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Ablation of Polyester Capillaries by Electrothermal Pulsed Plasma Discharge

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Abstract

Plasma propulsion systems have become the most attractive systems for satellite engines due to their simplicity and reliability. This research was carried out to manufacture an electrothermal pulsed plasma thruster system using a polyester capillary. This study includes a measurement of ablated mass with different input voltage values and with increasing in the number of shots. It was found that by increasing the input voltage from 1.5 kV to 4 kV, the ablated mass increases from 120.6 µg to 432.6 µg. The experimental results were compared to the theoretical data obtained from the ETFLOW model; the calculated ablated mass increased from 136 µg to 447 µg, which is in good agreement with the measured results. Also, the model was used to study the behavior of some physical parameters with discharge time, such as plasma density, velocity, and temperature. Finally, the exit velocity was calculated as a function of peak current.

Keywords: PPT, electrothermal discharge, ablated mass, thrust, impulse, specific impulse.

1. Introduction

Pulsed plasma thrusters (PPTs) have become the most attractive type of electric propulsion systems because PPTs have a simple design, have a small size, are reliable, and can work with lower power levels giving a variable thrust [1]. So, PPTs have become a favorable system for satellite control, and are used for altitude control, and station-keeping missions [2]. The first flight of PPTs was in the 1964s with the Soviet Union aboard Zond-2[3]. The scientific idea behind creating thrust to spacecraft by PPTs is to produce plasma and expel it out of the thruster.

Pulsed plasma thrusters can be classified into two major classes according to the mechanism of generation thrust: electrothermal (ET), and electromagnetic (EM). In electrothermal systems, the thrust is produced by the thermal expansion of the plasma. Electrothermal PPT gives a higher level of thrust than Electromagnetic, however, it gives lower specific impulse [4]. Many propellants are used such as solid, liquid, and gas. The common propellants used are polymers because of their reliability, and high electrical resistivity which prevent the forming of short circuits between the cathode and anode. Polymers can work with a large range of temperatures and densities. The most attractive used polymer is Teflon which gives the best performance until now [5].

The performance of PPT is determined by the value of ablated mass from the propellant surface, the impulse given by this mass, and the specific impulse of the thruster. Despite the advantages of the polymer as propellants, they suffer from late-time ablation, the mass continues to be ablated after the end of discharge due to high temperature inside the capillary which decreases the thruster efficiency [6]

“Yanan Wang” [7] Studied the influence of charging voltage and the cavity geometry on the value of plasma resistance in the capillary and the impulse value. It has been shown that with increasing voltage, the plasma resistance decreases, resulting in a decrease in transfer efficiency. Also, the impulse bit increases with the charging voltage and cavity length. In contrast, the increase in cavity diameter reduces the output impulse bit. “Hirokazu Tahara” [8] found that specific impulse decreased with increasing cavity length and increased with increasing cavity diameter [9] or shot number. Also, the impulse bit rapidly decreases with increasing shot number. These results agree with “Toshiiaki Edamitsu” who studied the ablated mass and impulse for PPT with different diameters and lengths of the capillary tube [10].

In this study, an Electrothermal PPT (ETPPT) was designed using polyester propellant which can withstand high pressure values. The ablated mass of polyester was measured with different values of input voltage and with increasing number of shots. The experimental values are compared to calculated values from the ETFLOW model. The model was built based on some essential equations such as the conservation of mass, conservation of momentum, and conservation of energy. Also, we used the model to study some physical parameters of ET discharge as a function of discharge time such as plasma temperature, density, and ablated mass. In addition, the change in exit velocity with peak current was calculated.

2. Experimental Setup

Figures 1, 2 and 3 show the components of the (ETPPT). it consists of two electrodes, one is a hollow anode with a diameter of nearly 1.5 cm connected to a copper extension, and the other electrode is a 4 mm diameter rod, between the two electrodes, there is an insulating material with a 1.7 cm inner diameter which is a host for the propellant. The thruster works with a glass vacuum chamber 27 cm high and 23 cm in diameter.

Figure 1: The ETPPT electrodes.

