Auto-ignition Behaviors of the GAP/CL-20 Propellant under Thermal Stimulation

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1 Introduction

The comprehensive performance of solid propellant restricts the development of aviation and aerospace, and directly promotes the upgrading of equipment and power system [1]. With further development of equipment and aerospace power technology, traditional propellant cannot meet an increasing energy demand gradually, and all countries begin to explore a plan to improve the energy of propellants. Since 1987, the United States synthesized hexanitrohexaazaisowurtzitane (CL-20) for the first time, which is currently the highest energy elemental explosive [2]. Then, GAP/CL-20 propellant, which has a significant increase in energy, was born.

Many researchers have focused on the studies of explosive safety and combustion for GAP/CL-20 propellant. In order to explore factors affecting the combustion of GAP/CL-20 propellant, Zhou et al. [3] tested static burning rate of propellant by using underwater acoustic emission method, and calculated the propellant pressure exponent by linear regression method. Results show that propellant pressure exponent decreases with the decrease of CL-20 and Al powder particle size and the increase of AP particle size. Zhang et al. [4] studied energy potential of CL-20 and calculated explosive energy of the quaternary explosive mixture of GAP, CL-20, oxidant and combustible agent. Results show that energy density of this system can be improved significantly by using lithium perchlorate as oxidant. Ying et al. [5] investigated the influence of CL-20 particle size on the combustion of GAP/CL-20 propellant, and measured the burning rate of CL-20 at different pressures at 14μm and 115μm by using a burning rate-strand burner method, and calculated pressure exponents. Wang et al. [6] studied morphology and thermal decomposition of GAP/CL-20 propellant through differential thermal analysis, thermogravimetric analysis and scanning electron microscopy experiments, and established a cook-off model of GAP/CL-20 propellant solid rocket motor. Li et al. [7] studied the morphology and pyrolysis of GAP/CL-20 propellant through TG, DTA and SEM experiments, and also simulated and verified a cook-off of three-dimensional solid rocket motor at different heating rates.

It can be seen that current researches on the combustion of GAP/CL-20 propellant mainly focused on the measurement of material burning rate and calculation of pressure exponent. In addition, there is no research on other combustion performance of GAP/CL-20 propellant at present. As a kind of advanced high-energy propellant, it is also quite necessary to fully explore its combustion. Therefore, in order to explore the combustion of GAP/CL-20 propellant under rapid thermal stimulation, this paper carries out tests based on rapid compression machine (RCM) for GAP/CL-20 propellant, and its temperature rise

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rate can reach up to 2×10^4 K/s.The effects of different temperatures and pressures on the auto-ignition of GAP/CL-20 propellant were investigated, and its critical conditions were obtained.

2 Experimental Specification

Rapid compression machine is mainly composed of the high-pressure air tank, the driving section, the hydraulic section, the compression section, combustion chamber, the control and data acquisition system, distribution system, oil-pressure system and optical system, etc. Its working mode is gas driven, hydraulic braking [8, 9], and the optical system adopts shadow imaging principle [10]. During the experiment, changes of pressure in the combustion chamber were recorded by a pressure sensor (Kistler 6125C) and a charge amplifier (Kistler 5018A), and whole combustion process were recorded by a high-speed cameria (PhantomV611, resolution of 512 pixel × 512 pixel). The method of generating rapid thermal stimulation is based on our previous work [9]. Before compression begins, the hydraulic chamber is first filled with hydraulic oil, and then each piston is locked at the position of Bottom Dead Center (BDC). GAP/CL-20 propellant sample is fixed in combustion chamber with a tungsten needle, and then a specific mixture (Ar/N_2) is filled into the combustion chamber. At the beginning of compression, compressed air in the high-pressure tank drives the piston linkage mechanism rapidly to the Top Dead Center (TDC) by releasing oil pressure in the hydraulic chamber. At the same time, the pressure acquisition system triggers and starts to record pressure changes in combustion chamber, and the high-speed camera triggers and starts to record the changes of sample. When pistons reach TDC and the combustion chamber reaches the pre-designed environmental conditions, the sample will react due to rapid thermal stimulation. If the sample does not catch fire or explode, the pressure in the combustion chamber will not rise after compression, and the high-speed images will not appear fire phenomenon, and vice versa. The temperature at end of compression (EOC) can be calculated according to the adiabatic core hypothesis [11] and the ideal gas equation of state. The previous work [12] improved the combustion chamber piston structure, so as to ensure the uniformity of temperature in the combustion chamber during working. According to the literature, the average piston velocity during compression is 11 m/s, so it can be determined that auto-ignition of the sample is not triggered by shock wave [9].

