Study on Ignition Delay Time of Al/Mg Fuel-rich Propellant under Tangential Air Flow

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Abstract. Solid propellant, as the power source of propulsion system, has obvious influence on the internal ballistic characteristics of ramjet. The ignition and combustion characteristics of solid propellant help to reveal the combustion mechanism and have important guiding significance for estimating the performance of propulsion system. In this paper, the ignition and combustion characteristics of Al/Mg fuel-rich propellant under tangential air flow were studied. Laser ignition experiment was carried out on the Al/Mg fuel-rich propellant at different tangential air flow rates and tangential air flow components. The results show that the air flow rate and air flow composition can affect the flame shape and the brightness of the propellant. At the same time, with the increase of air flow rate, the more obvious the erosion combustion effect on the propellant burning surface. The air flow rate also affects the ignition delay time. When the air flow rate is low, the ignition delay time decreases with the increase of air flow rate. When the air flow rate is 0.8L/min, the ignition delay time is reduced to the minimum of 350ms, but with the air flow rate continues to increase, the ignition delay time is increasing. As the oxygen content in the air flow increases, the ignition delay time increases. However, when the oxygen content is less than 14% or higher than 21%, the effect of oxygen content on the ignition delay time is weakened.

1. Introduction

The solid fuel ramjet is one of the widely applied propulsion systems, because it can offer high specific impulse in a simple configuration [1]. The ingredient of solid fuel has an important impact on the performances of solid fuel ramjet. Solid propellants are widely used in missile and satellite propulsion systems. As the power source in the propulsion system, the research on ignition and combustion characteristics of solid propellant is of great significance to the performance prediction of the propulsion system. Al/Mg fuel-rich propellant which is a composite propellant based on the addition of magnesium and aluminium particles, ensures the higher calorific value and improves the ignition and combustion efficiency. Due to its unique ignition and combustion characteristics, it has attracted a great deal of attention from researchers.

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 [2-5]. 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 [6]. With the improvement of the reliability and applicability of the propulsion system, solid propellants need to be applied in a more complex environment. Different combustion environments, such as ambient pressure, oxygen content and air flow, affect the ignition and combustion performances of Al/Mg fuel-rich propellant, resulting in ignition failure, combustion flame instability and so on. When the solid fuel burns in the ramjet, the high-temperature tangential air flow blows through the sur-face of solid fuel, which involves heat conduction, heat exchange and convection, and participates in a series of complex chemical reactions [7]. This complex physical and chemical pro cess makes it very difficult to study the ignition and combustion characteristics of solid fuels. In view of the above problems, laser ignition experiments of Al/Mg fuel-rich propellant under tangential air flow conditions were carried out to study the influence of different air flow rate and air flow components on ignition and combustion characteristics. It can provide basic theoretical reference for the application of Al/Mg fuel-rich propellant in ramjet.

2. Experimental Setup

2.1. Samples
The composition of composite solid propellants with Al/ Mg particles additives is shown in table 1. In the experiment, a cylindrical specimen was used, which was Ø5mm in diameter and 5 mm in length. In order to ensure the accuracy of experimental data and the clarity of experimental phenomena, the experimental samples were coated with high-temperature resistant insulating rubber on the surrounding sides to prevent flame over when burning.

Table 1. The composition of composite solid propellants.

| Composition | Mass fraction | Particle diameter |
|-------------|---------------|-------------------|
| AP          | 36.0 %        | (100-120) μm      |
| HTPB        | 20.0%         |                   |
| Al          | 20.0%         | ~5μm              |
| Mg          | 20.0%         | ~5μm              |
| Others      | 4.0%          |                   |

2.2 Experimental System
Experiments were carried out on the small-scale sealed laser ignition platform which was improved on the basis of our previous work [8], adding air flow intake system to the side of combustion chamber. The schematic diagram of the experiment system is shown in figure 1. It mainly consists of control system, CO2 laser, optical system, combustion chamber, air flow intake system and the data acquisition system. In the air flow intake system, two high-pressure cylinders are equipped with nitrogen and oxygen, respectively. The flow valve is used to control the content of nitrogen and oxygen in the mixture, and the air flow rate is adjusted by the rotor gas flowmeter. The gas enters the combustion chamber through the gas-conducting metal tube. The center of the metal tube is kept at the same level as the surface of the propellant to ensure that the tangential air flows through the propellant surface. Since additional burning gas in the burning environment under the air flow conditions, the pressure will increase. However, to ensure constant pressure during the measurement, a pressure valve added to chamber automatically controls the intended pressure conditions. The ignition and combustion process of Al/Mg fuel-rich propellant is recorded by a high speed camera.
The experiment was carried out at room temperature of 25℃ under atmospheric pressure. The test conditions included the laser heat fluxes of 1.86W/mm², 2.23W/mm² and 2.79W/mm², the air flow velocity of 0.2L/min-1.2L/min, and the different content of nitrogen and oxygen in the mixture. A summary of all the experimental conditions is showed in Table 2. Five sets of tests were performed under different experimental conditions.

