System Tradeoffs for Pulsed MPD Thruster in Space Mission Application

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A pulsed MPD thruster can be operated at a high specific-impulse, but it may impose an excessive power and weight penalty on the system for space mission applications. In order to determine the minimum weight thruster-power supply system, the possible system tradeoffs are studied in detail. Based on the experimental observation that dependable operation of a high-performance pulsed MPD thruster is limited by a critical value of the ratio (applied current)^2/propellant flow rate, a method for determination of proper thruster operation conditions such as: the discharge energy per pulse, the pulse width, the pulse repetition frequency, the propellant flow rate, etc. for optimal system design is developed. As an illustration, this analytical scheme is applied for the design of 4.46×10^{-3} N (1 mlb) average thrust pulsed MPD system. The calculation indicates that the system can be designed to operate at a specific impulse of 1180 sec and an efficiency near 23% with approximately 11 kg of the system weight.

Nomenclature

b = proportionality constant for thrust
C = degree of mismatch between mass and power pulses
d = diameter of electrode, subscripts A and C refer to anode and cathode, respectively
E = energy discharge per pulse
E_s = energy supplied per pulse
e = thruster efficiency
I_0 = total-impulse, N-sec
g = gravitational acceleration
I_p = impulse-bit for each pulse, N-sec/pulse
I_{sp} = specific-impulse, sec
J = applied current at electrodes
J_s = applied current at condensers
M_c = condenser bank mass
M_F = fixed weight of the complete system
M_p = total propellant mass
M_{pp} = propellant mass per pulse
M_s = mass of power supply
m_c = specific weight of condenser bank, kg/joule
m_s = specific weight of power supply, kg/kw
$\dot{m}$ = propellant flow rate, g/sec
P_s, P_t = supplied, and thrust power, respectively
q = pulse repetition frequency
T = thrust, Newton
t_c = condenser charge-up times $\approx 1/q$
t_m = mass discharge time
t_0 = total duration of thruster operation for the mission
t_p = energy discharge time, or pulse width
V = applied voltage at electrodes
V_s = applied voltage at condensers
z = impedance across the electrodes
η = condenser bank discharge efficiency
$(\ )_c$ = critical or maximum credible value

1. Introduction

A PLASMA arc thruster relies on electromagnetic forces to accelerate the propellant. This is in contrast to other auxiliary electric propulsion systems, such as ion or colloid thrusters, which are electrostatically accelerated devices. In some occasions, the electromagnetically accelerated group is further subdivided between the magnetoplasmadynamic (MPD) thrusters and the pulsed plasma thrusters[1]; but with the development of the short-pulsed self-magnetic MPD thruster the distinction between these two subgroups starts to disappear.

A pulsed MPD thruster operates in quasi-steady state at a repetitively pulsed power level two to three orders of magnitude higher than, but at an average power level comparable to or lower than, those of a steady-state MPD thruster. Below the critical operating condition, the increase in specific impulse and efficiency with power has been observed[2]; thus, the pulsed MPD thrusters offer an improved performance and reduced heat-transfer problem over the steady-state counterpart for the low-average-power auxiliary-propulsion mission. Moreover, the duty cycle of the pulse chain is adjustable and it provides the pulsed MPD thruster with versatility. However, from the system point of view, the pulsed MPD thruster has the disadvantage of requiring a power conditioning subsystem to produce the desired high-peak-power and pulse wave form. The power conditioning subsystem is not 100% efficient, and it also adds substantial weight to the total flight system.

It is the purpose of this paper to examine the parameters that affect the performance of pulsed MPD thrusters and use this information to illustrate an approach for the system tradeoff design. Specifically, a compromised system design is presented in the following for a pulsed MPD thruster at 117 w (1.75 Mw peak) averaged power level with 1180 sec specific impulse and 23% efficiency. This thruster system would be quite attractive for future flight operations because of its moderate weight and high performance.