In order to study auto-ignition behavoirs of GAP/CL-20 propellant, it is necessary to strictly regulate pressure and temperature in combustion chamber during test, which are closely related to the volume and specific heat of the mixture. Therefore, in the test, argon (Ar, with purity 99.99%) and nitrogen (N_2, with purity 99.99%) will be used to meet the requirements. In addition, according to the window of chamber, GAP/CL-20 propellant is shaped to a cuboid of 3 mm×3 mm×5 mm. The dosage for each test is 50 mg. And the components of GAP/CL-20 propellant are shown in Table 1.

Table 1 The components of GAP/CL-20 propellant

Components	GAP	CL-20	AP	AI	NC	NG	Others
Proportion	15%	35%	10%	18%	10%	10%	2%

3 Experimental Results and Discussion

3.1 Effect of EOC Pressure and Temperature

Figure 1 and Figure 2 respectively correspond to high-speed images and pressure traces at different EOC temperatures when EOC pressure (P_C) is controlled at 3.0 MPa. In these high-speed images, the EOC instant is 0 ms, and 25 ms in Figure 2 indicates 25 ms after EOC. It can be seen that no ignition occurred in the sample through high-speed images and pressure trace at 3.0 MPa and 677.29 K. The EOC temperature is then raised while EOC pressure remains constant. When temperature rises to 716.59 K, GAP/CL-20 propellant sample ignited, and through high-speed images, it was found that the ignition spot first appeared at 52 ms, which means its ignition delay time (IDT) is 52 ms, and its burning duration was 398 ms. When temperature continues to rise to 748.95 K, the high speed images showed that the ignition spot appeared at 29.5 ms, and its burning duration was 382 ms. When temperature was 782.03 K, its IDT was 19.2 ms, and its burning duration was 371 ms. Therefore, it can be found from the high-speed images that with the increase of T_C, the auto-ignition of the sample will gradually advance and its IDT and burning duration will shorten. Based on the pressure traces, a faster and earlier pressure rise was also observed as EOC temperature increased.

