Comparing the Performance of Co-Axial and Parallel-Plate Gas-Fed PPTs *

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IEPC-99-209§

Abstract

The effects of capacitance, electrode geometry, and inductance-per-unit length on gas-fed pulsed plasma thruster (GFPPPT) performance are explored with efficiency and thrust-to-power measurements on thrusters with varying geometries. In a previous work we have shown that an electromagnetic model of acceleration leads to a scaling of the performance with the square-root of capacitance and inductance-per-unit-length. We have also experimentally verified the scaling with the capacitance. In the present work we show that large values of capacitance can adversely affect the propellant utilization efficiency which in turn linearly affects the overall efficiency of a GFPPPT. This leaves the inductance-per-unit-length as the promising performance scaling parameter. Although parallel-plate electrode geometries typically have higher values of inductance-per-unit-length, coaxial electrode geometries are shown to have higher measured performance at similar operating conditions. The lower than expected performance from parallel-plate thrusters is attributed to wall losses and non-axial current sheet acceleration profiles.

turned to empirical, parametric studies to understand how electrode configuration impacts performance. Specifically, the advantages and disadvantages of the two main types of electrode geometry, co-axial and parallel-plate, have for long been a topic of debate. Experimental data have yet to uncover the best configuration for performance (efficiency and thrust-to-power ratio) over a wide range of operational parameters.

Recent activity at the Electric Propulsion and Plasma Dynamics Lab (EPPDyL) of Princeton University in cooperation with Science Research Laboratory, Inc. (SRL) and the Advanced Propulsion Group at NASA Jet Propulsion Laboratory (JPL) has focused on designing gas-fed PPTs (GFPPPTs) with modular components such as capacitance[1] and electrode geometry[2] to measure the various effects on performance. Through analytic models of electromagnetic acceleration, the performance of GFPPPTs is expected to scale with the square-root of the product of capacitance and inductance-per-unit-length while being independent of propellant mass. In actual GFPPTs, however, a portion of the injected propellant mass may escape the electrode volume before being entrained by the accelerating current sheet. This results in a low propellant utilization efficiency which adversely impacts the overall performance. The propellant utilization efficiency is shown to scale with the inverse of capacitance which limits the extent to which the performance can be improved by varying the capacitance. This leaves the inductance-per-unit-length as the most promising design parameter that can influence overall performance over a wide range of operational conditions.

The purpose of this paper is twofold: 1) to help verify the relation of inductance-per-unit-length (and hence electrode geometry) to GFPPT performance in a systematic way, and 2) to discuss which ele-

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3 Presented at the 26th International Electric Propulsion Conference, Kitakyushu, JAPAN, October 17-21,1999.
trode geometry (co-axial or parallel-plate) is better for overall performance.

The paper begins by describing the four different GFPPTs used in performance testing. The following section defines the propellant utilization efficiency and derives a theoretical relation for the dependence of performance on capacitance and inductance-per-unit-length. Next, performance measurements are presented and trends in the data are used to discuss the effects of inductance-per-unit-length. Finally, there is a discussion of other factors such as wall losses and non-uniform current sheet profiles which could influence the debate on which electrode geometry is better.

2 The SRL Family of GFPPTs

The SRL family of GFPPTs has been described before in refs. [1, 2] and will only be summarized here. SRL-GFPPTs use modern pulse forming technology to create a series of high-repetition rate pulses that are grouped in bursts. During one burst of pulses, propellant flows at a constant rate filling the discharge volume just before the next pulse occurs. If the time between pulses, \( \tau_p \), is too long or the electrode length, \( L_{elec} \), is too short, a slight amount of propellant mass may be lost as described in more detail in Section 3.1 and shown schematically in Fig. 1. The overall performance of GFPPTs is related to the driving capacitance, electrode configuration, propellant loading, and many other parameters that have been explored through the creation of many generations of GFPPT designs [1, 2].

Table 1: Thruster electrode configuration, capacitance, and inductance-per-unit-length. Because PT5, 6, and 8 have slightly flared electrodes the inductance-per-unit-length value, \( L' \), shown here is the average value.

