Research paper

Influence of grain geometry and ignition strength on combustion characteristic of TEGDN propellant in a closed vessel

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Received: August 5, 2015 Accepted: April 5, 2018

Abstract

Three kinds of propellant grains that have single, 7 and 19 perforations containing triethyleneglycol dinitrate (TEGDN) with a same web thickness were tested in a closed vessel to investigate the effects of the grain geometry and the ignition strength on the combustion characteristics. The web thickness of the three kinds of propellants was intended to be the same to avoid its influence on the combustion performance. The ratio of grain length to outer diameter of three kinds of TEGDN propellants is the same. Therefore, the influence of the ratio of grain length to outer diameter on burning progressivity is minimized as much as possible. The web thickness is twice the inner diameter of the perforations for the 7-perf and 19-perf grains. The inner perforation diameter of the single-perforation grain is large as possible to keep the combustion neutral. Due to the increasing numbers of perforations of TEGDN propellant, the progressivity of the 19-perf grain increases significantly compared with single and 7-perf grain at the same ignition strength.

As the ignition strength increases, the initial gas generated rate increases. However, it does not benefit the burning progressivity. When the number of perforations increases from 7 to 19, increasing the ignition strength may reduce the combustion stability due to gas flow inside the perforations. Meanwhile, the slivering of 19-perf grains begins earlier and lasts for a longer burning time than 7-perf grains. Thus, the burning rate drops gradually after the beginning of slivering. Results show that the burning gas generation rules can be controlled through the grain configuration and ignition conditions during the combustion process.

Keywords: triethyleneglycol dinitrate (TEGDN) propellants, grain geometry, ignition, burning rate, progressivity

1. Introduction

Nitrocellulose (NC) and nitroglycerine (NG) based gun propellants are highly prone to accidental initiation because of external stimulus (fire, shock wave, and impact). To reduce the risks, high energy insensitive propellants are an attractive alternative for conventional NC/NG based propellants. Triethyleneglycol dinitrate (TEGDN) is used extensively as an important energetic plasticizer in NC/NG based propellants to improve the low temperature mechanical properties of gun propellant. TEGDN has good dissolving capacity to NC and its thermal stability is better than NG. It is added to the NC/NG based propellant system to replace partially the NG, resulting in an increase in the force of double-base (DB) propellants and a reduction in the sensitivity to the external stimulus. This kind of propellant is denoted as TEGDN propellant in this paper. Meanwhile, the use of energetic thermoplastic elastomers (ETPE) in its formulation is regarded as a practical method to formulate high energy insensitive propellants[1), 2)]. Many efforts were devoted to applying the TEGDN propellant containing ETPE as a potential propellant charge for an electrothermal-chemical (ETC) gun and high energy insensitive propellant charge in large caliber guns[3)].

Much research on the thermal decomposition and thermal safety of TEGDN propellant has been reported.

Guo et al.[4] studied the influence of moisture content on the thermal stabilities of double-base propellant and multi-nitro ester propellant using a heat flux calorimeter C80. The results showed that the self-accelerating decomposition temperatures of their mixtures with water are much lower than that of pure propellants, and keep decreasing with the increasing of moisture content. Yi et al.[5] prepared the composite modified double base (CMDB) propellants containing 3,6-bis (1H-1,2,3,4-tetrazol-5-yl-amino)-1,2,4,5-tetrazine (BTATZ) without and with the ballistic modifier and investigated their thermal behaviors, nonisothermal decomposition reaction kinetics, thermal safety and burning rates using the thermogravimetric (TG) and differential scanning calorimetry (DSC) methods. Yi et al.[6), 7)] also investigated the effects of pressure and TEGDN content on the decomposition reaction mechanism and kinetics of the DB gun propellant composed of mixed ester of TEGDN, NG and NC by high-pressure differential scanning calorimetry (HPDSC). The thermal safety of gun propellant composed of TEGDN, NG and NC was studied using the characterization methods of the self-accelerating decomposition temperature, critical temperature of thermal explosion, adiabatic time to explosion, 50% drop height of impact sensitivity (H50), critical temperature of hot spot initiation caused by impact, safety degree, critical thermal explosion ambient temperature, and thermal explosion probability[8]. In addition, the catalyst effects of nanometer $CuCr_2O_4$[9], nanometer $MnCr_2O_4$[10], ballistic modifier Bi-NTO complex[11], and NiO nanoparticles[12] on the thermal decomposition of TEGDN propellant were investigated using TG analysis, DSC, mass spectrometry, and Fourier transform infrared spectroscopy.

