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The effect of pressure and oxygen concentration on the ignition and combustion of aluminum–magnesium fuel-rich propellant

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ABSTRACT

In order to better understand how future candidate solid propellants may affect combustion characteristics in ramjet motor, the aluminum–magnesium fuel-rich propellant was tested on a sealed high-pressure laser ignition platform. The laser ignition experimental device was designed and built, then the ignition and combustion characteristics of aluminum–magnesium fuel-rich propellant under different pressures and oxygen concentrations in environment gas were studied. The comprehensive impacts of pressure and oxygen concentration on ignition delay time and burning rate were appraised. The results displayed that the ignition delay time was decreased with the increase of pressure and oxygen concentration. The effect of pressure on ignition delay time was weaker than oxygen concentration. The impact of oxygen concentration on ignition was very complex. When the oxygen concentration of environment gas was less than that of the oxidizing gas from the propellant pyrolysis products, the ignition gas phase reaction occurred in the dispersion region of the solid propellant pyrolysis product, the initial flame was close to the propellant surface. In contrast, when the oxygen concentration was larger than the pyrolysis oxidizing gas, the ignition gas phase reaction occurred in the diffusion zone of the propellant pyrolysis products and the environment gas, the initial flame appeared far from the propellant surface. The burning rate of aluminum–magnesium fuel-rich propellant increased with the increase of pressure and oxygen concentration, where their effect on burning rate is accord with B-number theory. Comparing the experimental measurements with an analytical model, the results showed good consistency. The function of oxygen concentration and pressure could explain the effect on burning rate and ignition delay time, because pressure and oxygen concentration were favorable for the heat transfer, radiation and convection from the flame. The function of the combined influences of pressure and oxygen concentration on burning rate was established by a power law fitting. The good fitting is consistent with the experimental measurements, and shows that the scaling is valid for a full range of pressure and oxygen concentration tests to predict burning rate.

1. Introduction

The ignition process of the solid propellant has a significant effect on the interior ballistic characteristics of the ramjet motor. The research on the ignition characteristics of solid propellant has great significance to reveal its ignition and combustion mechanism, employ and develop new propellant. As early as the 1960s, many researchers began to carry out a large number of research working on the ignition performance of solid propellants, including ignition theory, ignition test method and ignition performance [1–6]. However, the ignition of solid propellant involves an array of complicated physiochemical processes which is affected by the ignition energy, the propellant component, the ignition pressure and the ambient gas [7]. During the past decades, a large number of researchers have devoted to the study of ignition processes and proposed a lot of theoretical models [8]. But the ignition and combustion of solid propellant have not been fully understood.

Ignition delay time which is related to the heat flux, the initial temperature, the ambient gas, the ambient pressure and the composition of the solid propellant, is one of the most important parameters of the ignition process. Ohlemiller [9,10] studied the effects of ambient pressure, oxygen concentration, laser flux density and the laser radiation absorption coefficient on ignition delay time. The experimental results showed that as the laser flux density, oxygen concentration and pressure decreased, the ignition delay time gradually increased until the energetic material could

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not be ignited. Nan [11] studied the ignition characteristics of three composite propellants to obtain the ignition law of the HTPB propellant, two types of high energy propellants under different heat flux density, ambient pressure and original temperature conditions. Xu [12] investigated the effect of the oxygen content, burning rates and the laser radiant flux on the ignition delay time of HTPB propellants with a CO_2-laser ignition apparatus. The results showed that the ignition delay time was shortened along with the increase of oxygen content, burning rates and the laser radiant flux. The addition of ultra-fine aluminum powder could improve the ignition properties of HTPB propellants significantly and make ignition delay time shortened. Ulas [13] analyzed the effects of propellant component, heat flux and ambient pressure on the ignition performance in detail, and established the mathematical expression of the relationship between ignition delay time and laser heat flux. In summary, it can be seen that the impact of various factors on the ignition delay time was not detailed theoretically in which only qualitative analysis is available in most previous studies.