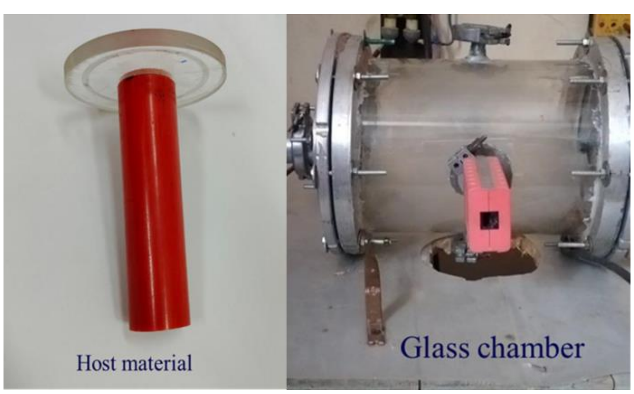

Figure 2: The Chamber and the Host tube.

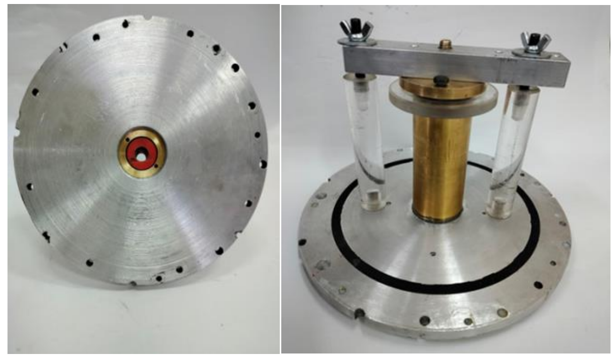

Figure 3: All ETPPT components installed together.

Figure 4 shows a schematic diagram of the ETPPT device. The DC power supply charges the capacitor bank, then it is discharged in the system by the air gap switch producing the Arc. During the arc, the energy is radiated and absorbed by the inner wall of the propellant causing ablation [11] [12]. The ablated particles are dissociated and ionized forming plasma. The plasma is expelled out of the thruster due to the high-pressure gradient inside the capillary. Depending on the mass of the expelled propellant and its velocity, the value of impulse and specific impulse can be determined to describe the efficiency of the thruster.

The ablated particles from the capillary's wall form a shield of high vapor gas that absorbs part of incoming radiation and reduces the amount of energy falling to the wall, only a fraction of heat flux is transmitted to the wall, and this affects the value of the heat transfer coefficient. This mechanism is called the vapor shielding effect [13]. After the discharge occurs, the ablation process of the propellant continues for a while due to the high surface temperature of the inner wall. The ablated particles are injected at a low speed that cannot contribute to the impulse process.

The experiment was carried out with different values of applied voltage. The voltage varied between 1.5 kV to 4kV. The signal of current has 19 µs in duration. The capacitor bank is 5.32 µF. The propellant used is polyester with 5 cm in length and 4mm in diameter.