However, little research on the fundamental chemical and physical properties of TEGDN related with combustion characteristics has been reported. It is well known that the burning performance of propellant in a closed chamber plays a very important role in the interior ballistics. To understand the combustion process and mechanisms of TEGDN propellant in a large caliber gun, the effect of the geometry and ignition condition on the combustion performance at constant volume need to be elucidated to predict the dynamic combustion performance at gun conditions.

On the burning process and performance of conventional gun propellant, the influence of web thickness, ratio of grain length to web thickness, instant burning surface, and form function on the burning rate and progressivity of propellant are reported. Also, if one holds the charge weight, composition, and configuration constant but varies the grain size, then the larger grains will give much lower peak pressures and higher muzzle pressures than the smaller grains. That is, as grains become larger, their burning behavior becomes more progressive. However, little research has been reported to consider the size effect with different configuration and ignition gas flow on the burning progressivity of TEGDN propellant. In this paper, three kinds of propellant grains that have single, 7 and 19 perforations containing TEGDN with the same web thickness were tested in a closed vessel to investigate the effects of the grain geometry and the ignition strength on the combustion characteristics. The web thickness of the three kinds of propellants was intended to be same to avoid its influence on the combustion performance. The ratio of grain length to outer diameter of all three kinds of TEGDN propellants is the same. Therefore, the influence of ratio of the grain length to outer diameter on progressivity is minimized as much as possible. The web thickness is twice the inner diameter of the perforations for the 7-perf and 19-perf grains. The inner diameter of the single-perforation grains is as large as possible to keep the combustion neutral. The geometry of all three kinds of TEGDN propellant was carefully designed to obtain approximately neutral combustion. The results will benefit the propellant formulation and charge design of TEGDN propellant in a large caliber gun.

2. Experimental

The sample used in the experiment is a TEGDN propellant composed of 59 wt.% nitrocellulose (NC), 29 wt.% nitroglycerine, 10 wt.% triethylene glycol dinitrateand (TEGDN) and 2 wt.% cenralite (C2). The web thicknesses were intended to be the same for all three kinds of TEGDN propellant. However, due to limitations in the manufacturing process, the actual size and related parameters of the propellant grains are different. Table 1 lists the actual average size of the three kinds of TEGDN propellant grains. For each propellant type, 200 grains were measured. Figure 1 shows their 3D graphs.

The burning process and properties of the three kinds of TEGDN propellant were performed used a 100 ml-closed bomb similar to that used in Ref. 13). Figure 2 illustrates the closed bomb test setup.

The experimental loading density of tested propellants is 0.2 g/cm^3. The conventional electric igniter consists of nitrocellulose propellant powder and a fuse powered by power supply. The mass of ignition nitrocellulose powder used in the closed bomb tests was 1.1 g, 1.5 g, and 2.0 g. Transient pressures in the combustion chamber were

Table 1 Actual average size of three kinds of TEGDN propellant grains.

Propellant type	Grain length (L)[mm]	Inner diameter (d_0) [mm]	Outer diameter (D_0) [mm]	Web thickness ($2e_1$) [mm]	L/D_0 [mm]	L/d_0 [mm]	$L/2e_1$ [mm]
13/1	6.713	3.018	5.316	1.149	1.26	2.22	5.84
13/7	7.907	0.576	6.996	1.317	1.13	13.73	6.00
13/19	11.925	0.504	9.904	1.184	1.20	23.66	10.07

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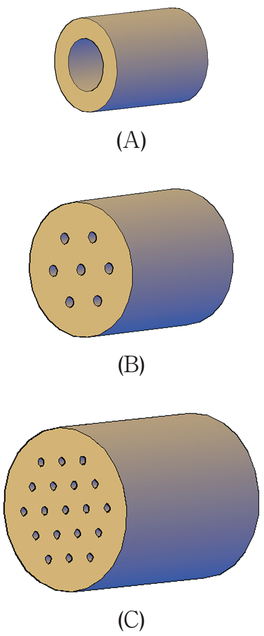

Figure 1 3D graph of three kinds of TEGDN propellant grains: (A) 13/1 TEGDN propellant grain; (B) 13/7 TEGDN propellant grain; (C) 13/19 TEGDN propellant grain.