2. Characteristics of Pulsed MPD Thruster

The thrust produced by MPD devices has been identified[3] as consisting of: 1) aerodynamic pressure force, 2) magnetic pumping, 3) magnetic blowing, 4) aerodynamic swirl, and 5) Hall current acceleration. In the range of the large electric power input required to maintain the self-induced magnetic field in the MPD devices, the contribution from the aerodynamic sources is found to be relatively small compared with others. If the contribution from the Hall current is also

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neglected, the MPD thrust can be approximated by a relation[3,4]

$$T = bJ^2 \tag{1}$$

with the constant b given as

$$b = (\mu_0/4\pi) \cdot [\tfrac{1}{2} + \ln(d_A/d_C)] \tag{2}$$

The validity of Eqs. (1) and (2) under various range and type of mass flow rates, propellants, electrode geometries, etc. has been investigated experimentally[2,5] and the following have been found.

1) The thrust is proportional to the current squared while the proportionality constant b is dependent on the geometric ratio d_A/d_C. For a given electrode configuration, the changes in mass flow rate and/or molecular weight of propellant do not seem to alter the value of b.

2) Within the range of experimental conditions for which the measurements were made, a parameter $J^2/\dot{m}$ seemed to reach a critical value for each type of noble gas propellants. Above a certain critical value of $J^2/\dot{m}$, the MPD operation was observed as increasingly unstable and erratic, and the reliability of the corresponding MPD performance began to disintegrate. In this respect, the critical value of $J^2/\dot{m}$ could be related to the onset of starvation of the propellant feed whereupon the ingestion of environmental and/or eroded material is induced.

3) The specific impulse and the efficiency of the MPD thruster tend to increase as the value of $J^2/\dot{m}$ is increased. Consequently, the limit of the MPD performance would be encountered when the parameter $J^2/\dot{m}$ reaches its critical value. It is interesting to note that the exhaust velocity at the critical condition can be shown[6] to correspond to the Alfven critical velocity. However, this velocity is not necessarily a limiting factor for all pulsed MPD accelerators tested by other investigators.

In view of the importance of the preceding statements in providing a basis for the system optimization, further discussions are given below to explain their specific influences.

The performance of a thruster is usually characterized by two parameters; the specific impulse I_{sp} and the over-all acceleration efficiency e. In mathematical forms, they are expressed as

$$I_{sp} = \text{thrust/flow rate} = T/\dot{m}g = b/g(J^2/\dot{m}) \tag{3}$$

and

$$e = \text{kinetic power/input power} = \tfrac{1}{2}\dot{m}u^2/JV \tag{4}$$

which can be simplified to

$$I_{sp} = u/g; \quad e = \tfrac{g}{2}(T \cdot I_{sp})/JV \tag{5}$$

by introducing the relation $T = \dot{m}u$. By combining Eqs. (5) and (1) the expression for the efficiency can be written more conveniently in terms of plasma impedance z as

$$e = b \cdot I_{sp} \cdot g/2z = (b^2/2z)(J^2/\dot{m}) \tag{6}$$

Inspection of Eqs. (3) and (6) indicates that the specific impulse and the efficiency are directly proportional to the parameter $J^2/\dot{m}$. Of course, this criterion is derived from Eqs. (1) and (2) which involves a certain degree of oversimplification.[3,4]

Results of experimental studies concerning the performance of a pulsed MPD thruster are reported in Refs. 2 and 6. The critical values of $J^2/\dot{m}$ as a function of d_A/d_C and the molecular weight of propellants have been experimentally determined for thrusters operating in the range of 0.1 to 10 Mw peak input power with pulse durations of 1 to 2 msec. This information together with newly obtained experimental data for the shorter pulse MPD operations will be used in the present paper to illustrate the procedures for system design optimization. The experimental determination of the MPD performance was carried out by utilizing Avco's Wire Suspended Torque Table for the impulse bit measurements. In addition, the mass flow wave forms and the current and the voltage wave forms across the electrodes were measured. A detailed description of the experimental arrangement is given in Ref. 2.