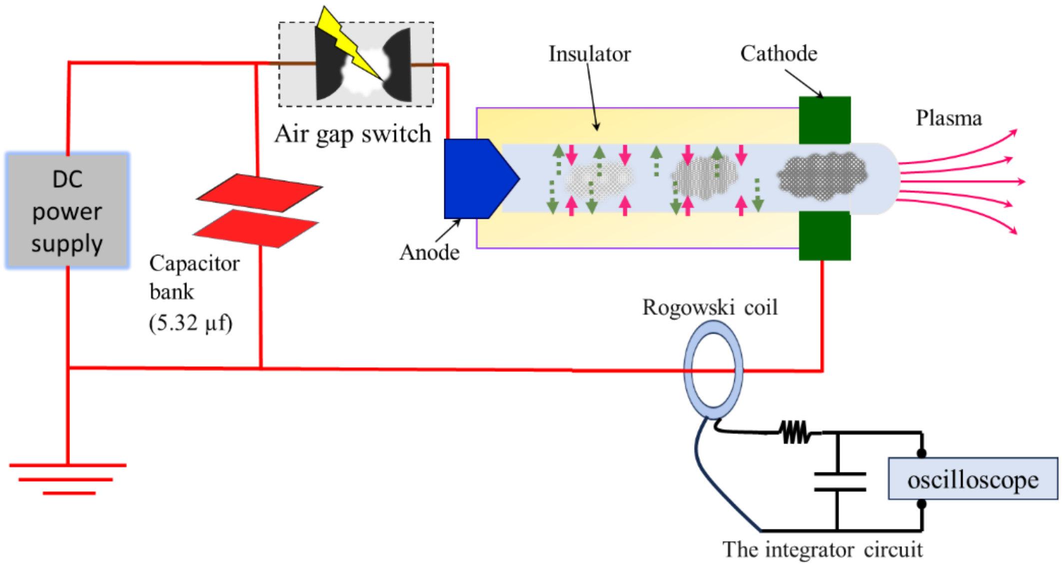

Figure 4: The schematic diagram of the ETPPT device

3. Chemical Properties of Polyester

The chemical structure of used polyester is shown in Fig.5 [14]. The propellant is manufactured by adding peroxide by 0.01% percentage to the liquid polyester for solidification process. All chemical properties used in this study are summarized in Table 1. The molar mass is calculated by knowing the molar mass of each atom, and the dissociation energy of the polymer is calculated by knowing the dissociation energy of each covalent bond [15].

4. Governing Equations

A. Radiation heat equation:

The radiation heat flux (q) (W/m^2) [16, 17] could be given by [18, 19]:

$$q = F_t \sigma_s \left(T^4 - {T_{vap}}^4\right) \qquad (1)$$

Where σ_s is Stefan–Boltzmann constant, T is plasma temperature, T_{vap} is the vaporization temperature of the capillary, and F_t is the energy transmission factor (grey factor) which describes the amount of energy deposition through the vapor shield. The rate of ablation($\dot{n}$) ($m^{-3}.sec$) could be given by:

$$\dot{n} = \frac{2q}{R\, H_{sub} A_P} \qquad (2)$$

Where n is the number density of the plasma (number/ m^3), v is the plasma velocity (m/ sec^2) and H_{sub} is the specific heat of sublimation (joule/kg), A_P is the mass of the atom that constitutes plasma (kg/ atom).

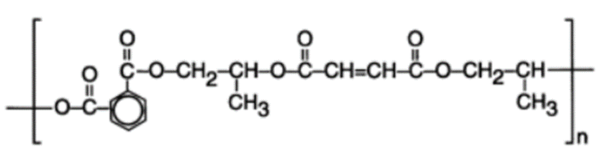

Figure 5: chemical structure of polyester

Table 1: chemical properties of polyester

Physical properties	Value
Molar mass(g/mol)	334.281
Dissociation energy (kJ/mol)	17056
Thermal conductivity(W/mK)	0.28
Density (g/cm^3)	1.17
Boiling point(k)	419.15
Specific heat (J/kg.K)	1030

The pressure inside the capillary (P) (N/m^2) is given by:

$$P = \left(n_e + \sum_{i=0}^{i_{max}} n_i\right) k_B T + \frac{k_B T}{24\pi {\lambda_D}^3} \qquad (3)$$

with **i** = 0 representing the neutral species and higher **i** 's representing the higher ionization levels, $\lambda_D$is the is Debay length $\equiv (\frac{\varepsilon_0 k_B T}{n_e e^2})^{1/2}$, and k_B is Boltzmann constant. Taking into account that the effect of the viscous drag is negligible.

B. Discharge current equation:

The current value can be measured by the Rogowski coil by knowing the value of input voltage and capacitance. Using the following equation to calculate current [20]:

$$I = \frac{((1+f)\pi C\, V)}{\tau} \qquad (4)$$

where C is the capacitance of the capacitor bank, V is the input voltage, τ is periodic time, and f is the reversal ratio which can be calculated from the peaks of signals (I_1, I_2, I_3, I_4) by:

$$f = \frac{1}{4}(f_1 + f_2 + f_3 + f_4) \qquad (5)$$

$$f_1 = \frac{I_2}{I_1}, f_2 = \frac{I_3}{I_2}, f_3 = \frac{I_4}{I_3}, f_4 = \frac{I_5}{I_4}$$

Figure 6 represents the short signal measured at 4kV using a Rogowski coil connected to the integrator circuit. The integrator circuit consists of a 10 kΩ resistor connected parallel to a capacitor with 10 nF.