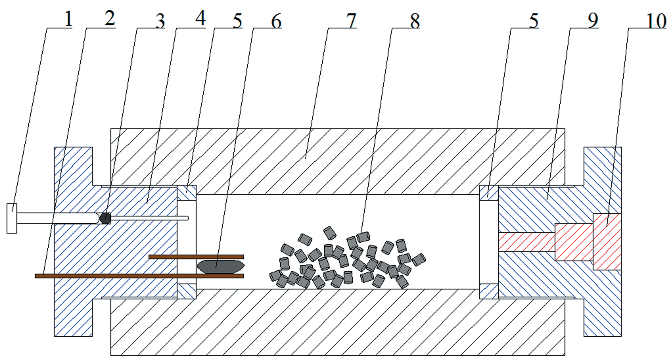

Figure 2 Schematic of closed bomb test setup: 1- bleed valve, 2 - igniter rod, 3 - steel ball, 4 - ignition bolt, 5 - washer, 6 - ignition powder, 7 - main body, 8 - tested propellant sample, 9 - bolt with pressure transducer, 10 - pressure gauge.

recorded by a Kistler pressure sensor and data acquisition system with a sample rate of 1 MHz.

As in Ref. 14), the dynamic vivacity depends on the propellant compositions and actual burning surface area. It has been used to assess the geometric progressivity of propellant and fracture degree of propellant surface area.

Dynamic vivacity can be derived from the closed vessel pressure history and defined as

$$L(t) = \frac{\mathrm{d}p(t)/\mathrm{d}t}{p(t)^* p_\mathrm{m}} \tag{1}$$

Relative pressure B is defined as

$$B = \frac{p(t)}{P_\mathrm{m}} \tag{2}$$

where p_m is the maximum pressure in the closed bomb test.

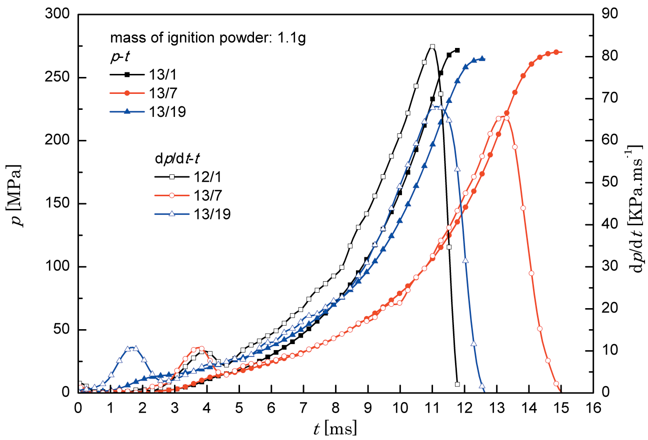

Figure 3 Pressure-time (p-t) curves and dp/dt-t curves of the three kinds of TEGDN propellant when the mass of ignition powder is 1.1 g.

3. Results and discussion

3.1 Influence of grain geometry on combustion performance

The pressure-time history (p-t curve) and the dp/dt-t curves of the three kinds of TEGDN propellants burning in a closed vessel under the same test condition are shown in Figure 3. The mass of ignition powder is 1.1 g. Compared with the 13/1 samples, the burning time of the 7-perf and 19-perf samples indicate a longer burning time with the increase of actual web thickness listed in Table 1. However, the maximum pressure is related with the charge mass in the closed vessel and has almost no change in the experimental conditions. The dp/dt-t curves have two peaks: the first peak is due to the ignition process and the second peak corresponds with the inflexion in the pressure-time history. For the same ignition conditions, the burning time to peak ignition pressure and the peak ignition pressure should be the same. The experimental data agrees with this expectation for the 13/1 and 13/7 TEGDN propellants. However, as seen from Figure 3, the burning time to peak ignition pressure of the 13/19 TEGDN propellant is earlier than the other two kinds of TEGDN propellant. The ignition peaks of the three kinds of TEGDN propellant are almost same with a value of 10 MPa for 1.1 g ignition powder under the experimental conditions. Thus, the start-point of the combustion time for 1.1 g ignition powder is set as the time point at which the chamber pressure reaches to 10 MPa. It should be noted that the physical state of the ignition powder should be the same for each propellant type at the same ignition mass theoretically. However, in the actual experiments, due to the measurement error, the nonuniformity of microstructure of the ignition powder et al., the ignition peak position and its peak values is sometime different, as can be seen from the p-t and dp/dt-t curves. Therefore, the burning time of ignition peak is dependent on the state of ignition powder at the same mass of ignition powder.