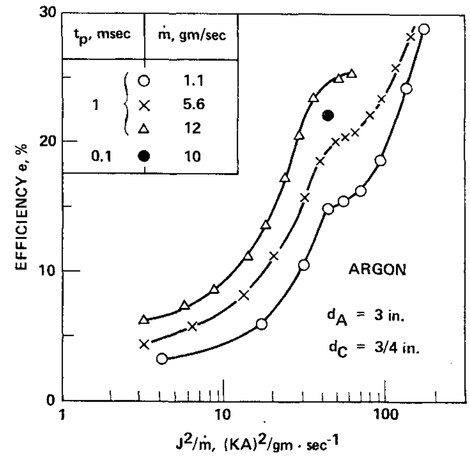

Fig. 1 Efficiency vs $J^2/\dot{m}$.

The efficiency of the thruster with a 7.62-cm (3-in) anode and a 1.9-cm ($\frac{3}{4}$-in.) cathode is plotted in Fig. 1 as a function of $J^2/\dot{m}$ for three different argon flow rates. It is shown that the efficiency increases steadily as the values of $J^2/\dot{m}$ are increased. This trend continues until $J^2/\dot{m}$ reaches the critical value at which point the efficiency ceases to increase. Far beyond the critical point, the efficiency starts to increase again, but this result could be misleading due to the participation of the spurious propellant which is unaccounted for in the data analysis. The curves shown in Fig. 1 also indicate the increase in efficiency at fixed $J^2/\dot{m}$ as the flow rate is increased. This is due to the decrease in plasma impedance of the thruster when the flow rate is increased.

For a fixed electrode geometry ($d_A = 7.62$ cm, $d_C = 1.9$ cm, $b = 0.187 \times 10^{-6}$ N/amp^2), the efficiency vs input power for argon flow rates of 1.1, 5.6, and 12.0 g/sec is plotted in Fig. 2. It indicates the initial sharp increase in efficiency as the input power is increased. At the vicinity of the critical point, the efficiency no longer increases so rapidly and it soon reaches an asymptotic value. As in Fig. 1, the critical efficiency in Fig. 2 is indicated to be higher for the larger flow rates.

In our experimental study, it is also observed that the critical efficiency, i.e., the maximum credible efficiency, is lower for the heavier propellants. The main reason for this behavior is that the critical values of $J^2/\dot{m}$ for the heavier propellants are lower than those for the lighter propellants, and that the maximum efficiency is proportional to the critical

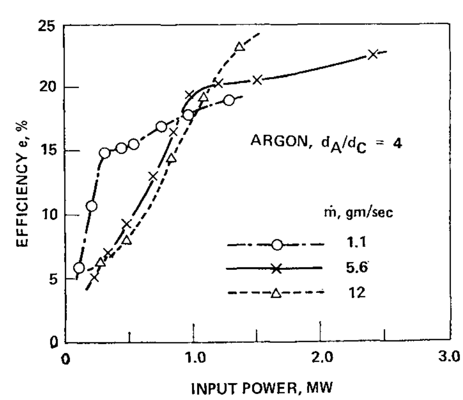

Fig. 2 Efficiency vs input power.

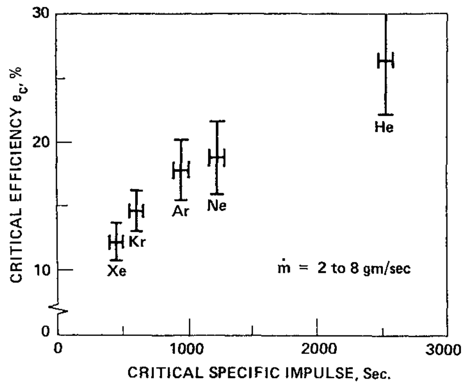

Fig. 3 Efficiency vs specific impulse at critical conditions for various propellants.

value of $J^2/\dot{m}$ as given by Eq. (6). The similar dependence of $(I_{sp})_c$ on the propellant molecular weight is also observed which confirm the relationship given by Eq. (3).

