Study on the Interactions between Plasma Jet and the Propellants

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Abstract: In this work efforts were taken to shed light on the interactions mechanisms between plasma and the propellants in the Electrothermal Chemical (ETC) gun through both simulations and experiments. The propellant surface regression effect was added in the present numerical model and the influence of propellant composition and ignition schemes were investigated.

Keywords: Electrothermal chemical gun, plasma propellant interaction, ignition scheme

1. Introduction

Electrothermal-chemical (ETC) launch technology has drawn continuous interest for decades for its promising potential in improving the performance of current launch devices\cite{1-3}. In addition, ETC launch technology can advance the utilization of certain propellants, among which a typical example would be the energetic thermoplastic elastomer (ETPE) propellant. ETPE has excellent features including low sensitivity, high energy density, moisture immunity, and high environmental acceptability\cite{4}. However, the low sensitivity may cause ignition problems, leading to longer ignition delays or even ignition failure with conventional ignition methods, and plasma ignition is supposed to be a promising solution.

Although the advantages of ETC launch technology has been widely accepted, the mechanisms of some key phenomena in this technology are still not sufficiently unraveled, among which the interactions between plasma and the propellants should be the most prominent one. In this work a numerical model for the interaction process was developed to take into account the propellant surface regression effect neglected in the former PPI model\cite{5}. With this method the interaction features of four propellants differing in the cyclonite (RDX) proportion. Then the influence of different plasma ignition schemes was analyzed in terms of heat flux and propellant surface condition after interacted with the plasma. Results are supposed to shed light on the plasma propellant interaction mechanisms in different ignition schemes.

2. The Numerical Model

In the plasma ignition process, the pre-ignition interactions are crucial to the ignition characteristics\cite{6}, since it shapes the ignition environment, including propellant temperature and the amount of gasified propellants. In the pre-ignition stage, ablation is supposed to be the main mechanism, and on the propellant surface, the energy consumed in ablation and heating of the propellant should compensate the heat flux from the plasma. This process can be described by equation (1)-(3).

\[
\frac{\partial T}{\partial t} = \frac{\lambda}{C_p \rho} \frac{\partial^2 T}{\partial x^2}
\]

\[
\frac{\partial T}{\partial t} = \frac{1}{\rho} q - \Delta H T
\]

\[
T = L_t = T_i
\]

In the equations \(T(x,t)\) is the temperature at position \(x\) and time \(t\). \(L_t\) is the thickness of the propellant, and \(T_i\) is the room temperature. \(\rho, C_p\) and \(\lambda\) are respectively the density, specific heat and heat conductivity of the propellant. \(q\) is the heat flux from plasma. \(\Delta H\) and \(\Gamma\) are respectively the ablated mass flux from the propellant surface and the ablation enthalpy. \(\Gamma\) can be determined by solving the kinetic ablation model thoroughly described in ref. \cite{7}. The plasma temperature required by the ablation model was assumed to be constant 15000K, which is reasonable for atmospheric arc plasma \cite{8, 9}. Another parameter needed by the ablation model, the plasma number density, was obtained by the state equation: \(p = n_p k T_p\), in which \(p, n_p,\) and \(T_p\) are respectively the pressure, number density and temperature of the plasma adjacent to the propellant surface, and \(k\) is the Boltzmann constant. \(p\) was measured during the experiments.

![Fig.1 Method to deal with the burning face regression](image)

During the plasma-propellant interaction process, the surface propellant will continuously regress inwardly.
This effect will make the internal propellant right beneath the ablated propellant layer become the surface after its exposure to the plasma, and its temperature become the surface temperature. Since the surface temperature is a key parameter in determining the ablation rate [7], the propellant surface regression should be taken into account. In the present work, this surface regression effect was fulfilled by constantly removing ablated propellant layers from the surface, and adding new layers with temperature $T_i$ to the opposite end, as illustrated in Fig. 1.

3. Interaction Features of Different Propellants

There were four kinds of propellants involved in the study, and the detailed compositions are listed in Table 1, where NC, NG, DNT, DBP, BAMO, and AMMO are respectively nitrocellulose, nitroglycerin, 2,4-dinitrotoluene, dibutyl phthalate, 3,3’-bis(azidomethyl) oxetane and 3-azidomethyl-3-methyloxetane. Propellant properties were approximated by mass-averaging the properties of pure compositions. Sources of the properties include National Institute of Standards and Technology (NIST) WebBook and literatures [10-13].