Figure 4 shows the curves of burning rate, u, versus pressure of three kinds of TEGDN propellants. The burning rate are calculated from the pressure-time curves in the closed bomb data by using the gas state equation and parallel-layer burning rules according to the method

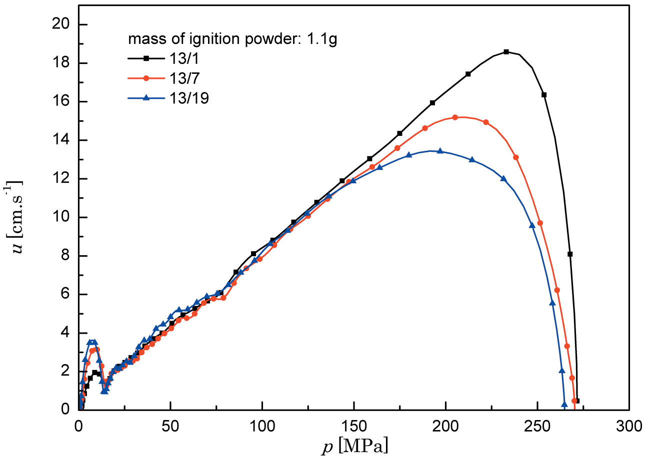

Figure 4 Burn rate (u-p) curves of the three kinds of TEGDN propellant when the mass of ignition powder is 1.1 g.

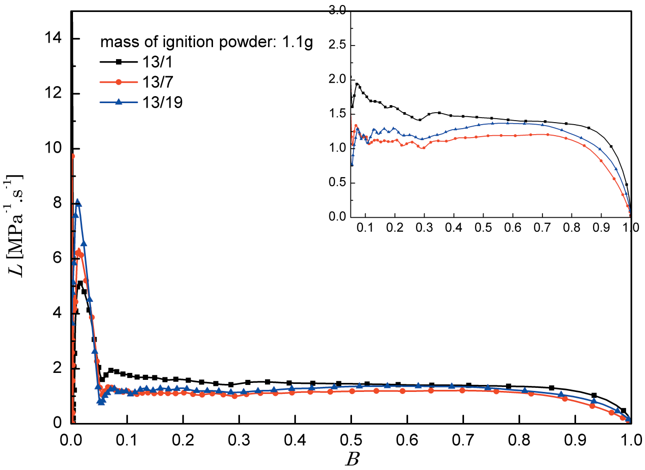

Figure 5 Dynamic vivacity curves of the three kinds of TEGDN propellant when the mass of ignition powder is 1.1 g (the inset figure shows detail of the curves with the ignition event removed).

in Ref. 15).

Figure 4 shows that, after the ignition process has ended, there is a linear relationship between the burning rate and pressure for the three kinds of TEGDN propellant samples. It is well known that in the design of multi-perforation propellant grains, although the total reacting area as a function of the mass fraction of burnt propellant is increasing and results in a progressive burning, its side effects should not neglect. One of them is the slivering point. Due to the manufacturing limitations, there exists an inevitable difference in size even in the same lot of propellants. And in turn, size variability of propellant grains will result in an earlier slivering point and a longer “sliver” burning process. The maximum burning rate occurs when the web burns through and the remaining “slivers” burn in a regressive manner. Compared with the 13/1 propellants, the 7-perf and 19-perf geometries indicate an earlier decrease of burning rate after 150 MPa, which is regarded as a “slivering” burning process in a regressive manner. The 19-perfs TEGDN propellants have earlier and longer “sliver” burning because there are a larger number of perforations that have an increasing area as the propellant burns.

Figure 5 shows the dynamic vivacity curves versus the relative pressure.

As seen from Figure 5, the three kinds of TEGDN propellant are almost neutral burning as would be expected due to the pre-designed grain size and burning area. However, due to the increase in the number of perforations, the 19-perf geometry always has a greater progressivity than the 7-perf and single-perf geometries.

The ignition gas flow inside the perforations plays an important role during the ignition process and can lead to augmented burning within the perforations. To elucidate the influence of ignition gas flow on the burning progressivity, different ignition strengths are applied to the ignition of the three kinds of TEGDN propellant in the next section.