<table>
<thead>
<tr>
<th>Thruster</th>
<th>Geometry</th>
<th>Cap. (( \mu )F)</th>
<th>( L' ) (nH/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PT5</td>
<td>Co-axial</td>
<td>130</td>
<td>( \sim 2.8 )</td>
</tr>
<tr>
<td>PT6a</td>
<td>Co-axial</td>
<td>63</td>
<td>( \sim 1.3 )</td>
</tr>
<tr>
<td>PT6b</td>
<td>P-Plate</td>
<td>63</td>
<td>( \sim 4.9 )</td>
</tr>
<tr>
<td>PT8</td>
<td>P-Plate</td>
<td>63</td>
<td>( \sim 6.3 )</td>
</tr>
<tr>
<td>PT9a</td>
<td>P-Plate</td>
<td>130</td>
<td>2.83</td>
</tr>
<tr>
<td>PT9b</td>
<td>P-Plate</td>
<td>130</td>
<td>5.68</td>
</tr>
</tbody>
</table>

All the relevant parameters of the designs tested in this study are illustrated in Table 1. Of these thrusters, only PT8 and PT9 have not been introduced in the literature and a more detailed description of them follows.

2.1 PT8

PT8 is a slightly flared\(^1\) parallel-plate GFPPT that belongs to the group of GFPPTs including PT6 and PT7 called the “quad thrusters” which are explained in more detail in ref. [2]. Compared to the first quad designs, PT8 has three major modifications: it uses a new lower-energy RF system to initiate the discharge, it uses a non-axial propellant injection scheme to reduce the axial cold gas velocity and improve propellant utilization, and it has a set of ferrite blocks around the electrodes to reduce magnetic field fringing effects and increase the inductance-per-unit length. Although the magnetic field of PT8 has yet to be measured, it is assumed that the ferrite blocks will remove the fringing effects of the finite parallel-plate geometry and provide a uniform magnetic field with an \( L' \) value of approximately 6.3 nH/cm. PT8 has the highest value of \( L' \) out of all the thrusters used in this study.

2.2 PT9

PT9 uses the capacitors and thruster casing from PT5 (see ref. [1]) with a modular set of parallel-plate electrodes for testing various values of inductance-per-unit-length. All the electrodes are made from 1/8" thick 70% tungsten 30% copper plates with dimensions of 1" x 4" (width x length) or 1/2" x 4". There

\(^1\)Although PT6b and PT8 have slightly flared electrodes with expansion angles of < 10°, they will be classified here using the conventional term “parallel-plate”.

Figure 1: Schematic drawing of the high-repetition pulse sequence in SRL-GFPPTs and the injected propellant mass distribution just before a pulse. The time between pulses, \( \tau_p \), is typically between 100-500 \( \mu \)s with the accelerated mass much greater than the non-accelerated mass, \( m_{used} \gg m_{lost} \).
are two places to mount the electrodes at distances of either 1" or 1/2" apart, and both mountings include a uniform, axially directed propellant flow. This gives four different electrode configurations (aspect ratios) and three different inductance-per-unit-length values. Two of the four configurations were tested for this study including the smallest (PT9a, H/W = 0.5, L' = 2.83 nH/cm) and largest (PT9b, H/W = 2, L' = 5.68 nH/cm) values of inductance-per-unit-length.

For discharge initiation, PT9 uses a high voltage (2 kV) low energy (50 mJ) spark between a sharp, 10 mil tungsten wire and the cathode of the thruster. Although erosion rates have yet to be measured accurately for this thruster, visible damage to thruster components is greatly reduced compared to damage seen in life-tests with the surface-discharge plugs in PT7 [2]. The main purpose of PT9 is to test different inductance-per-unit-length configurations at similar operational conditions to those tested with the co-axial set of electrodes in PT5 which has roughly the same value of L' as PT9a.

3 Performance Considerations for Both Geometries

This section of the paper will document the calculations used to compare the performance of both co-axial and parallel-plate GFPTTs tested at EPDPYt and NASA JPL. Conventional definitions for efficiency, thrust-to-power ratio, and specific impulse will be used as defined in ref. [1]. A derivation of the propellant mass utilization efficiency is shown to depend on electrode length, discharge pulse frequency and propellant type. The derivation of this efficiency helps to show why the capacitance can not be raised to an arbitrary value without possibly wasting propellant. Through the use of an electromagnetic acceleration model for GFPTT discharges, the trade-offs between the predicted thruster performance and the propellant utilization efficiency will be discussed. Through this analysis, the inductance-per-unit-length is found to be an important parameter in performance scaling. Finally, calculations of L' for the two geometries are presented.