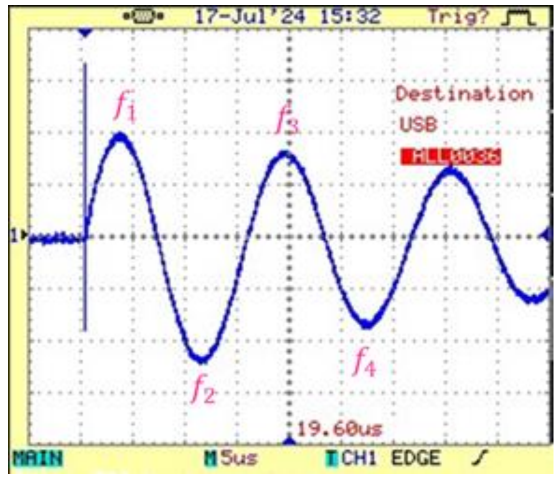

Figure 6: Short signal of 4 kV.

5. Results and Discussion.

A. Discharge current curve

Figure 7 shows the discharge current signal with an input voltage of 3 kV. The current reaches its peak of 5.66 kA at 3.66 µs. Figure 8 shows the I-V curve in which the current increases with the applied voltage increase following the linear law of I [kA] = 1.3846 V[kV] + 0.981.

B. Experimental, calculated ablated mass

Figure 9 shows the experimental and calculated variation of the ablated mass as a function of input voltage. The measured ablated mass increased from 120.6 µg to 432.6 µg by increasing the input voltage from 1.5 kV to 4 kV and increasing voltage leads to an increase in the radiation heat flux falling onto the inner surface of the capillary which increases the ablated mass. Theoretically, the mass increases with peak current from 136 µg to 447 µg, which agrees with measured values.

Figure 10 shows the increase in total ablated mass with the number of shots at 1.5 kV, the ablated mass increased from 0.06 g after 500 pulses to 0.24g after 5000 shots. The average ablated mass per pulse is 91µg. The ablation rate started to decrease after 2000 pulses due to an increase in the capillary radius with a decrease in the heat flux incident on the inner wall of the capillary. Increasing the number of shots raises the carbonization rate in the inner wall of the capillary as shown in Fig. 11.

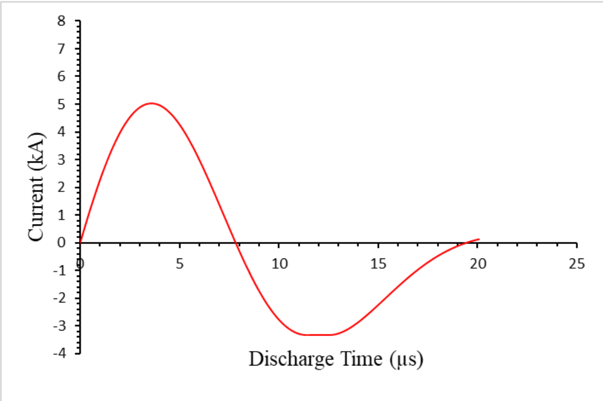

Figure 7: Signal of discharge current with input voltage 3kV.