3.2 Influence of ignition strength on combustion performance

Figures 6–8 show the pressure-time history and dp/dt-t curve of the three kinds of propellant at three ignition masses of 1.1 g, 1.5 g and 2.0 g, respectively.

As seen from Figures 6–8, with the increase of ignition mass from 1.1 g to 2.0 g, the ignition peak increases accordingly, indicating the ignition pressure increase from 10 MPa to 20 MPa. However, the start point of combustion time is still set as the time point at which the chamber pressure reaches to 10 MPa for better understanding of their difference.

Figures 9–11 show the curves of burning rate versus pressure for the three kinds of TEGDN propellant at three ignition masses of 1.1 g, 1.5 g and 2.0 g, respectively.

As seen from Figures 9–11, it is obvious that increasing the ignition mass has significantly increasing influence during the ignition phase. After ignition, the burning rates versus pressure are very similar for the three ignition masses. Compare with single-perf and 7-perf samples, there is slightly oscillation of burning rate in the combustion process for the 19-perf samples when the ignition mass increases from 1.1 g to 2.0 g under the same test and data acquisition conditions. It could be concluded that the ignition gas flow inside the perforations has some influence on the burning process - this might lead to augmented burning within the perforations.

To compare the influence of different ignition mass on the three kinds of TEGDN propellant, Figure 12 and Figure 13 show the curves of burning rate versus pressure when the ignition mass is 1.5 and 2.0 g, respectively.

Under the test conditions, the ratio of grain length to outer diameter on progressivity is minimized between the three kinds of TEGDN propellants as much as possible. However, while the ratio of grain length to inner diameter increases from 2.22 for 13/1 propellant to 23.66 for 13/19 propellant, the pressure and burning oscillation became severe as seen from Figure 4, Figure 12 and Figure 13.

4. Conclusions

Three geometries of TEGDN propellant, pre-designed with the same web thickness and ratio of grain length to outer diameter, were tested in a closed vessel to

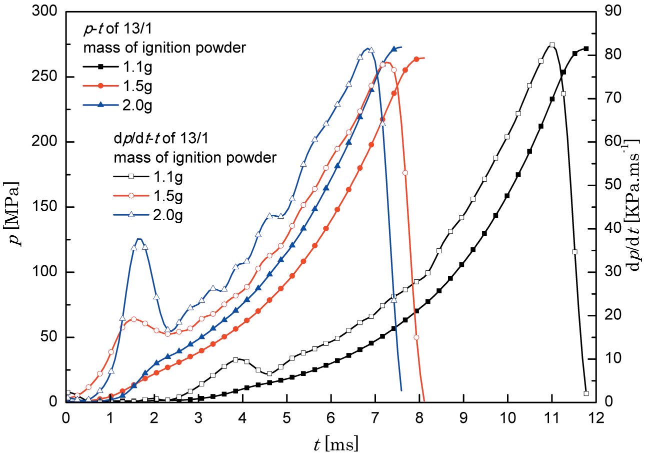

Figure 6 Pressure-time (p-t) curves and dp/dt-t curves of 13/1 tube TEGDN propellant at three ignition masses of 1.1 g, 1.5 g and 2.0 g.

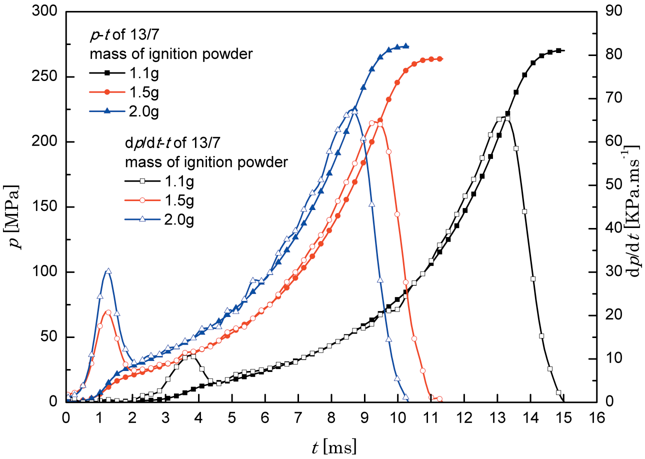

Figure 7 Pressure-time (p-t) curves and dp/dt-t curves of 13/7 TEGDN propellant at three ignition masses of 1.1 g, 1.5 g and 2.0 g.