3.1 Propellant Utilization Efficiency

In high repetition rate GFPTTs the total mass bit value, m_bit, used for overall performance calculations is a product of the the steady mass flow rate, \( \dot{m} \), and the time between pulses, \( \tau_p \), during a burst. As shown schematically in Fig. 1, depending on the electrode length and the mean thermal velocity of the cold gas, \( v_{th} \), some of the mass included in this efficiency calculation might not actually be accelerated by the discharge. Using the maximum possible thermal velocity, \( v_{th} \), the axial extent of the cold-gas column before each discharge can be estimated by,

\[
\ell_{gas} = v_{th} \tau_p = \tau_p \sqrt{\frac{3kT}{m_w}}, \tag{1}
\]

with the total mass bit including all the injected propellant mass,

\[
m_{bit} = \dot{m} \tau_p = \dot{m} \frac{\ell_{elec}}{v_{th}} + \dot{m}(\tau_p - \frac{\ell_{elec}}{v_{th}}) = m_{used} + m_{lost}. \tag{2}
\]

As an example, using argon and a pulse frequency of 4 kHz, \( \ell_{gas} \approx 10 \text{ cm} \) and the electrodes must be made at least 10 cm long or some portion of the gas will escape the electrode volume.

The propellant mass utilization efficiency, \( \eta_{pu} \), can now be defined as the ratio of the electrode length, \( \ell_{elec} \), to the gas column length, \( \ell_{gas} \),

\[
\eta_{pu} = \frac{\ell_{elec}}{\ell_{gas}} = \frac{\ell_{elec}}{\tau_p} \sqrt{\frac{m}{3kT}} = \frac{m_{used}}{m_{bit}}. \tag{3}
\]

Obviously even if the electrodes are longer than the gas column, the propellant utilization efficiency can not exceed 100%.

3.2 System Wide Trade-offs for Maximizing Propellant Utilization

From Eq. (3), maximizing the propellant utilization efficiency can include selecting a large molecular weight propellant, pulsing at a high frequency, using long electrodes, or a combination of these prescriptions. Changing these parameters, however, may have an adverse effect on performance and there are recognizable trade-offs in terms of predicted electromagnetic performance. In ref. [1] we derived the following theoretical expressions for GFPTT performance,

\[
\eta_h \propto \frac{u_a}{2} \sqrt{\frac{CL'}{\ell_{elec}}} \quad \frac{T}{P} \propto \sqrt{\frac{CL'}{\ell_{elec}}}, \tag{4}
\]

where \( \eta_h \) is the thrust efficiency and \( u_a \) is the velocity of the current sheet at the end of the electrodes. These relations assume that the discharge is mainly an inductive load that reaches the end of the electrodes at the moment the capacitor is fully drained. This expression for thrust efficiency represents the maximum obtainable efficiency when the propellant utilization efficiency is 100%. The overall efficiency,
\( \eta \), the product of the thrust efficiency and the propellant utilization efficiency,

\[
\eta = \eta_t \eta_{pu} = \frac{\dot{m}_{bit} u_e^2}{E},
\]

where the mass averaged exhaust velocity, \( u_e \), is calculated from the impulse bit,

\[
\bar{u}_e = \frac{I_{bit}}{m_{bit}} = \eta_{pu} u_e.
\]

Note that the thrust-to-power ratio does not depend on \( \eta_{pu} \).

**Large Molecular Weight Propellant.** At a fixed plenum temperature, larger molecular weight propellants yield a lower thermal velocity. Compared to smaller molecular weight propellants at similar mass loading conditions, heavier molecules will also provide a smaller gas-dynamic pressure in the discharge chamber before the pulse begins, however, they have a higher viscosity coefficient. The choice of propellant molecule may effect the conductivity of the plasma and possibly cause frozen flow losses which could also adversely effect performance although this remains to be studied in GFPPPTs.