The burning rate of solid propellant is one of the most important factors in determining the performance of ramjet motor. The burning rate depends on a number of factors, such as the pressure of combustion chamber, the initial temperature of solid propellant, the percentage of high-energy materials in the propellant content, the burn sensation of the flammable matters, the additional chemical matters and the percentage of oxidant dosage [14]. In the design of ramjet motor, the burning rate should be determined carefully. As a result, many researchers have conducted extensive experimental and theoretical studies to obtain the mathematical expression of burning rate in stable combustion. The well-known burning rate formula of solid propellant is Vielle's Law $\dot{r} = kp_c^n$, where p_c is the pressure of combustion chamber, k is the initial constant temperature of the propellant, n is called as the pressure index. The burning rate ($\dot{r}$) is mainly dependent on the initial temperature of the propellant and the pressure of combustion chamber. The increase of pressure is one of the most important factors in increasing the burning rate. As the pressure increases, the burning flame profile changes, the flame size decreases, and the propellant burns faster [15]. The initial temperature of solid propellant is also one of the factors that affect the burning rate. When the initial temperature increases, the combustion terminal pressure is increased, the combustion duration is shortened, and the specific impulse is increased [16]. Wu [17] studied the burning rate at different pressure by adding high-energy metal-based materials to the solid propellant. It is found that the high-energy propellants containing metallic additives had a higher burning rate than those without any high-energy fuel additives. In addition, the oxygen concentration also affects the burning rate but is rarely concerned.

The development of the new missile weapon has made some requirement for the propulsion system which proposes to a small volume, light weight, far range, fast speed and simple structure. The solid fuel ramjet motor has become an attractive topic because of the high specific impulse can realize the full supersonic cruise of the missile [18]. The aluminum–magnesium fuel-rich propellant which has advantages of the high combustion efficiency, low oxygen consumption for high altitude conditions, is widely used in solid fuel ramjet motor. However, the solid fuel ramjet motor still needs oxygen from the external air to assist combustion, so the external air parameters such as pressure and oxygen concentration (oxygen volume fraction, Y_{O_2}) will affect the ignition process of aluminum–magnesium fuel-rich propellant and the performance of solid fuel ramjet motor. In this paper, the influences of environmental oxygen concentration and pressure on the ignition and combustion process of aluminum–magnesium fuel-rich propellant were studied by laser ignition facility. The experimental data were associated with a theoretical analysis model to analyze the behaviors of ignition and combustion. The coupling of theoretical analysis with experimental data illustrated how the ambient pressure and oxygen concentration influenced the ignition and burning of aluminum–magnesium fuel-rich propellant. This study can provide a reference for the design of solid fuel ramjet motor to be used in the large altitudes condition.

Table 1
Composition of aluminum–magnesium fuel-rich propellant.

Composition	Mass fraction	Particle diameter
AP	36.0 %	(100–120) μm
HTPB	20.0%	
Al	20.0%	∼24 μm
Mg	20.0%	∼30 μm
Others	4.0%	

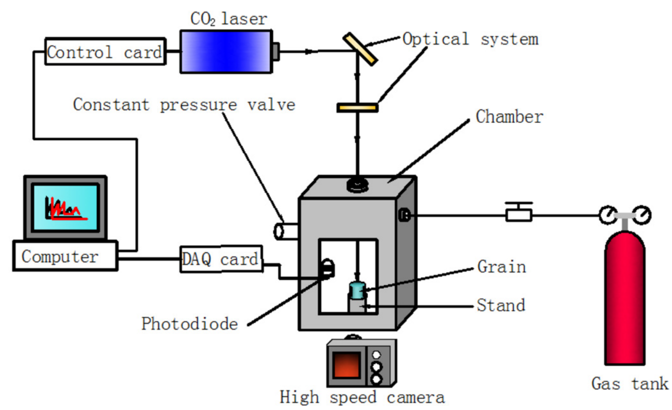

Fig. 1. Schematic of the experimental system.

2. Experimental setup

2.1. Samples

The composition of aluminum–magnesium fuel-rich propellant which was produced for ground direct-connected experiments of solid rocket ramjet by Xi'an Modern Chemistry Research Institute is shown in Table 1. In the experiment, a cylindrical specimen was used, which is ∅4 mm in diameter and 7 mm in length. In order to ensure the accuracy of experimental data and the clarity of experimental phenomena, the experimental sample was coated with high-temperature resistant insulating rubber on the surrounding sides to prevent flame over when burning.

2.2. Experimental system

Experiments were carried out on the sealed high-temperature and high-pressure laser ignition platform. The schematic diagram of the experiment system is shown in Fig. 1. It mainly consists of control system, CO_2 laser, optical system, combustion chamber and the data acquisition system. The control system is composed of computer software and control card, which can control laser loading time and radiation of CO_2 laser. CO_2 laser is the ignition source with the power of 300 W. The optical system consists of a plane mirror and a focusing mirror at the top of the combustion chamber. The function of the optical system is to change the horizontal laser beam emitted from the laser to a vertical laser beam, which reaches the surface of the propellant and completely covers the end face of the specimen of ∅4 mm. The combustion chamber whose size is $150 \times 150 \times 300$ mm has an observation window of 50×100 mm in the horizontal direction and a laser entrance window of 20 mm in diameter on the top. The data acquisition system can acquire the laser light signal and the propellant initial flame