In Fig. 3 the efficiency vs the specific impulse under the critical operating conditions for various propellants is shown. It summarizes the tendency that the lighter the propellant molecular weight the higher the maximum credible values of both the thruster efficiency and the specific impulse. The spread of the data for each propellant reflects again the dependence of the efficiency on the propellant flow rate.

3. Condition for Minimal System Weight

According to the thruster performance characteristics presented in the preceding section, the optimal performance can be attained when the thruster is operating at the critical value of $J^2/\dot{m}$. For a given MPD thruster geometry of $d_A/d_C = 4$, the critical values of $J^2/\dot{m}$ for helium, neon, argon, krypton, and xenon have been experimentally determined as: 135, 62, 45, 32, and 25 $(\mathrm{ka})^2/\mathrm{g} \cdot \mathrm{sec}^{-1}$, respectively. This criterion will provide the desired system design value for the ratio $J^2/\dot{m}$, but the values for other individual parameters such as: J, $\dot{m}$, t_p, q, and I_p must be determined from other considerations.

One of the most important restrictions imposed on the flight mission propulsion system is its total weight. Therefore, the minimization of the total weight becomes a primary concern here for the system design.

The total mass of the pulsed MPD thruster system is the sum of the masses of: the total propellant, the power generator, the power storage, and other fixed hardware. Consequently, it is required to express these masses in terms of the energy discharge E for the determination of the optimization condition.

Energy Discharge and Impulse

The energy discharge from the condenser bank is given by a simple equation

$$E = \eta E_s = VJt_p = zJ^2t_p \tag{7}$$

for an idealized square wave pulse.

The impulse bit produced by the energy discharge is

$$I_p = Tt_p = I_0/(q \cdot t_0) \tag{8}$$

and combination of Eq. (8) with Eqs. (7) and (1) yields

$$I_0 = bt_0qE/z \tag{9}$$

Equations (3) and (7) provide an expression

$$I_{sp} = bE/(\dot{m}zt_pg) \tag{10}$$

Total Mass of Propellant

The propellant mass per pulse M_{pp} is calculated by multiplying the mass flow rate $\dot{m}$ by the duration of the mass feed pulse t_m, whereas the total propellant mass M_p is the product of M_{pp} and the total number of pulses for the entire operation.

Considering certain mismatches between the power pulses and the mass pulses, which is represented by a constant C (defined by $t_m = Ct_p$ for the square wave pulse forms), the combination of Eqs. (3, 8 and 10) gives

$$M_{pp} = \dot{m}t_m = mCt_p = CI_p/(gI_{sp}) \tag{11}$$

$$M_p = M_{pp} \cdot q \cdot t_0 = CI_0/(gI_{sp}) = (CI_0\dot{m}zt_p)/(bE) \tag{12}$$

Masses of Condenser Bank and Power Supply

For practical design applications, the masses of the condenser bank and the power supply can be determined as

$$M_s = m_sP_s = (m_s \cdot E_s)/t_c = (m_sEq)/\eta \tag{13}$$

and

$$M_c = m_cE_s = (m_cE)/\eta \tag{14}$$

It will be noted that the quantity $(E \cdot q)$ in Eq. (13) is equal to $(I_0z)/(bt_0)$ from Eq. (9) and can be considered invariant with respect to E for a given thruster. The quantities I_0 and t_0 are specified according to the mission and the value of b is fixed for a given thruster geometry as discussed in Sec. 2. The plasma impedance z may vary slightly with $\dot{m}$ and changes its values across the critical operating point, but it is practically independent of E for the range of subcritical operation as shown in Fig. 4.

