Study on the solid propellant burning rate enhanced by plasma in the closed bomb

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Abstract: A closed bomb experimental system is employed to discuss the ignition and combustion characteristics of the solid propellant with the capillary plasma generator (CPG). 4/7 high-nitrogen solid propellant, 5/7 high-graphite solid propellant and 5/7 low temperature sensitivity coated propellant are ignited in the closed bomb. Compared with the experimental results with the conventional ignition, the ignition delay time with the CPG is reduced and the burning process of the propellant is enhanced. The pressure changing rate is used to analyse the enhanced gas generation rate (EGGR) of the propellant with the plasma. Compared with the pressure changing rate with different igniters, the enhanced gas generation rate during electrical discharge (EGGRDED) is proved. When 4/7 high-nitrogen solid propellant and 5/7 low temperature sensitivity coated propellant are ignited in the closed bomb, the enhanced gas generation rate post electrical discharge (EGGRPED) appears. The EGGRPED is mainly influenced by the composition of the propellant. The influence of the electrical parameters of the CPG and the distance between the CPG and the solid propellant is studied by the closed bomb experiments. The ignition delay time and the burning time of the propellant reduce with the increasing of the electric power or the decreasing of the distance between the CPG and the propellant. Depending on the pressure changing rate in the closed bomb experiments, the EGGRDED increases with the increasing of the electric power or the decreasing of the distance between the CPG and the propellant, while the EGGRPED is not influenced by the electric power or the distance between the CPG and the propellant.

1. Introduction

In the electrothermal-chemical (ETC) launch, a plasma generator (PG) is used to replace the conventional ignition. The ignition and combustion process of the propellant with the plasma is quite different from that with the conventional ignition. The process of the interior ballistics can be improved and the projectile muzzle can be increased in the ETC launch [1].

Closed bomb experiments are taken to analyze the ignition and combustion phenomena of the propellant with or without plasma [2]-[5]. In the closed bomb experiments, the influence of the charging structure and the temperature of the propellant is analyzed [6]. The physical and chemical analysis of the propellant ignited in the interrupted closed bomb experiments is carried out by the
scanning electron microscopy (SEM) and X-Ray fluorescence (XRF) spectroscopy [7]-[9]. In order to analyze the ignition characteristics of the propellant in the chamber, low electric energy is used in ETC launch [10] and gun simulator [11].

In this paper, a closed bomb experimental system is established. Different kinds of solid propellants are ignited by the conventional ignition or the capillary plasma generator (CPG). In the closed bomb experiments, the input electric energy of the CPG and the distance between the solid propellant and the CPG are changed. The ignition delay time, the time of the maximum of the pressure and the pressure in the closed bomb are measured. The burning time of the propellant and the pressure changing rate are calculated. Depending on the experimental results, the influence on the ignition and combustion of the propellant with the plasma is analyzed.

2. Experimental system setup of the closed bomb
The structure diagram of the closed bomb experimental system is shown in figure 1. It is contained by the pulse forming network (PFN), the closed bomb and the measuring & controlling system. The PFN contains four modules which can be used independently as a system circuit [4]. Each module contains a 1220μF capacitor, a 40μH inductance, a high power switch, a crowbar circuit and a surge protection resistor. The closed bomb is a high-pressure thick-walled cylinder, the volume is 145 cm³, and the maximum of the allowed pressure is 500MPa. The igniter mounted at the left side of the closed bomb can be changed. The electric primer is used as the conventional ignition in the closed bomb experiment. The length of the CPG used in the closed bomb is 60mm, and the inner diameter is 6mm [12]. The solid propellant sample is placed in the closed bomb, and the distance between the CPG and solid propellant can be changed.

![Figure 1. Structure diagram of the closed bomb experimental system.](image)

The experimental measuring system is composed of sensors and a data acquisition equipment. Gas pressure is measured by a Kistler 6215 pressure sensor. High voltage probe and Rogowski coil are used to measure the voltage and current of the CPG. JV5200 transient recorder is used to record the experimental data. There are 8 channels for the collection in the transient recorder, and the sampling frequency is 20MHz.
3. Results and discussions of the closed bomb experiments

In order to analyze the ignition and combustion characteristics of the solid propellant with the plasma, 4/7 high-nitrogen solid propellant, 5/7 high-graphite solid propellant and 5/7 low temperature sensitivity coated propellant are used in the closed bomb experiments. In order to analyze the influence of the electrical parameters of the CPG and the distance between the CPG and the propellant, the discharge voltage of the capacitor and the distance between the CPG and the propellant are changed in the closed bomb experiments.

