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Application of transient burning rate model of solid propellant in electrothermal-chemical launch simulation

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Abstract

A 30 mm electrothermal-chemical (ETC) gun experimental system is employed to research the burning rate characteristics of 4/7 high-nitrogen solid propellant. Enhanced gas generation rates (EGGR) of propellants during and after electrical discharges are verified in the experiments. A modified 0D internal ballistic model is established to simulate the ETC launch. According to the measured pressure and electrical parameters, a transient burning rate law including the influence of EGGR coefficient by electric power and pressure gradient (d*p*/d*t*) is added into the model. The EGGR coefficient of 4/7 high-nitrogen solid propellant is equal to 0.005 MW^{-1}. Both simulated breech pressure and projectile muzzle velocity accord with the experimental results well. Compared with Woodley's modified burning rate law, the breech pressure curves acquired by the transient burning rate law are more consistent with test results. Based on the parameters calculated in the model, the relationship among propellant burning rate, pressure gradient (d*p*/d*t*) and electric power is analyzed. Depending on the transient burning rate law and experimental data, the burning of solid propellant under the condition of plasma is described more accurately.

Keywords: Solid propellant; Electrothermal-chemical launch; 0D internal ballistic model; Transient burning rate law

1. Introduction

Electrothermal-chemical (ETC) propulsion is considered to be an attractive technology to improve the projectile muzzle kinetic energy [1]. The ignition delay time can be reduced by adjusting the electric power [2,3], and a compensation for the variation in initial charge temperature is possible [4–6].

Closed comb experiments are taken to analyze the phenomena of propellant combustion with or without plasma [7,8]. EGGR of propellants during and after electrical discharges were verified in the experiments. An EGGR coefficient is used to evaluate the effect of electric power [9,10]. Because of EGGR, pressure gradient changes rapidly. The effect of pressure gradient (d*p*/d*t*) on burning rate should be considered, especially at a large ratio of input electric energy to propellant impetus.

In this paper, the firing tests using a 30 mm ETC gun are described. A 0D internal ballistic model is used to simulate the ETC launch. A transient burning rate law including the influence of EGGR coefficient by electric power and pressure gradient (d*p*/d*t*) is added into the model. The accuracy of the simulated data is analyzed.

2. 30 mm ETC gun firings

2.1. Experimental setup

Fig. 1 shows a diagram of a pulse forming network (PFN) used in ETC launch. It contains four modules which can be used independently as a system circuit. Each module contains a 1220 μF capacitor, a 40 μH inductance, a high power switch, a crowbar circuit and a surge protection resistor. In the 30 mm ETC gun experimental system, the load is a capillary plasma generator (CPG) with 72 mm in length and 8 mm in diameter. The structure diagram of the 30 mm ETC gun is shown in Fig. 2. The chamber volume is 356 cm^3 and the length of the barrel is 2.75 m. A pressure sensor is added at the breech of the gun, and velocity measuring screens are used to measure the projectile velocity.

The experimental measurement system is composed of sensors and a data acquisition equipment. Gas pressure is measured by a Kistler 6215 pressure sensor. A resistive divider and Rogowski coil are used to measure the voltage and current at both ends of the CPG, respectively. JV5200 transient recorder is used to record the experimental data. There are 8 channels for

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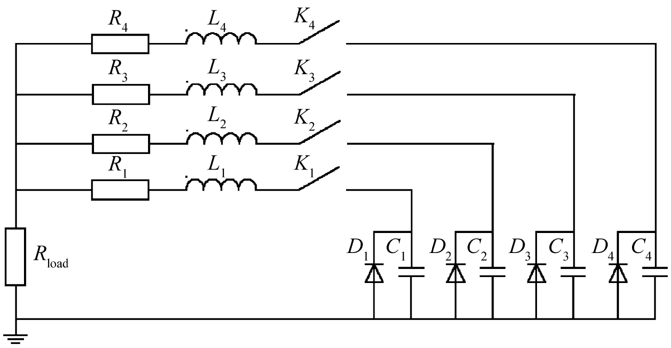

Fig. 1. Circuit of the 30 mm ETC gun experimental system.