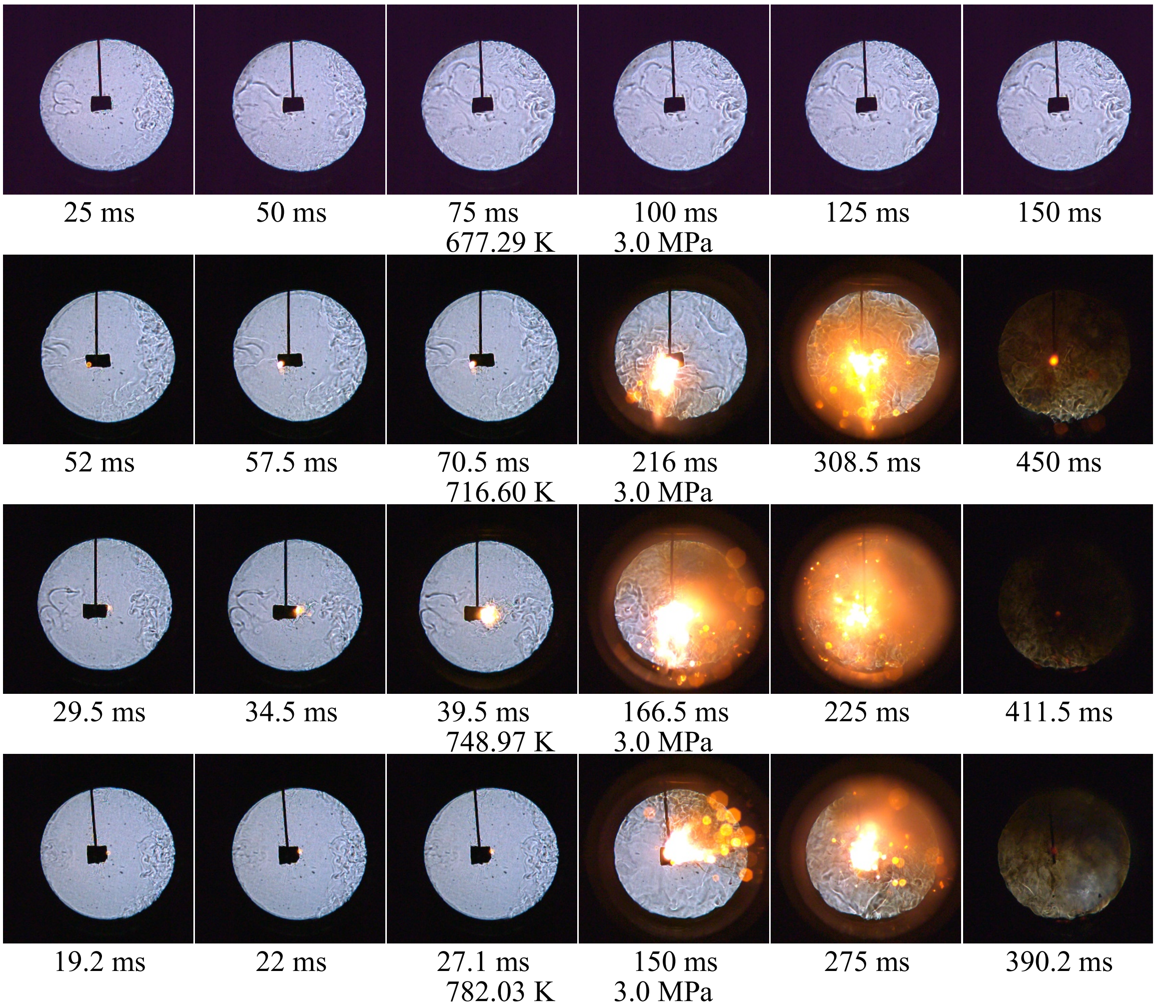

Figure 1: High-speed images of 50 mg GAP/CL-20 samples at 3.0 MPa and different temperatures

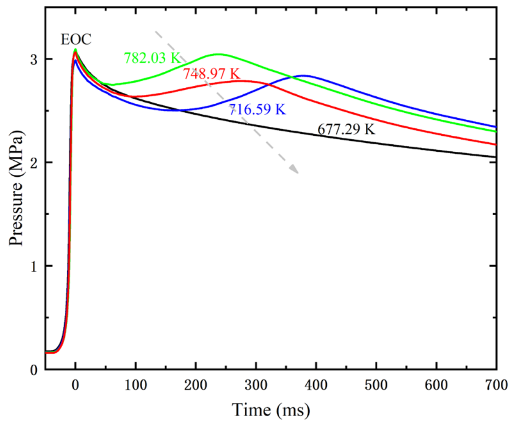

Figure 2: Pressure evolutions of 50 mg GAP/CL-20 samples at 3.0 MPa and different temperatures

In addition, the effect of EOC pressure on auto-ignition behavior of GAP/CL-20 propellant was conducted when the EOC temperature was controlled at about 925 K. The high-speed images and pressure traces are shown in Figure 3 and Figure 4. As we can be seen from Figure 4, no auto-ignition occurred at 1.5MPa. When EOC pressure increased to 2.0 MPa, sample ignited, and the ignition spot first appeared at 19.3 ms, after which sample began to burn slowly until complete. When EOC pressure reached 2.5 MPa, the ignition spot appeared at 11.3 ms ,which was earlier than 2.0 MPa. When EOC pressure was further increased to 3.0 MPa, its IDT became shorter. According to pressure trace in Figure 10, it can also be found that the increase of EOC pressure significantly promotes the combustion of the sample. When EOC pressure is too low (1.5 MPa), the sample will not ignite.