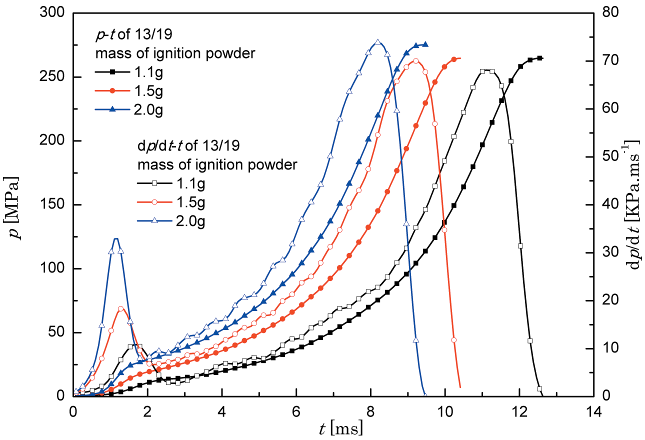

Figure 8 Pressure-time (p-t) curves and dp/dt-t curves of 13/19 TEGDN propellant at three ignition masses of 1.1 g, 1.5 g and 2.0 g.

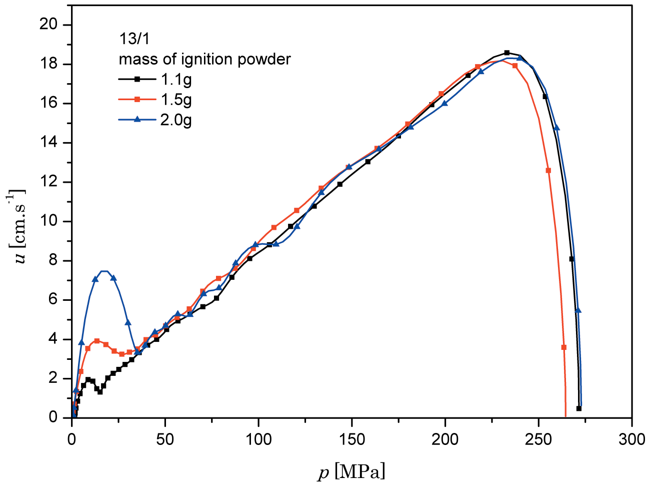

Figure 9 Burn rate (u-p) curves of the 13/1 TEGDN propellant at three ignition masses of 1.1 g, 1.5 g and 2.0 g.

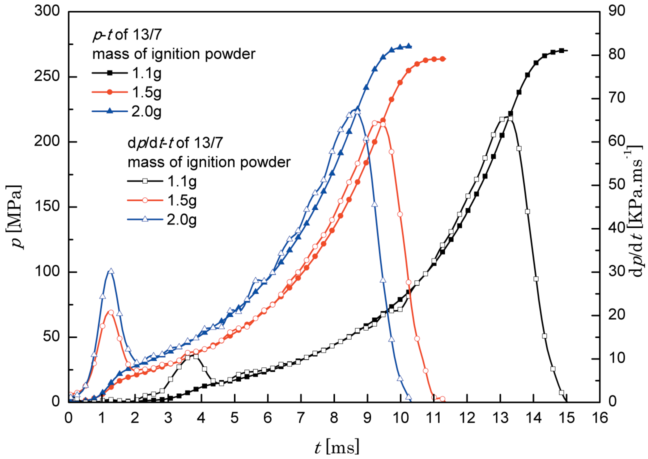

Figure 10 Burn rate (u-p) curves of the 13/7 TEGDN propellants at three ignition masses of 1.1 g, 1.5 g and 2.0 g.

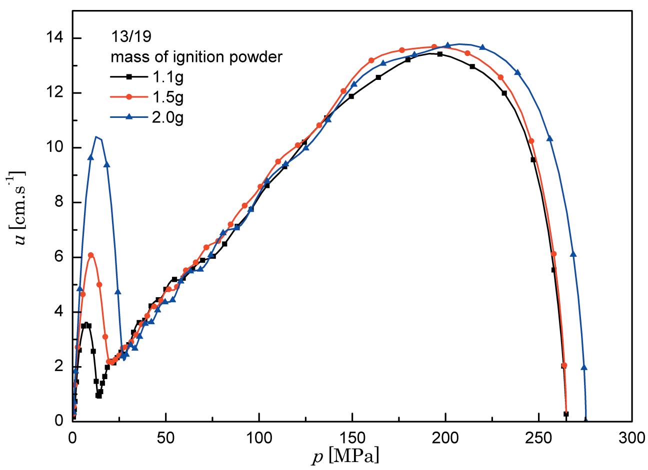

Figure 11 Burn rate (u-p) curves of 13/19 TEGDN propellant at three ignition masses of 1.1 g, 1.5 g and 2.0 g.

investigate the effect of the grain geometry and ignition strength on the combustion characteristics.