**High Pulse Frequency.** The minimum time between pulses (the highest pulse frequency) is regulated by the time to charge the main capacitor. It is proportional to the capacitance magnitude and can be reduced by simply using smaller capacitance values or increasing the charging current, however, the latter choice can also decrease the power conditioner performance. The benefit of setting the pulse rate to the maximum the capacitance will allow is shown in Fig. 2 where the overall efficiency can be seen to increase to its maximum value as the pulse frequency increases at a constant mass flow rate. Note that the impulse bit, and therefore the thrust-to-power ratio, does not change within the error of the measurements and is not dependent on the propellant utilization efficiency.

A contrary argument to decreasing the capacitance can be seen from Eq. (4) and experimental evidence in ref. [1] which suggests that the performance of a GFPPPT increases with the square-root of the capacitance. This trade-off between the discharge performance and the propellant utilization efficiency points to using smaller capacitances until \( \eta_{pu} \) is exactly unity. Yet, although the overall efficiency may now be optimized, the maximum possible performance still occurs at the highest values of capacitance. Therefore, decreasing the capacitance of a GFPPPT may not be the best way to improve the propellant utilization efficiency and should only be used if no other avenue is possible. On the other hand, increasing the capacitance to boost performance makes it more and more difficult to obtain reasonable propellant utilization. This points to using the inductance-per-unit-length parameter instead of capacitance as a way to increase performance as further described in Section 3.3.

**Electrode Length.** It can be seen from Eqs. (3) and (4) that there is a complex trade-off between lengthening the electrodes to use all the propellant effectively and a decrease in the predicted performance. At the same time, if the electrodes are short and the mass bit is small (typically where the highest performance occurs), then the current sheet will not reside within the electrodes long enough to absorb all the energy from the capacitor. In addition, the total inductance change with a short set of electrodes may not be large enough for efficient electromagnetic acceleration. Therefore, the electrode length, the operational mass bit, and the capacitance must be chosen so that \( \eta_{pu} \) is near 100% and that the current sheet is at the end of the electrodes just as the capacitor is fully drained. There is also the possible factor of increased viscous and heat transfer losses from longer electrodes that has been noticed in these studies and will be explained further in Section 5.1.

### 3.3 Inductance-per-Unit-Length

The magnitude of the inductance-per-unit-length, \( L' \), is one of the most important differences between parallel-plate and co-axial electrode geometries. It is calculated by integrating the magnetic flux through a volume inclosed by the discharge. The inductance
of $L'$ as is the case with most of the GFPTTs tested here as shown in Table 1.

4 Measured Performance

Performance of four different GFPTTs have been measured over various mass bits, energy levels, capacitance values, etc. to form an extensive data base that can be used to compare the performance of co-axial vs. parallel-plate electrode geometries. In these comparisons, the performance will be gauged by graphs of efficiency as a function of specific impulse. The thrust-to-power ratio is proportional to about one-fifth the ratio of efficiency to specific impulse. Many of the experimental protocols and methods for calculating performance from the measured quantities have been documented previously[1, 2] and will not be repeated here. In all the data presented here, the overall efficiency (as defined in Section 3) is used to compare the various GFPTT designs. Note that since the specific impulse calculation is also dependent on the propellant utilization efficiency, performance curves of overall efficiency vs. specific impulse will have the same form as those of thrust efficiency vs. exhaust velocity which are described by Eq. (4). Performance measurements of the quad thrusters, PT6-PT8, were conducted at NASA JPL while PT5 and PT9 were tested at EPPDyL.

4.1 PT6 and PT8 Performance

The performance of PT6 and PT8 was measured with both parallel-plate and co-axial electrodes using argon for propellant over many different mass bits. The discharge energy was kept constant at 2 J/pulse to form the performance database shown in Fig. 4.

All three thrusters can be compared at the highest mass bit values which correspond to specific impulse values between 0-1000 s. In this region, PT8 has the best efficiency and thrust-to-power ratio, however, not quite as much as expected due to the higher value of $L'$. PT8 has an inductance-per-unit-length about five times larger than PT6a (co-axial) but the efficiency is not even twice as large except at the lowest specific impulse values. Similarly, the performance of the parallel-plate configuration of PT6 does not show the expected factor of 1.9 improvement over the co-axial configuration. Near 1800 s, PT8 and PT6b have very similar performance even though PT8 has an $L'$ value about 30% larger. At $I_{sp}$ values greater than 2000 s (lowest mass bit values), PT8's performance drops and increases again in a form seen previously in ref. [1] where two modes of GFPTT operation were identified (see Section 4.2 for further discussion of this
Figure 4: Efficiency vs. specific impulse for PT6 and PT8 with argon at various mass bits. All data shown is taken at 2 J per pulse using a 63 μF capacitor. A proportional error bar for the middle of this data set is also shown.