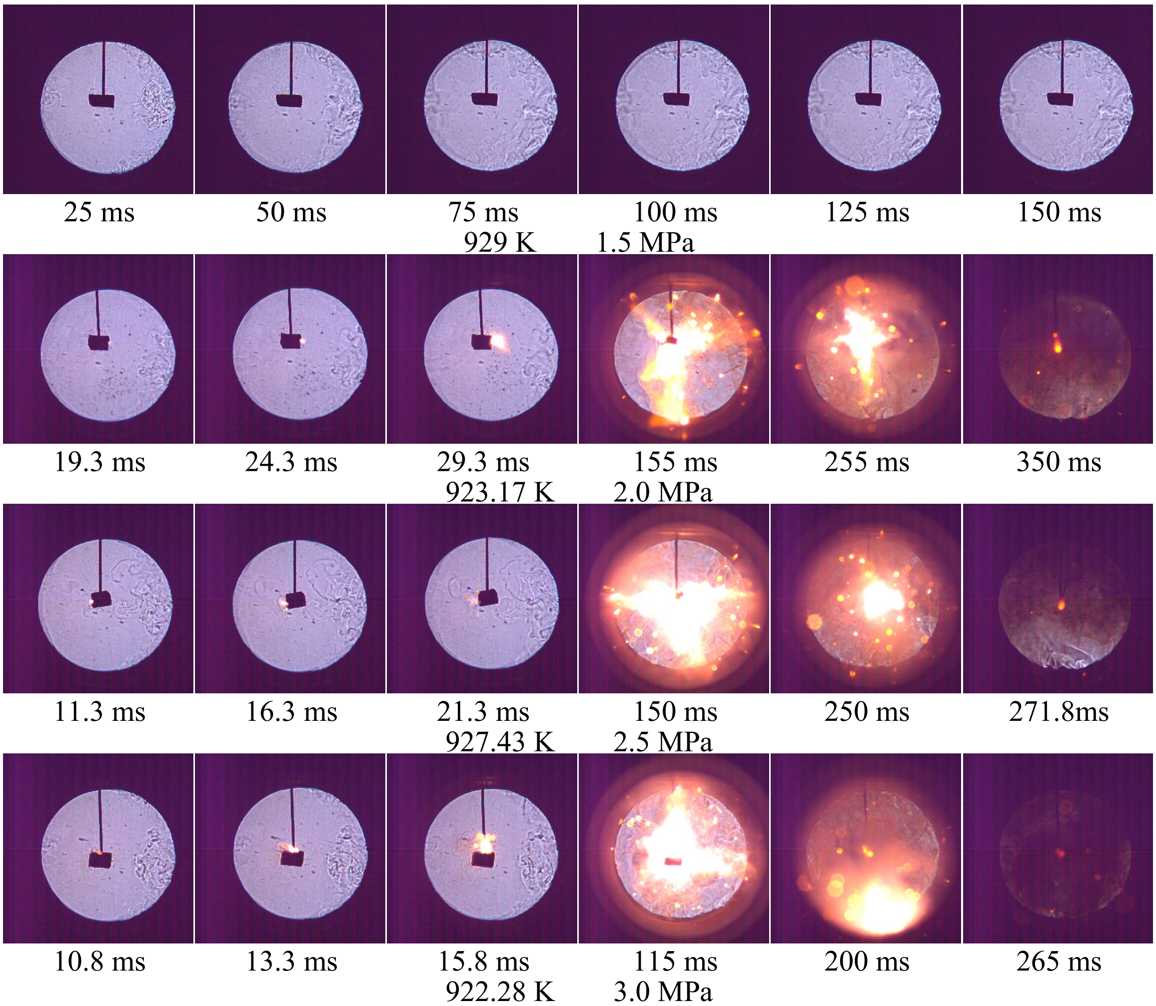

Figure 3: High-speed images of 50 mg GAP/CL-20 samples at 925±3 K and different pressures

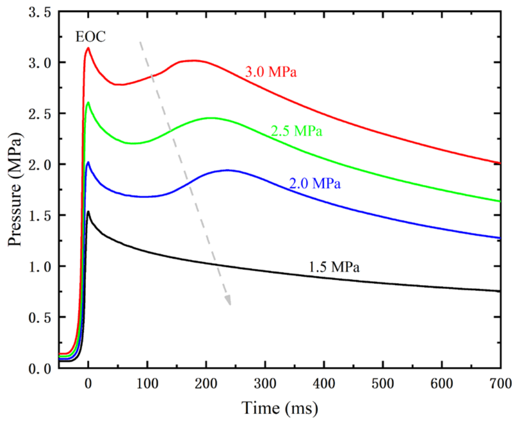

Figure 4: Pressure evolutions of 50 mg GAP/CL-20 samples at 925±3 K and different pressures

3.2 Critical Ignition of GAP/CL-20 Propellant

It is confirmed from the previous section that there is a critical condition that distinguishes the ignition from the non-ignition conditions with the change of temperatures and pressures. Therefore, the ignition critical condition can be obtained by adjusting the temperature and pressure of the EOC.