When the ratio of grain length to inner diameter increased from 2.22 for 13/1 propellant to 23.66 for 13/19 propellant, the pressure and burning oscillation became severe. With increasing numbers of perforations of TEGDN propellant, the progressivity of the 19-perf grain increases more significantly than that for the single and 7-perf grain at the same ignition strength.

As the ignition strength increases, the initial gas generation rate increases. However, it does not benefit the burning progressivity. After ignition, the burning rates versus pressure are almost the same for the three ignition masses. It could be concluded that the ignition gas flow

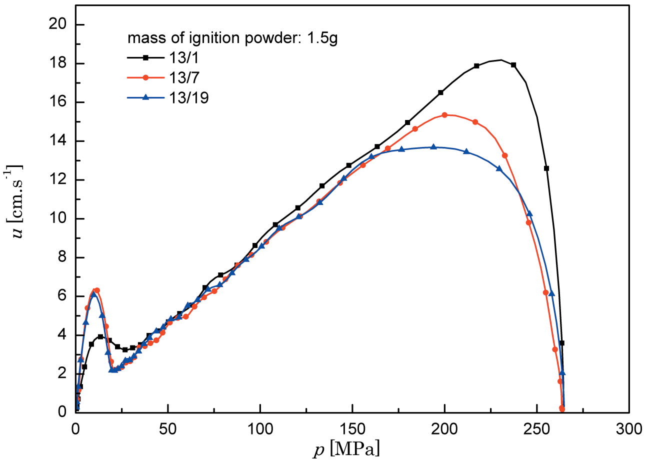

Figure12 Burn rate (u-p) curves of the three kinds of TEGDN propellant when the mass of ignition powder is 1.5 g.

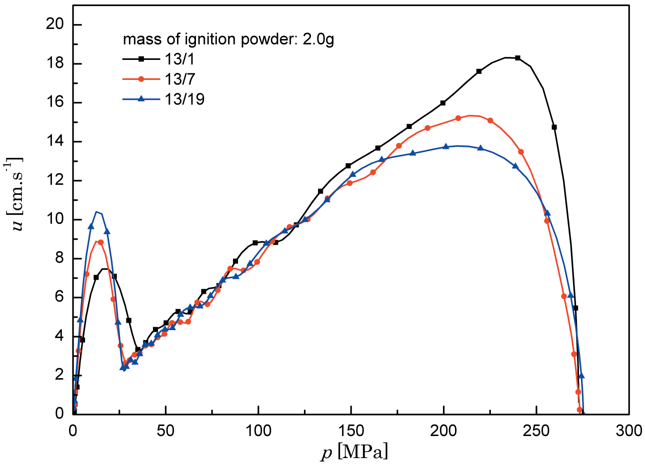

Figure13 Burn rate (u-p) curves of the three kinds of TEGDN propellant when the mass of ignition powder is 2.0 g.

inside the perforations has some influence on the burning process, such as augmented burning inside the perforations. When the number of perforations increases from 7 to 19, increasing ignition strength may reduce the combustion stability due to the gas flow inside the perforations. Meanwhile, the slivering of 19-perf grains begins earlier and lasts for a longer burning time than the 7-perf grains. Thus, the burning rate drops gradually after the beginning of slivering.

During the actual burning process, due to the very difference of the size of individual grain, the slivering point begins earlier than theoretic values. For perf-augmentation burning, perhaps the slivering point begins earlier. To understand better the influence of augmented burning in the perforations, and the effect of this on the slivering point and burning progressivity, the theoretical and actual point of slivering need to be investigated further for the combustion of single, 7 and 19 perforated propellants.

Acknowledgement

This work was supported in part by the National Natural Science Foundation of China (No. 51376092) and the Foundation of Science and Technology on Combustion and Explosion Laboratory of China (9140C350202130C 35122).

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