Table 1 Propellants compositions

<table>
<thead>
<tr>
<th>Propellants</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF3</td>
<td>56%NC, 26.5%NG, 9.0%DNT, 4.5%DBP, 4% other additives</td>
</tr>
<tr>
<td>GR5</td>
<td>45%NC, 20%NG, 25%RDX, 5%DNT, 5% other additives</td>
</tr>
<tr>
<td>ETPE1</td>
<td>80%RDX, 20%BAMO/AMMO</td>
</tr>
<tr>
<td>ETPE2</td>
<td>75%RDX, 25%BAMO/AMMO</td>
</tr>
</tbody>
</table>

In order to obtain the plasma pressure and interaction duration required in the numerical model, experiments were carried out using the setup shown in Fig. 2. The measured voltage and current tracks were recorded to determine the discharge duration, and the propellant surface pressure were captured to calculate plasma number density. Besides total ablated masses of propellants were measured by weighing the propellant sample before and after the test, which are listed in Table 2 and help to determine the average heat flux from the plasma.

![Fig. 2 Gap discharge experimental setup](image)

Before studying the interaction characteristics of different propellant, the influence of surface regression was evaluated. Shown in Fig. 3 are the calculated ablation rate and propellant surface temperature for SF3 with 5kV charged voltage. The results show significant discrepancies between results with surface regression and those without. For the calculated ablation rate, neglecting surface regression will overestimate the result by 100%.

Table 2 Measured Ablated mass of the propellants

<table>
<thead>
<tr>
<th>Propellants</th>
<th>Ablated mass (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5kV charged voltage</td>
</tr>
<tr>
<td>SF3</td>
<td>4.02</td>
</tr>
<tr>
<td>GR5</td>
<td>3.20</td>
</tr>
<tr>
<td>ETPE1</td>
<td>3.82</td>
</tr>
<tr>
<td>ETPE2</td>
<td>3.45</td>
</tr>
</tbody>
</table>

![Fig. 3 Influence of surface regression on calculated propellant](image)

The calculated average heat flux with the test results of different propellants are illustrated in Fig. 4, from which one can see that all estimated heat fluxes are at the order of $10^7$ W/m$^2$, and for each propellant increasing the charged voltage by 2kV leads to approximately 30% increase in the heat flux on average.

![Fig. 4 Calculated plasma heat flux for gap discharge setup](image)

The calculated surface regression rates are listed in Table 3 and the average surface temperatures and ablation rates during the stable stage of the interaction process are listed in Table 4. Results illustrate that the ETPE propellants generally have higher $T_c$, lower $\Gamma$ and lower $v_0$, indicating that they are more invulnerable under plasma impingement, which is consistent with their characteristics. Further, ETPE1 has a lower $T_c$, $\Gamma$ and $v_0$ than ETPE2, which indicates the cause of the low vulnerability is related to the RDX proportion and a lower...
percent of RDX will lead to higher regression rate of the ETPE propellants. This conclusion can be confirmed by comparing interaction characteristics of SF3 and GR5. Due to the addition of 25% RDX in its composition, GR5 has lower $\Gamma$ and $v_i$ than SF3. In the real plasma ignition process, a higher $v_i$ will increase the amount of propellant in the burning gas and promote the ignition process, which seems to imply a preference in a lower RDX percentage. However, since RDX is the main energetic ingredient in ETPE propellants, reducing its proportion will lower the energy released by the reactions in the burning gas, canceling the benefit of higher $v_i$. Therefore the actual influence of RDX proportion on the ignition process also depends on the ratio of ignited RDX in the burning gas, which is related to detailed gas phase chemical reaction mechanisms and needs to be covered in further studies.

Increasing the charged voltage has relatively small influence on the propellant surface temperature, but will lead to considerable growths in the ablation rate and the surface regression rate, which will benefit the ignition process. This effect is especially true for ETPE propellants, indicating the ignition of ETPE propellants can be enhanced by increasing the charging voltage.

Table 3 Calculated surface regression rate of the propellants

<table>
<thead>
<tr>
<th>Propellants</th>
<th>Surface regression rate (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5kV charged voltage</td>
</tr>
<tr>
<td>SF3</td>
<td>0.0309</td>
</tr>
<tr>
<td>GR5</td>
<td>0.0248</td>
</tr>
<tr>
<td>ETPE1</td>
<td>0.0131</td>
</tr>
<tr>
<td>ETPE2</td>
<td>0.0133</td>
</tr>
</tbody>
</table>

Table 4 Average surface temperature and ablation rate

<table>
<thead>
<tr>
<th>Propellants</th>
<th>Surface temperature (K)</th>
<th>Ablation rate (kg/(m²s))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5kV</td>
<td>7kV</td>
</tr>
<tr>
<td>SF3</td>
<td>574.84</td>
<td>591.71</td>
</tr>
<tr>
<td>GR5</td>
<td>576.50</td>
<td>592.00</td>
</tr>
<tr>
<td>ETPE1</td>
<td>620.46</td>
<td>630.85</td>
</tr>
<tr>
<td>ETPE2</td>
<td>621.93</td>
<td>632.81</td>
</tr>
</tbody>
</table>

4. Characteristics of Different Plasma Ignition Schemes

Generally there are two types of plasma ignition schemes, the radial discharge scheme and the axial discharge scheme. In this work, a gap discharge setup (shown in Fig. 2) is utilized to study the characteristics of radial discharge ignition scheme and a capillary discharge setup (shown in Fig. 5) to the axial discharge ignition scheme.