It is suspected that wall losses and profile inefficiencies play a strong role in explaining why the performance of these thrusters did not scale with the square-root of inductance-per-unit-length as discussed in Section 5. Considering these performance measurements alone, however, the two parallel plate geometries did not meet up to expectations based on the increase in inductance-per-unit-length. Although the value of $L'$ does seem to play a role in performance as the co-axial geometry (lowest $L'$) had the smallest efficiency, another comparison of co-axial vs. parallel-plate geometries with similar inductance-per-unit-lengths should provide a more direct answer to this paper's main question.

4.2 PT5 and PT9 Performance

The performance of PT5 has been fully documented in ref. [1] and only one set of conditions using 130 μF at 4 J/pulse will be used here to compare co-axial vs. parallel plate electrodes. The parallel-plate thruster, PT9, was designed to test the impact of inductance-per-unit-length on performance in a controlled manner. The smallest value of $L'$ (PT9a) was made to be similar to that of PT5, about 2.8 nH/cm. The largest value of $L'$ (PT9b) is about twice that of PT9a or PT5 and is predicted to have a higher performance by a factor of the square-root of two. Figure 5 shows the performance of PT5 and PT9 over a wide range of specific impulse (mass bit) values. As seen from the graph, the co-axial electrodes outperform or at least match the performance of the parallel-plate configurations even with a factor of two increase in $L'$. In fact, the parallel-plate thruster with the largest inductance-per-unit-length, PT9b, has the lowest value of efficiency out of all the thrusters with an $I_{sp} > 1000$ s. PT5 and PT9a have similar performance above 3000 s (mass bits ≤ 0.3 μg/pulse), however, the co-axial geometry of PT5 has much better performance than either of the parallel-plate geometries at specific impulse values below 2000 s. Again, other loss mechanisms may be playing a significant role in reducing the performance of the parallel plate thrusters as described in the next section of this paper.

Examining the data sets further, there is a "hitch" present where the efficiency decreases and then increases again at about 1500 s for PT5 and PT8 with PT9a and PT9b having a similar yet smaller trend occurring near about 800 s. This phenomenon has yet to be fully explained, however, performance measurements from PT5 over a more wide range of capacitance values showed that this region marks the division between two modes of GFPPT operation. A possible explanation includes the transition between two types of acceleration mechanisms: electrothermal dominated acceleration at lower $I_{sp}$ values where the efficiency is relatively constant and electromagnetic dominated acceleration at higher $I_{sp}$ values where the efficiency varies linearly with the specific impulse. The explanation could also include a possible decrease in the current sheet’s ability to sweep up the propellant effectively at higher exhaust velocities (higher $I_{sp}$) and lower mass bits where gas dynamic pressures are low. Finally, at the highest velocities, it is very likely that the current sheet travels down the
full extent of the electrodes before it can use all the energy stored in the capacitor. The full explanation could involve a combination of all these reasons and is under further investigation at EPPDyL.

5 Discussion

Although higher performance at similar values of inductance-per-unit-length could be considered to be the strongest argument for choosing co-axial electrodes over parallel plate electrodes, there are other factors which should be considered in this context. Among the most important of these issues are possible wall losses and non-uniform current sheet acceleration profiles present in both geometries.

5.1 Possible Wall Losses

Previous estimates of viscous stress in quasi-steady MPD thrusters[3, 4] have shown through order-of-magnitude arguments that it is not a significant loss mechanism at high powers. In GFPPPTs, this same analysis shows this to be true near the beginning of the discharge when the current and voltage are large and the sheet velocity is relatively small. However, this is not true at later stages when the Lorentz force has decayed and the gas velocity, temperature, and pressure are high. With longer electrodes, viscous losses could significantly influence the final velocity which could explain the discrepancies found in Section 4.2.