3.1. Ignition experiments of different solid propellants

In the closed bomb experiments, 4/7 high-nitrogen solid propellant, 5/7 high-graphite solid propellant and 5/7 low temperature sensitivity coated propellant are ignited by the conventional ignition and the CPG. The weight of the propellant is 36.1g, and the propellant is placed in the middle of the closed bomb. One module of the PFN is used, and the discharge voltage of the capacitor is 10kV. The parameters and results of the experiments are shown in table 1. $E_{pl}$ is the input electric energy of the CPG. The value of the $E_{pl}$ is 0, when the propellant is ignited by the conventional ignition. $t_{ig}$ is the ignition delay time of the propellant (the time when the pressure is larger than 20MPa), $t_{end}$ is the time of the maximum of the pressure, and $p_m$ is the maximum of the pressure.

| No. | Propellant                        | $E_{pl}$(kJ) | $t_{ig}$(ms) | $t_{end}$(ms) | $p_m$(MPa) |
|-----|-----------------------------------|--------------|--------------|---------------|------------|
| 1   | 4/7 high-nitrogen propellant      | 0            | 1.673        | 4.95          | 300        |
| 2   | 4/7 high-nitrogen propellant      | 71.4         | 0.197        | 2.44          | 319        |
| 3   | 5/7 high-graphite propellant      | 0            | 1.79         | 5.9           | 303        |
| 4   | 5/7 high-graphite propellant      | 69.7         | 0.275        | 3             | 326        |
| 5   | 5/7 low temperature sensitivity   | 0            | 10.52        | 17.52         | 262        |
| 6   | coated propellant                 | 68.2         | 0.386        | 4.538         | 287        |

The measured pressure curves in the closed bomb and electric power curves of the CPG are shown in figure 2. When 4/7 high-nitrogen solid propellant is ignited by the CPG, the ignition delay time reduces from 1.673ms to 0.197ms, the burning time ($t_{end}$- $t_{ig}$) reduces from 3.277ms to 2.243ms, and the maximum of the pressure increases from 300MPa to 319MPa. When 5/7 high-graphite solid propellant is ignited by the CPG, the ignition delay time reduces from 1.79ms to 0.275ms, the burning time reduces from 4.11ms to 2.725ms, and the maximum of the pressure increases from 303MPa to 326MPa. When 5/7 low temperature sensitivity coated propellant is ignited by the CPG, the ignition delay time reduces from 10.52ms to 0.386ms, the burning time reduces from 7ms to 4.152ms, and the maximum of the pressure increases from 262MPa to 287MPa. When the propellant is ignited by the plasma, the ignition delay time and the burning time are reduced, and the burning process of the propellant is enhanced.
In order to analyze the enhanced combustion of the propellant with the plasma, the pressure changing rate is calculated by the measured pressure. The pressure changing rate curves are shown in figure 3. When the propellant is ignited by the conventional ignition, the pressure changing rate curve has only one spike. After the propellant is ignited, the pressure changing rate increases with the increasing of the pressure. The maximum of the pressure changing rate appears near the end of the combustion. The discharge time of the CPG at the discharge voltage of 10kV is 1.5ms. Compared with the pressure changing rate with the conventional ignition, the pressure changing rate curve with the CPG has another spike during the discharge of the CPG. The enhanced gas generation rate during electrical discharge (EGGRDED) is proved. Compared with the maximum of the pressure changing rate with the conventional ignition, the maximum of 4/7 high-nitrogen solid propellant increases from 162MPa/ms to 205MPa/ms, and the maximum of 5/7 low temperature sensitivity coated propellant increases from 99MPa/ms to 147MPa/ms, while the maximum of 5/7 high-graphite solid propellant stays at 160MPa/ms. The enhanced gas generation rate post electrical discharge (EGRPED) appears, when 4/7 high-nitrogen solid propellant and 5/7 low temperature sensitivity coated propellant is ignited by the CPG. The EGRPED is influenced by the composition of the propellant.

**Figure 2.** Pressure and electric power of different solid propellants.

**Figure 3.** Pressure changing rate of different solid propellants.
3.2. Ignition experiments with different electrical parameters

In order to analyze the influence of the electrical parameters of the CPG, the discharge voltage of the capacitor is changed. The weight of the 4/7 high-nitrogen solid propellant placed in the middle of the closed bomb is 36.1g. The parameters and results of the experiments are shown in table 2. $U_c$ is the discharge voltage of the capacitor.