The comparison of the pressure curves are shown in Fig. 6, from which one can see the capillary discharge has a much higher overall pressure output than the gap discharge. Besides, for the gap discharge scheme, increasing the charging voltage has very limited influence on the average pressure value after the spike near the start point, only intensifies the oscillations.

The surface conditions of propellants are examined by SEM after the experiments. Fig. 7 displays the surfaces conditions of SF3 and ETPE2 after interacting with both the gap discharge and capillary discharge plasma at 5kV charging voltage. For the gap discharge scheme, SF3 displayed a uniform and smooth surface after the experiment, whereas ETPE2 surface became coarser after interacting with plasma. For the capillary discharge scheme, surfaces for SF3 and ETPE were all covered with small pits. Besides, the pits in ETPE surface tend to be bigger and distribute more sparsely than in SF3 surface. In the gap discharge scheme, the smooth surface of SF3 was caused by the fact that the melt products of SF3’s main compositions (NC and NG) have similar properties, so that they can mix homogenously. For ETPE propellant, the boiling point of BAMO/AMMO (~766K) is much higher than RDX (~507K). Therefore under plasma impingement, the RDX evaporated more quickly, leaving un-decomposed BAMO/AMMO on the surface.

The gap discharge plasma shapes the propellant surfaces mainly by melting, whereas the capillary discharge plasma shapes the surfaces by bombard. The pits on the propellant surfaces in the capillary discharge scheme were mainly caused by the bombard of un-decomposed ablation products in the plasma jet. As for the gap discharge scheme, the plasma mainly consisted of ionized air, which was unable to cause bombard on the propellant surface. The higher plasma pressure in the
capillary discharge scheme was also responsible for the formation of these pits, for the strong blowing effect took away melted propellant and enlarged the already formed pits. This effect can explain why ETPE has larger pits than SF3, since ETPE is much softer and easier to be enlarged than SF3.

![Fig. 7 Surface condition of propellant SF3 and ETPE after ignited by radial and axial schemes](image)

As discussed above the heat fluxes for the gap discharge setup were all at the order of $10^5$ W/m², however, for the capillary discharge the heat fluxes are quite different. Porwitzky and Das both pointed out that the heat flux for the capillary discharge plasma with similar charging voltage is at the order of $10^6$ W/m² [5, 14]. Porwitzky deduced the heat flux in the same manner as in the present work, whereas Das deduced the heat flux from measured propellant surface temperature. Since the temperatures of atmospheric arc plasmas are almost constant, then the radiation heat fluxes for both ignition schemes are almost the same, leaving convective heat flux mainly responsible for the differences between heat fluxes in different ignition schemes. This conclusion is consistent with the experimental results. As illustrated in Fig. 6, the capillary discharge scheme has a pressure an order higher than the gap discharge scheme. According to ref. [15], the convective heat flux has an increasing exponential dependence on plasma number density, which is closely related to plasma pressure.

Generally the propellant surfaces in the capillary discharge scheme are coarser than in the gap discharge scheme. A coarser surface indicates a larger surface area, which leads to enhancement of the ignition process. Therefore in this respect the capillary discharge scheme has better performance than the gap discharge scheme.

5. Conclusion

In this work the plasma propellant interaction process was investigated through experiments and simulations. Based on the findings the following conclusions can be drawn:

1. The propellant surface regression effect has significant influence on calculated ablation rate and propellant surface temperature, and in order to get correct results this effect should be taken into account.
2. ETPE propellants have higher surface temperature, lower ablation rate and lower surface regression rate than SF3 and GR5, consistent with their low vulnerability. Reducing the RDX proportion in the ETPE will increase its surface regression rate. However the reduction of RDX may lead to less energy feedback from the burning gas. An optimized RDX proportion calls for a balance between surface regression rate and gas phase energy release.
3. In the gap discharge scheme, the propellant surfaces are mainly shaped by the melting effect, whereas in the capillary discharge scheme, the propellant surfaces are mainly shaped by the bombard of ablation products.
4. The heat flux for the capillary discharge scheme is an order higher than the gap discharge scheme. The difference is mainly caused by the portion of the convective heat flux. The capillary discharge scheme has better performance than the gap discharge scheme in terms of energy flux and propellant surface enlargement.

Reference