Figure 5 shows the ignition and non-ignition conditions at different temperatures and pressures. It can be seen that whether the GAP/CL-20 propellant can ignite in RCM depends on EOC temperature and pressure. In addition, the critical EOC temperature of sample is also related to EOC pressure. It indicates that when environmental conditions (pressure and temperature) of samples are in the ignition region, GAP/CL-20 propellant will auto-ignite and induce high risk of explosion. Specifically, the critical EOC temperature decreases significantly as pressure increases from 1.0 MPa to 3.0 MPa. The critical EOC temperature shows a very weak drop when pressure is above 3.0 MPa. In addition, these safety thresholds can provide guidance for the safe use of GAP/CL-20 propellant.

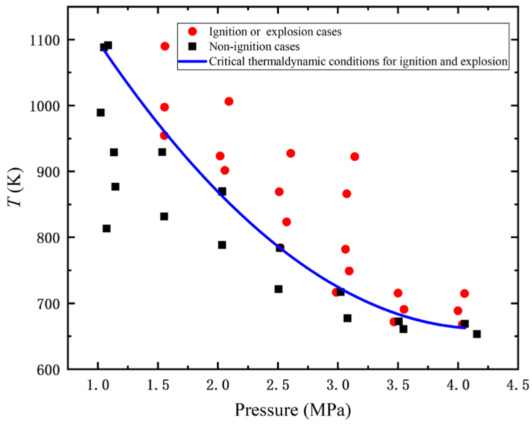

Figure 5: The test points and regions about ignition at different temperatures and pressures (in EOC)

3.3 Average burning rate

It is known from the previous section that burning duration of 50 mg GAP/CL-20 propellant samples under different environments can be obtained through experimental data of RCM. Therefore, we can calculate the average burning rate of GAP/CL-20 propellant samples under different conditions according to the sample mass and combustion duration. For example, its average burning rate is 0.116 g/s at 3.0 MPa and 716.60 K. And the average burning rate rises from 0.126 g/s to 0.133 g/s with the increase of EOC temperatue (from 748.97 K to 782.03 K). Besides, its average burning rate also rises with the increase of EOC pressure, and all details are shown in Figure 6.

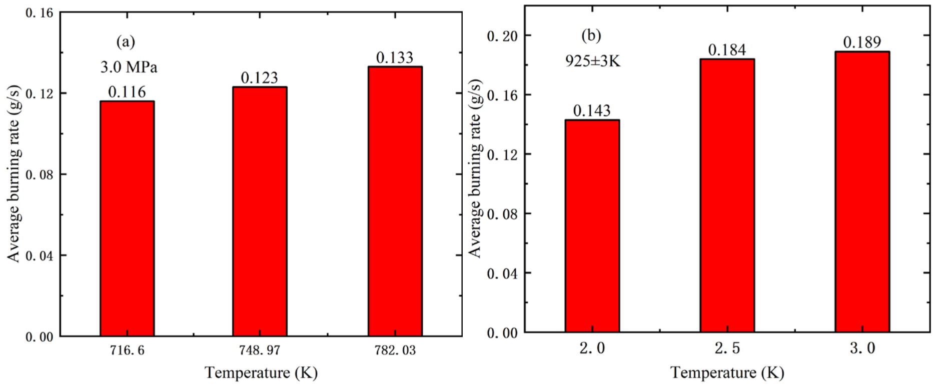

Figure 6: Average burning rate of 50 mg GAP/CL-20 propellant samples under different conditions

4 Conclusions

In this paper, auto-ignition bahavoirs of GAP/CL-20 propellant were investigated by using a rapid compression machine. Results showed that when EOC pressure was controlled to 3.0 MPa, with the increase of EOC temperature, auto-ignition and pressure rise of GAP/CL-20 propellant samples were advanced, and its burning duration was shortened. When EOC temperature was controlled at 925 K, auto-ignition of GAP/CL-20 propellant samples also showed similar characteristics with the increase of EOC pressure. From high-speed images and pressure traces at different EOC pressures and temperatures, critical ignition conditions of GAP/CL-20 propellant which separate the ignition region and non-ignition region are also obtained. When condition is lower than the critical condition, GAP/CL-20 propellant samples would not ignite, which indicates that they are in a safe environment. And the critical ignition temperature decreases rapidly with the increase of pressure when pressure is at 1.0-3.0 MPa. When pressure is higher than 3.0 MPa, the increase of pressure will lead to a slower decrease of critical ignition temperature. Apart from these, we can also calculate the average burning rate according to the sample mass and its combustion duration.

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