In an attempt to quantify this experimentally, PT9a was tested with and without Pyrex side walls. As shown if Fig. 6, the performance was increased when the Pyrex side walls were removed. Unfortunately in the tests without the side-walls at low mass bits, the arc was seen to periodically stretch out of the electrode volume and attach away from the electrodes. Since at low mass bits (\(\approx 1 \mu g/\text{pulse}\)), the additional mass of erosion products from spurious arc attachments can significantly impact the performance, these data points are not shown in Fig. 6. In addition, it was felt that although higher performance is possible without the side walls, PT9 should use the Pyrex side walls to contain the discharge for all the data used in this paper for comparison with other thrusters. In any case, the increase in impulse bit values at the higher mass bit conditions without side walls hints to the possible role of wall losses in limiting the performance that can be brought about by changing \(L\).

![Figure 6: Effect of Pyrex side walls on performance as a function of mass bit for PT9 at 4J/pulse with 1" x 1/2" electrodes using argon.](image)

5.2 Current Sheet Profile Losses

Current sheet profile losses can come in two different forms: a spatially non-uniform Lorentz Force acting on the current sheet, and a current sheet canting phenomenon seen in parallel plate thrusters that is currently under investigation at EPPDyL[7].

**Non-uniform Lorentz force.** For coaxial electrode geometry, the current density and hence the magnetic field are both proportional to \(1/r\) giving a Lorentz force that increases rapidly at the center electrode as \(1/r^2\). This non-uniformity would suggest that the current sheet runs along the center electrode very fast forming a cone-like structure which accelerates the gas in a non-axial manner. In more recent co-axial SRL-GFPPT designs an attempt is made to balance this non-uniform force by injecting more propellant near the center electrode. For parallel-plate thrusters, the Lorentz-force is expected to be more axially-directed at the center-line of the electrodes due to the finite width of the electrodes and the fringing magnetic field.

**Current sheet canting.** The other type of profile loss has been discovered by viewing filtered Imacon fast-framing camera pictures of parallel-plate discharges on micro-second time scales. As shown in Fig. 7, a picture of the current sheet shows a bifurcation and canting with the leading edge always moving along the anode first. If this emission represents the current conduction location, then the acceleration will not be directed axially and performance losses will result. It is entirely possible that this same canting is occurring in co-axial thrusters where a side-view of the discharge is difficult to obtain. If this
is true, then for the co-axial SRL-GFPPT designs where the center electrode is the anode, there could be an even more elongated current sheet and higher profile losses. To measure this effect, future work at EPPDYL will include reversing the polarity of one of the co-axial thrusters to see if the two non-uniform profiles can counteract each other. For parallel-plate thrusters, work is continuing at EPPDYL to understand and, if possible, eventually counteract this canting which could also eventually improve parallel-plate performance.

It should also be noted that parallel-plate geometries allow the application of external magnetic fields that would augment the self-induced field and possibly increase performance as has been demonstrated in APPTs.[8]. Due to the geometry of the electrodes, only a parallel-plate thruster can use this technique effectively. Future performance measurements at EPPDYL will include the effects of applied magnetic fields on parallel-plate geometries.

6 Summary and Conclusions

It has been shown through an analytic model of electromagnetic acceleration that two factors effect the thrust performance directly: capacitance and inductance-per-unit-length. Although the performance scaling with the square-root of capacitance has been demonstrated experimentally, raising the capacitance to an arbitrarily high level is not beneficial as we have shown that the propellant utilization efficiency decreases at higher values of capacitance. Inductance-per-unit-length then becomes the next best parameter to maximize, however, measured performance data shows that this is not necessarily the case. In fact, although $L'$ values are typically higher in parallel plate geometries, the trends in the data show that co-axial electrodes with moderate values of $L'$ have a higher efficiency and thrust-to-power ratio over many similar operational conditions. Although there is evidence that inductance-per-unit-length does play a role in performance, it is only apparent as long as other mechanisms such as viscous wall losses and non-uniform current sheet profiles do not dominate the performance.

Acknowledgments The authors wish to thank John Blandino, Jay Polk, and Chris Salvo at NASA JPL for their support and the use of the Advanced Propulsion Group's Facility.

References