**Table 2.** Parameters and results of the experiments with different discharge voltages.

| No. | $U_c$(kV) | $E_{pl}$(kJ) | $t_{ig}$(ms) | $t_{end}$(ms) | $p_{max}$(MPa) |
|-----|------------|--------------|--------------|---------------|----------------|
| 7   | 4          | 15.6         | 0.64         | 3.56          | 305            |
| 8   | 8.3        | 48.2         | 0.261        | 2.93          | 318            |
| 2   | 10         | 71.43        | 0.197        | 2.44          | 319            |

The measured pressure curves in the closed bomb and electric power curves of the CPG are shown in figure 4. With the increasing of the electric energy, the ignition delay time reduces from 0.64ms to 0.197ms, the burning time reduces from 2.92ms to 2.243ms, the maximum of the pressure increases from 305MPa to 319MPa. At the same distance between the CPG and the propellant, the ignition and enhanced burning process of the propellant is proportional to the electric power.

![Figure 4. Pressure and electric power with different discharge voltages.](image)

The pressure changing rate curves with different discharge voltages are shown in figure 5. During electrical discharge, the pressure changing rate increases with the increasing of the electric power. It is proved that the EGGRDED is influenced by the electric power. The maximum of the pressure changing rate stays at 205MPa/ms. It is proved that the EGGRPED is not influenced by the electric power of the CPG.
3.3. Ignition experiments with different distances

In order to analyze the influence of the distance between the propellant and the CPG, the place of the propellant in the closed bomb is changed. The weight of the 4/7 high-nitrogen solid propellant used in the closed bomb experiments is 36.1g. The parameters and results of the experiments are shown in table 3. The CPG is mounted at the left side of the closed bomb, the distance between the CPG and the propellant is the shortest when the propellant is placed at the left of the closed bomb, and the distance between the CPG and the propellant is the longest when the propellant is placed at the right of the closed bomb.

| No. | $U_d$(kV) | Place of the propellant | $E_{pl}$(kJ) | $t_{ig}$(ms) | $t_{end}$(ms) | $p_{max}$(MPa) |
|-----|----------|------------------------|--------------|--------------|--------------|----------------|
| 8   | 8.3      | middle                 | 48.2         | 0.261        | 2.93         | 318            |
| 9   | 8.3      | right                  | 46           | 0.33         | 3.15         | 310            |
| 2   | 10       | middle                 | 71.43        | 0.197        | 2.44         | 319            |
| 10  | 10       | left                   | 71.51        | 0.167        | 2.16         | 329            |

The measured pressure curves in the closed bomb and electric power curves of the CPG are shown in figure 6 and figure 7. When the discharge voltage is 8.3kV, with the increasing of the distance, the ignition delay increases from 0.261ms to 0.33ms, the burning time increases from 2.669ms to 2.82ms, the maximum of the pressure decreases from 318MPa to 310MPa. When the discharge voltage is 10kV, with the decreasing of the distance, the ignition delay decreases from 0.197ms to 0.167ms, the burning time decreases from 2.243ms to 1.993ms, the maximum of the pressure increases from 319MPa to 329MPa. With the similar electric power, the ignition and enhanced burning process of the propellant is inversely proportional to the distance between the CPG and the propellant.
Figure 6. Pressure and electric power with different distances at the discharge voltage of 8.2kV.

Figure 7. Pressure and electric power with different distances at the discharge voltage of 10kV.

The pressure changing rate curves with different distances are shown in figure 8. During electrical discharge, the pressure changing rate increases with the decreasing of the distance. The EGGRDED with the similar electrical parameters is inversely proportional to the distance between the CPG and the propellant. Post electrical discharge, the maximum of the pressure changing rate stays at 205MPa/ms. It is proved that the EGGRPDED is not influenced by the distance between the CPG and the propellant.
4. Conclusions

A closed bomb experimental system with the CPG is built to study the ignition and combustion of the solid propellant with the plasma. 4/7 high-nitrogen solid propellant, 5/7 high-graphite solid propellant and 5/7 low temperature sensitivity coated propellant are ignited by the conventional ignition and the CPG in the closed bomb. The ignition delay time is reduced by the plasma. Compared with the pressure changing rate curves with different igniters, the enhanced gas generation rate during electrical discharge (EGGRDED) is proved. Compared with the maximum of the pressure changing rate with different igniters, the enhanced gas generation rate post electrical discharge (EGGRPED) appears when 4/7 high-nitrogen solid propellant and 5/7 low temperature sensitivity coated propellant is ignited by the CPG. The EGGRPED is influenced by the composition of the propellant.

The influence of the electric power and the distance between the CPG and the propellant is studied by the closed bomb experiments with 4/7 high-nitrogen solid propellant. The EGGRDED increases with the increasing of the electric power or the decreasing of the distance between the CPG and the propellant, while the EGGRPED is not influenced by the electric power and the distance between the CPG and the propellant.

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