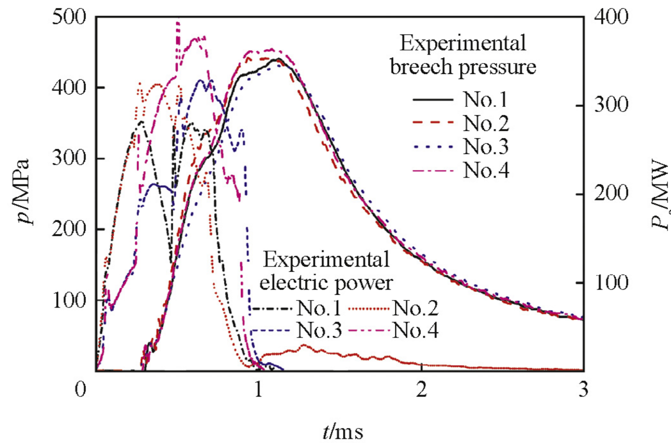

Fig. 3. Measured breech pressures and electric powers.

collection in the transient recorder, and the sampling frequency is 20 MHz.

2.2. Experimental results

The standard projectiles of 72.1 g were fired with 4/7 high-nitrogen propellant of 260 g in the experiment. The 4/7 high-nitrogen propellant is a homogeneous single-based propellant mainly containing nitrocellulose. The experimental conditions and results are listed in Table 1.

At a transferred energy of 192 kJ, the maximum breech pressure was about 441 MPa, and the muzzle velocity of the projectile reached 2085 m/s. At a transferred energy of 182 kJ, the maximum breech pressure was about 446 MPa, and the muzzle velocity of the projectile reached 2086 m/s. At a transferred energy of 200 kJ, the maximum breech pressure was about 438 MPa, and the muzzle velocity of the projectile reached 2088 m/s. At a transferred energy of 220 kJ, the maximum breech pressure was about 452 MPa, and the muzzle velocity of the projectile reached 2123 m/s. The discharge timing sequence can be adjusted to control the peak pressure and increase the projectile muzzle kinetic energy.

The breech pressures and transferred electric powers in the case of 4 different discharge timing sequences are shown in Fig. 3. For each case, a pulse current was applied for 1 ms, but the transferred energies were different because of different discharge timing sequences. An obvious pressure plateau is shown in the pressure curves in Fig. 3.

Fig. 4 shows the breech pressure gradient (dp/dt) curves in the case of 4 different discharge timing sequences. It can be seen from Fig. 4 that 3 spikes appear in the rising phase of pressure. The pressure gradient (dp/dt) is influenced by plasma, propellant burning process and projectile motion. At the beginning of the ignition process, there is a spike in the pressure gradient (dp/dt), which may be caused by the interference of CPG's electromagnetic field and pressure gradient (dp/dt) in the chamber. Then, the pressure gradient (dp/dt) increases rapidly during the electrical discharge. With the increase in pressure, the projectile begins to move. At this time, the propellant just begins to burn, and the influence of propellant combustion on chamber pressure can be ignored, while the motion of projectile makes the pressure gradient (dp/dt) decrease. Along with propellant combustion, the influence of propellant combustion on pressure increases. So the pressure gradient (dp/dt) increases again. At the end of the electrical discharge, the pressure gradient (dp/dt) decreases with the elec-

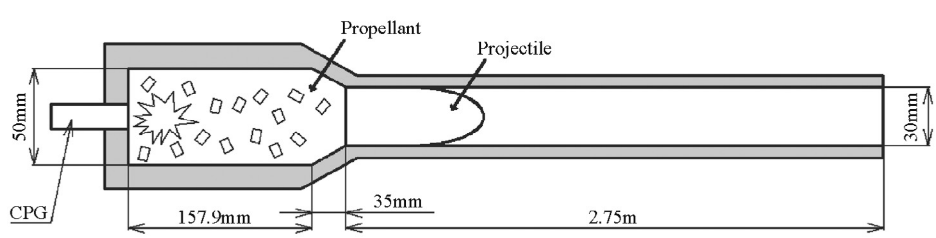

Fig. 2. Structure diagram of the 30 mm ETC gun.

Table 1
Conditions and results of the experiment.

No.	Discharge timing sequence/μs	Discharge voltage/kV	Maximum breech pressure/MPa	Projectile velocity/(m·s^{-1})
1	0, 0, 470, 470	9.448, 9.364, 9.59, 9.938	441	2085
2	0, 0, 250, 500	9.326, 9.281, 10.029, 9.979	446	2086
3	0, 250, 500, 500	9.497, 9.378, 10.184, 10.498	438	2088
4	0, 250, 250, 500	9.392, 9.942, 9.805, 8.775	452	2123