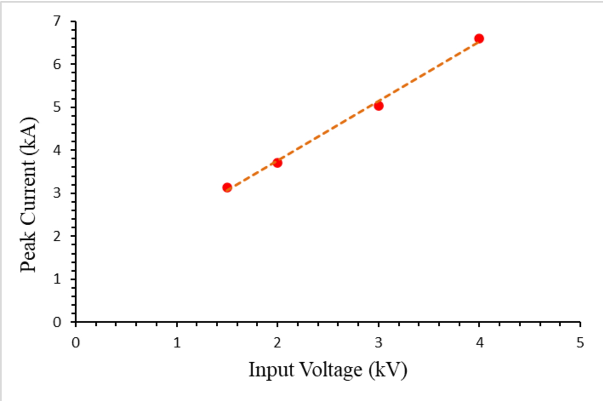

Figure 8: Increasing the peak current with different values of applied voltage

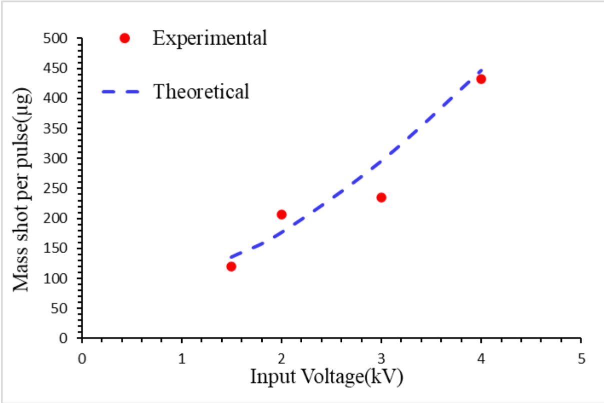

Figure 9: Variation the measured and calculated ablated mass with the peak current.

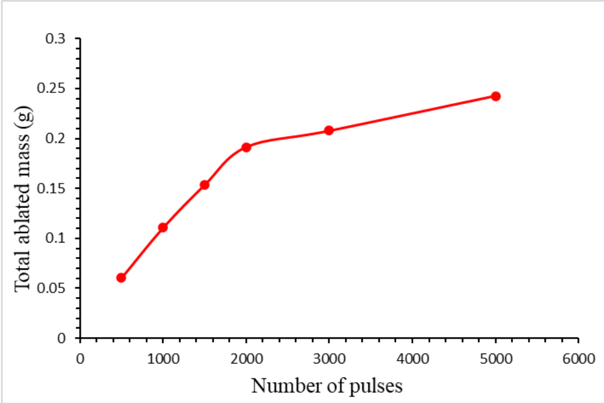

Figure 10: Increasing the total ablated mass with the number of shots

Figure 11: Carbonization of the propellant after pulses

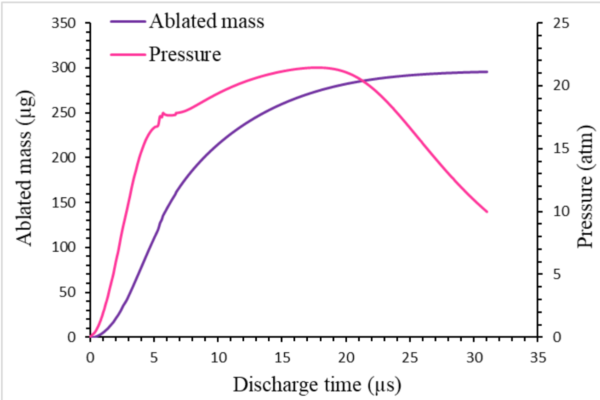

Figure 12: The variation of ablated mass and pressure with discharge time

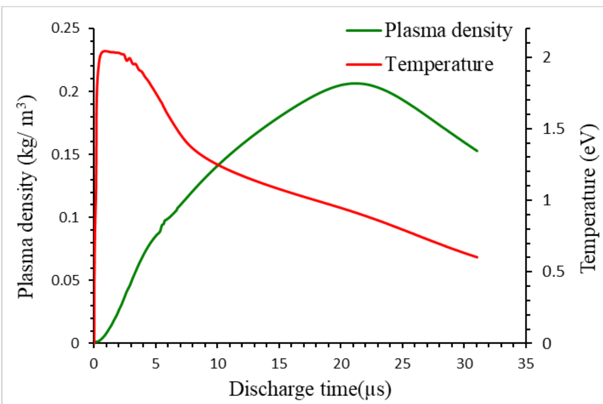

Figure 13: The variation of plasma density and temperature with discharge time.