Optimization of Thruster System

With the functional relationship of M and E derived as

$$M = M_p + M_c + M_s + M_F$$
$$= (CI_0\dot{m}zt_p/b)/E + (m_c/\eta)E + (m_s/\eta)zI_0/bt_0 + M_F \tag{15}$$

the condition $\partial M/\partial E = 0$ for a minimum system weight yields

$$E = [CI_0\dot{m}zt_p/(bm_c)]^{1/2} = [\eta I_0zM_{pp}/(bm_c)]^{1/2} \tag{16}$$

in which the values of $\dot{m}$ and t_p are yet to be determined. To this end one would eliminate E from Eqs. (10) and (16) to obtain

$$M_{pp} = C\dot{m}t_p = [(\eta I_0b/z)\, m_c][C/(g\, I_{sp})]^2 \tag{17}$$

and substitute the value of M_{pp} back to either Eqs. (10) or (16) to determine the required energy for producing the specified amount of impulse. We have now found the value of the product $(\dot{m}t_p)$, but the individual values for $\dot{m}$ and t_p must be

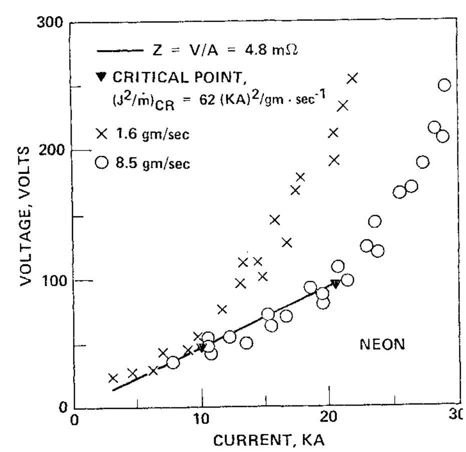

Fig. 4 Voltage-current characteristics for neon MPD thruster.

determined from the mechanical and physical constraints which are known only through semi-empirical relations. For example, the proper value of $\dot{m}$ can be evaluated from the known critical value of $J^2/\dot{m}$ for the particular thruster, together with the requirement on the minimum current to maintain the self magnetic acceleration. The choice of t_p is also limited because it is related to the current J for the given value of E. The inductance of the pulse generating network is another controlling parameter for t_p. A further discussion on these points is given in Sec. 4.

4. Application to System Design

The approach presented in the preceding sections can now be applied to the system design of an auxiliary-propulsion thruster for north-south station keeping. As commented in Ref. 1, the pulsed MPD thruster with maximum performance at 1-mlb thrust level will offer some advantages over the ion and colloid auxiliary-propulsion systems. At a comparable performance level, the former is more attractive than the latter from the point of view of reliability and total impulse life.

In order to illustrate the procedures for the optimal system design, let us consider a pulsed MPD thruster required to produce 1 mlb (4.46×10^{-3} N) average thrust for 10^7 sec duration. It follows that the total impulse is 44,600 N-sec for the thruster and the optimal values of e and I_{sp} must be secured at this level of operation. The maximum credible specific impulse is limited by the value of critical $J^2/\dot{m}$ as explained before, thus

$$(I_{sp})_c = (b/g)(J^2/\dot{m})_c = 1180 \text{ sec}$$

where the values for b and $(J^2/\dot{m})_c$ are obtained from the experimental data[2,5] as 0.187×10^{-6} N/amp^2 and 62 (ka)^2/g $\cdot$ sec^{-1}, respectively, for a pulsed neon MPD thruster with d_A/d_C of 4. Neon is chosen as the propellant in this design to take advantage of the fact that higher performance is offered by the lighter propellants.

The impedance for the thruster at the near critical operation is estimated from Fig. 4 as $z = 4.8$ mΩ, and accordingly, the thruster efficiency will be

$$e = (bI_{sp}g)/(2z) = 0.23$$

The wave forms of the power and mass feed pulses to produce 44,600 N-sec of total impulse by the thruster is determined from Eqs. (17, 11 and 8) to be

$$M_{pp} = 0.704 \times 10^{-6} \text{ kg},$$
$$I_p = (M_{pp} \cdot I_{sp} \cdot g)/C = 6.68 \times 10^{-3} \text{ N-sec}$$
$$q = I_0/(I_p \cdot t_0) = (1/1.5) \text{ sec}^{-1}$$

