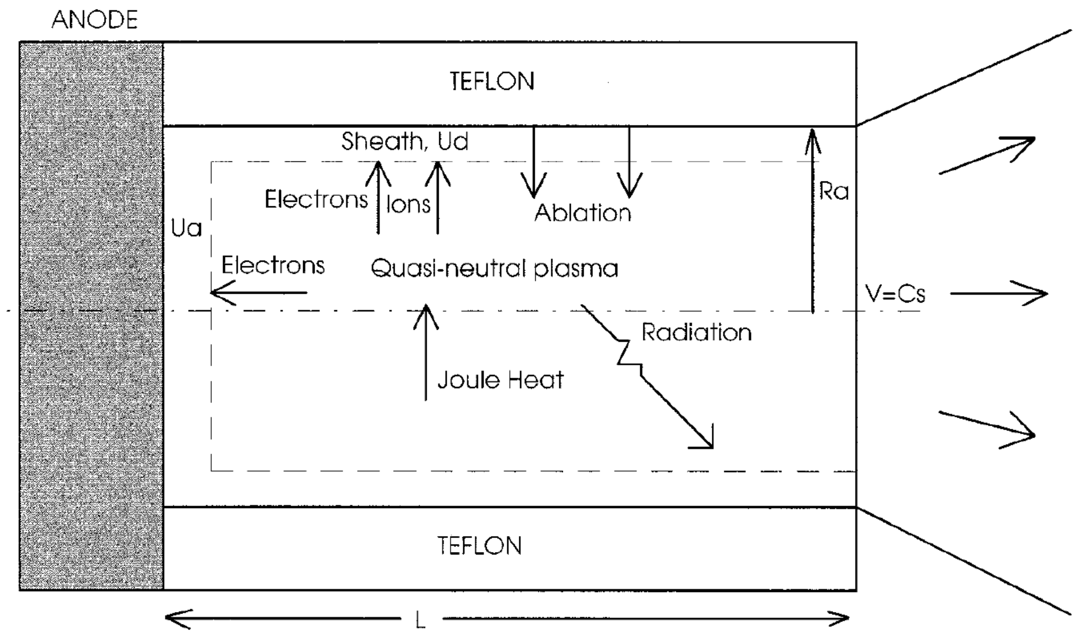


Figure 1. Schematic representation of the layer structure near the ablated surface.

Non-equilibrium kinetic layer near the surface of ablating material. Two extremes are the surface and the plasma bulk. In between one can imagine a kinetic non-equilibrium layer close to the surface with a thickness a few mean free paths (Knudsen layer). Then a collision dominated non-equilibrium layer where electron and heavy particle temperatures differ. At the right, all species reach thermal equilibrium.

Michael, K., Iain, D. B., Isak, I. B., "On the model of Teflon ablation in an ablation-controlled discharge," Journal of Physics D: Applied Physics, Vol. 34, No. 11, pp. 1675, 2001.

6.4.2 Electrothermal Model



Plasma heating with electrothermal acceleration. Energy balance in the quasineutral plasma column is:

Keidar, M., Boyd, I. D., Beilis, I. I., "Electrical discharge in the Teflon cavity of a coaxial pulsed plasma thruster," Plasma Science, IEEE Transactions on, Vol. 28, No. 2, pp. 376-385, 2000

6.4.3 Electromagnetic Model with Plume

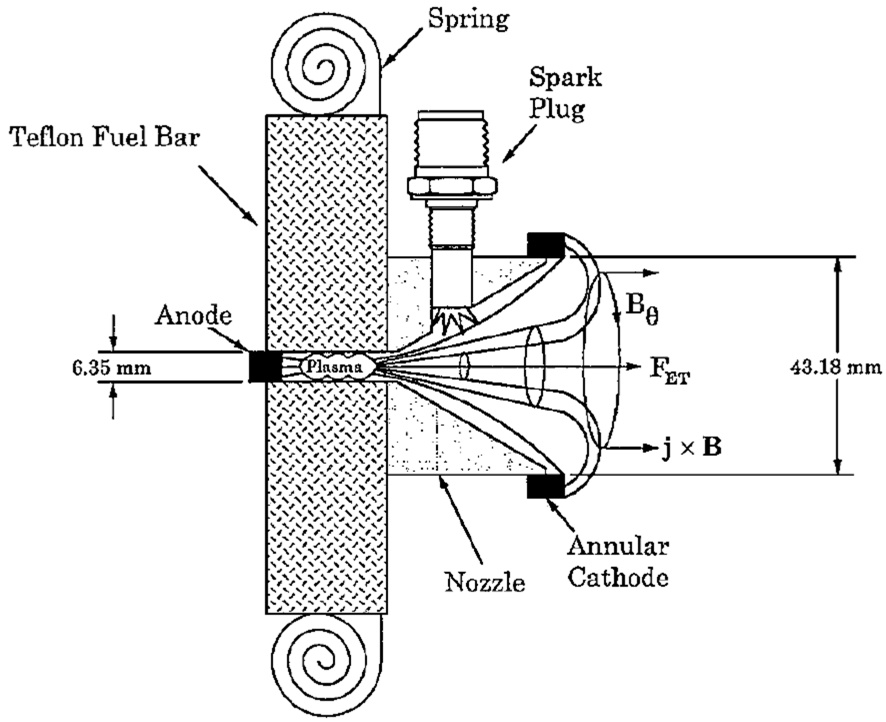


Fig. 1 Schematic diagram of the Illinois PPT-4.

Boyd, I. D., Keidar, M., McKeon, W., "Modeling of a Pulsed Plasma Thruster from Plasma Generation to Plume Far Field," Journal of Spacecraft and Rockets, Vol. 37, No. 3, pp. 399-407, 2000/05/01.