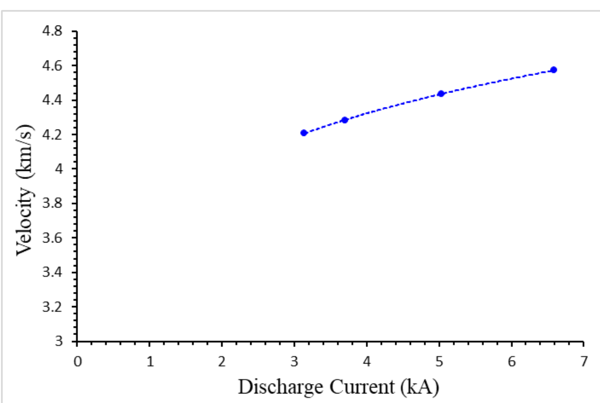

Figure 14: Change in velocity with the discharge current

C. Electrothermal Discharge Properties as a Function of the Discharge Time

Figure 12 shows the variation of the ablated mass and plasma pressure with the discharge time at a current of 5kA. The pressure value increases until the maximum value of 21.4 atm at a time of 17.7 µs, and the ablated mass reaches the maximum value of 295.7 µg by the end of the discharge. After the end of the discharge, the temperature inside the capillary remains high enough to continue the ablation process for a period of about twice that of the periodic time. The behaviors of the temperature and plasma density are shown in Fig. 13. The temperature rapidly increases to the maximum value of 2 eV at 0.8 µsec and starts to decrease when the plasma density starts to increase. The plasma density reaches the maximum value of 0.21 km/ m^3 at time 21 µs.

D. Calculations of the peak of velocity:

Figure 143 shows the change in peak velocity with changing the peak current. Increasing the peak current from 3.1 kA to 6.6 kA will increase the plasma peak velocity from 4.2 km/s to 4.6 km/s following the power law v[km/s] = 3.6988 I $[kA]^{0.1124}$. By increasing the peak current, the temperature increases, so, the exit velocity increases.

5. Conclusion

A capillary electrothermal system was designed using polyester propellant made by mixing polyester with 0.01% peroxide to make crosslinked. The ablation mass of polyester was studied with different variables such as input voltage and number of shots. The ablated mass increased from 120.6 µg to 432.6 µg with increasing the input voltage from 1.5 kA to 4 kA. Increasing the number of shots increases the total ablated mass from 0.06 g after 500 pulses to 0.24 g after 5000 shots. The values of ablated mass were calculated using ETFLOW modeling. The measured values were in good agreement with the calculated values, in which ablated mass increased from 136 µg to 447 µg.

The code of the ETFLOW model is built on some essential equations such as conservation of mass, momentum, and energy. The model was used to describe the behavior of some physical quantities such as plasma velocity, temperature, and pressure with discharge time. Also, the exit velocity of plasma was measured as a function of the peak current. The exit velocity increased from 4.2 km/s to 4.6 km/s with increasing the peak current from 3.1 kA to 6.6 kA.

Ethical Consideration:

This study was conducted according to the guidelines of the Declaration of Benha University and approved by the Ethics Committee of the Faculty of Science, Benha University (Code: BUFS-REC-2024-263Phy).

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تبخير الانابيب الضيقة المصنوعة من البوليستر بواسطة تفريغ البلازما النبضي الكهروحراري

مروة محمد أبوالحديد[1] ، محمد السيد عبدالقادر[2] ، فتحي بخيت دياب[2] ، طارق يوسف الرصاصي[1] ، محمد عبدالمنعم عبدالحليم[1]

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أنظمة دفع البلازما من أكثر الأنظمة المستخدمة في محركات الأقمار الصناعية جاذبية بسبب بساطتها وموثوقيتها. تم إجراء هذا البحث بقسم البلازما والاندماج النووي – هيئة الطاقة الذرية لتصنيع نظام دفع بلازمي نبضي كهربائي حراري باستخدام أنبوبة شعرية من مادة البوليستر. تتضمن هذه الدراسة قياس الكتلة المتآكلة للانبوبة الشعرية عند تغير كلا من جهد الدخل وزيادة عدد النبضات الكهربية. النتائج العملية بينت انه مع زيادة جهد الدخل من 1.5 كيلو فولت إلى 4 كيلو فولت، تزداد الكتلة المتآكلة من 120.6 إلى 432.6 ميكروجرام. تمت مقارنة النتائج التجريبية بالبيانات المحسوبة التي تم الحصول عليها من نموذج ETFLOW؛ ووجد ان الكتلة المتآكلة المحسوبة تزداد من 136 إلى 447 ميكروجرام، وهي تتفق جيدًا مع النتائج المقاسة عمليا. كما تم استخدام النموذج لدراسة سلوك بعض المعاملات الفيزيائية مع زمن التفريغ، مثل كثافة البلازما والسرعة ودرجة الحرارة. أخيرًا، تم حساب سرعة الكتلة المندفعة كدالة في ذروة التيار.