for an assumed system[7] with $C = 1.2$, $\eta = 0.85$, $m_c = 0.023$ kg/joule. Accordingly, the average thrust is (6.68×10^{-3} N-sec/pulse) $\times$ ((1/1.5) pulse/sec) $= 4.46 \times 10^{-3}$ N as initially specified. The product $\dot{m}t_p$ is calculated from M_{pp}/C as 0.586×10^{-6} kg which yields $\dot{m} = 5.86$ g/sec for $t_p = 10^{-4}$ sec. The choice of t_p here is arbitrary, but will be explained later. Then, it follows from Eqs. (10) and (7) that $E = 175$ joule/pulse; $J = 19.1 \times 10^3$ amp; average power $= 175$ joule/pulse $\times$ (1/1.5) pulse/sec $= 117$ w; peak power $= 175/10^{-4} = 1.75$ Mw. These values are reasonable in the sense that the current intensity is high enough to assure the self-magnetic operation but not too high to impose a difficulty in the pulse generating network for very small t_p. The lower limit of t_p is specified by the lower limit of inductance in the network. The validity of the quasi-steady operation, on which the present optimization analysis is developed, is weakened as t_p takes very small values. It must be noted that the magnitudes of $J^2/\dot{m}$, $\dot{m}t_p$, and E, are fixed for an optimized thruster system, and consequently $\dot{m}$ will be proportional to J^2 and inversely proportional to t_p. In the same token, t_p is inversely proportional to J^2.

Table 1 Summary of thruster characteristics

Propellant	Neon
Total impulse, I_0	44,600 N-sec
Total duration, t_0	116 days
Impulse bit, I_p	4.46×10^{-3} N-sec/pulse
Pulse width, t_p	1×10^{-4} sec
Pulse repetition frequency	0.667
Specific impulse	1180 sec
Efficiency	23%
Ratio $t_m/t_p = C$	1.2
Discharge efficiency	0.85
Condenser bank specific mass, m_c	0.023 kg/joule
Power supply specific mass, m_s	13.6 kg/kw
Energy discharge per pulse, E	175 joules
Peak current, J	19.1 ka
Average power	117 w
Peak power	1.75 Mw
Total propellant mass, M_p	4.5 kg
Mass of condenser bank, M_c	4.5 kg
Mass of power supply, M_s	1.9 kg

For an illustrative purpose, let us change the above design to $t_p = 10^{-3}$ sec which will be better from the pulse formation (especially for the propellant feed) point of view. The values of $\dot{m}$ and J are thus reduced to 0.586 g/sec and 6.04×10^3 amp, respectively. Based on the results of our experimental investigation, these values are considered to be rather improper for the following reasons.

1) The experimental results indicate that the plasma impedance z varies slightly as a function of $\dot{m}$ in the range of 2 to 8 g/sec at $(J^2/\dot{m})_c$ for the pulsed neon thruster. However, for $\dot{m} < 2$ g/sec, the value of z increases rather rapidly. With the mass flow rate of 0.586 g/sec, the plasma impedance will not be 4.8×10^{-3} Ω as we have previously estimated for the design calculations. It will be approximately twice as high and the efficiency will thus be reduced by a factor of 2.

2) The current intensity of 6 ka is close to the lowest limit of J for an effective self-magnetic operation. For the geometric configuration of the present design, it may be desirable to operate the thruster in $J = 10 \sim 20$ ka range.

The performance characteristics of the optimal thruster system which produces 4.46×10^{-3} N (1 mlb) average thrust for 10^7 sec is summarized in Table 1. The predicted values of efficiency, specific impulse and system weight, are all very attractive in comparison to other auxiliary propulsion devices with similar mission requirements.

5. Concluding Remarks

The approach presented in this paper is an extension of the work reported previously in Ref. 7. While the value of I_{sp} is optimized for minimum system weight in Ref. 7, the value of E is optimized in the present approach to minimize the system weight. In this latter case, the maximum credible value of I_{sp} is obtained by specifying the thruster operation at the critical value of $J^2/\dot{m}$.

The critical values of $J^2/\dot{m}$ for helium, neon, argon, krypton, and xenon have been experimentally determined as: 135, 62, 45, 32, and 25 (ka)^2/g $\cdot$ sec^{-1}, respectively. In this respect, it is more advantageous to use the lighter propellants than the heavier ones. This is related to the fact that, for the noble gases used in the present study, the excitation and ionization potentials are lower for the gases with higher atomic numbers.

For specified values of the average thrust level and total time duration of the space mission, the design procedures for system optimization are developed. The evaluation of the total mass contained in each pulse, the energy required per pulse, the impulse bit, and the pulse repetition frequency, is shown to be straighforward once the condition for optimization is derived. However, evaluation of the mass flow rate

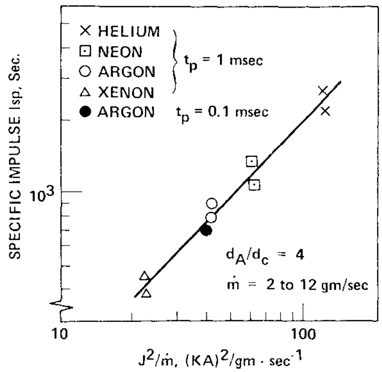

Fig. 5 Specific impulse vs $J^2/\dot{m}$ for various propellants.

and the pulse width is not quite that simple. With the magnitudes of $J^2/\dot{m}$, $\dot{m}t_p$ and E computed, it is important to note that t_p is inversely proportional to both $\dot{m}$ and J^2 while $\dot{m}$ is proportional to J^2. The proper values of t_p, $\dot{m}$ and, J^2 must be evaluated from the physical and electro-mechanical trade-off considerations. In essence, the current intensity must be high enough to produce substantial electromagnetic acceleration but not too high to cause any unreasonable reduction in t_p. A moderate amount of $\dot{m}$ is also required to maintain a high thruster efficiency.

To illustrate the design procedures for the system optimization, a pulsed MPD thruster with 4.46×10^{-3} N (1 mlb) average thrust and 10^7 sec total duration is considered. The appropriate value of t_p for this particular thruster system is found to be 0.1 msec which is an order of magnitude shorter than the pulse width that was used in the previous experiments.[2] Since many design criteria are supported by the experimental data, we have repeated some of our experimental measurements with the reduced pulse width of 0.1 msec. The comparison of the measured values of I_{sp} and e as shown in Figs. 1 and 5 indicates that the thruster performance is not jeopardized by the reduction in pulse width from 1 msec to 0.1 msec. This conclusion is partially substantiated by the experimental observations conducted at Princeton University and reported in Ref. 8.

An important factor relating to the short pulse width operation is the ratio C which represents the degree of mismatch between the power and the mass pulses. This ratio is usually greater than one because it is more difficult to produce very short mass pulses by the electromechanical propellant feed system. We have demonstrated successfully[2] the feasibility of using two-way solenoid valves to generate mass pulses with 1 millisecond pulse width. These valves are commercially available and quite unsophisticated in the design. With some improvements, it should be possible to generate pulses for 0.1 msec duration using the similar setup. It also appears possible to use a radiative control capillary feed system with liquid propellants for such a purpose.

Other design factors which will be important for the actual detailed system design consideration are the effects of the deviation from the assumed exact square wave form, and the stabilization time required for the thruster to attain the quasi-steady state operation. In this respect, the numerical values given in the present study for the efficiency and the weights of the illustrative system should be deemed as the representative gross figures. Some additional experimental studies will be needed to further improve the situation.

Lastly, the inspection of design specifications (summarized in Table 1) and the supporting experimental data reveals that the exemplified pulsed MPD thruster of Section 4, optimized for producing 4.46×10^{-3} N (1 mlb) average thrust during 10^7 sec total operation, can be quite competitive against other types of thrusters as an auxiliary propulsion system. The advantage of the present design lies on its moderately high efficiency and specific impulse, reasonable weight, high reliability, and relatively high total-impulse. Estimating that a continuous operation of the thruster for north-south station-keeping requires 1.48 mN of average thrust for each 1000 kg of spacecraft,[1] the thruster of the aforementioned design may be suitable for a spacecraft of 3 tons.

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