![Schematic of the experimental system.](image)

**Figure 1. Schematic of the experimental system.**

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| Test conditions | Values                                      |
|-----------------|---------------------------------------------|
| Pressure (MPa)  | 0.1                                         |
| Inlet air temperature (°C) | 25                                    |
| Air flow rate (L/min) | 0.2, 0.5, 0.8, 1.2                          |
| Heat flux (W/mm²) | 1.86, 2.23, 2.79                            |
| Air flow composition | Case 1: 10%O₂ and 90%N₂                    |
|                  | Case 2: 14%O₂ and 86%N₂                     |
|                  | Case 3: 18%O₂ and 82%N₂                     |
|                  | Case 4: 21%O₂ and 79%N₂                     |
|                  | Case 5: 30%O₂ and 70%N₂                     |

### 3. Results and Discussion

#### 3.1. Influence of Air Flow Rate on Ignition and Combustion Characteristics of Propellant

The high speed camera provided direct observation of the ignition and combustion process. Some typical images are shown in figure 2, when the external heat flux is 2.23W/mm², the pressure is maintained at 0.1MPa, air flow component is case4, under the different air flow rate conditions. As can be seen from figure 2, at different air flow rate conditions, the initial flame is formed next to the burning surface, and the initial flame moves along the direction of the air flow. The air flow rate affects the flame brightness. When the air flow rate is 0.8L/min, the flame brightness is highest and the outline is clear. By comparing the combustion process at each air flow rate, it can be found that the air flow rate has a great influence on the shape and brightness of the flame. At the air flow rate of 0.8L/min, the flame is brightest, which indicates that the air flow rate in this working condition can promote the ignition and combustion of Al/Mg fuel-rich propellant. When the air flow rate is 1.2L/min, it is obvious that the burning surface is not horizontal but has an inclination along the air flow rate due to the burning erosion effect of the air flow on the propellant surface. It is shown that the effect of erosion and combustion is more obvious with the increase of the air flow rate.
Figure 2. Typical images of ignition and combustion process with air flow rate at 0.2L/min, 0.5L/min, 0.8L/min, 1.2L/min.

The ignition delay time is obtained by using two photodiodes to monitor the laser and flame signals. Ignition delay time as a function of air flow rate is shown in figure 3 for various laser heat flux. The results in figure 3 are obtained at 0.1MPa and case 4. For different air flow rate, the experimental data show a decrease in ignition delay time with the increase of laser heat flux. From figure 3, it can be seen that the ignition delay time decreases with the increase of air flow rate. And the ignition delay time is reduced to a minimum of 350ms when the air flow rate increases to 0.8L/min. After that, as the air flow rate continues to increase, the ignition delay time is increasing. This is because the surface reaction of the propellant is mainly affected by the diffusion effect, when the air flow rate is low. The increase of the air flow rate makes the diffusion rate increase and the reaction rate of the propellant surface increase, so that the ignition delay time decreases. At air flow rate of 0.8L/min, this diffusion effect has the greatest effect on the surface reaction, promoting ignition and combustion, which is consistent with the combustion phenomenon of figure 2. When the air flow rate is higher than 0.8L/min, the influence of convective heat transfer on the surface reaction begins to show. As the air flow rate increases, the heat loss caused by convective heat transfer on the burning surface increases, leading to the increase of ignition delay time.

Figure 3. The effect of the flow rate on ignition delay time.
3.2. Influence of Air Flow Composition on Ignition and Combustion Characteristics of Propellant

At external heat flux of 2.23W/mm² and air flow rate of 0.8L/min, the laser ignition and combustion processes of Al/Mg fuel-rich propellant under different air flow compositions (case1: 10% O₂ and 90% N₂, case2: 14% O₂ and 86% N₂, case3: 18% O₂ and 82% N₂, case4: pure air) were recorded by a high-speed camera, as shown in figure 4. As can be seen from figure 4, the initial flame is formed on the burning surface of the propellant under different air flow composition conditions, but there is an obvious difference in flame shape and brightness during the burning process. When the oxygen content is lower, the shape of the flame is slender and the outline is clear with dull yellow light. When the oxygen content is higher, the flame is thicker. The closer to the propellant surface, the thicker the flame shape, with the blurred outline and the dazzling white light. This indicates that the increase of oxygen content makes the reaction of magnesium and aluminum particles more fully, the flame is more robust. The full combustion of magnesium makes the flame emit more dazzling white light.

In order to study the influence of tangential air flow composition on the ignition delay time of Al/Mg fuel-rich propellant, the ignition delay time obtained by the laser ignition experiment is shown in figure 5 under different air flow composition (case1: 10% O₂ and 90% N₂, case2: 14% O₂ and 86% N₂, case3: 18% O₂ and 82% N₂, case4: pure air, case5: 30% O₂ and 70% N₂) at the flow rate of 0.8L/min. As can be seen from figure 5, the ignition delay time decreases with the increase of heat flux. For the same heat flux, the ignition delay time decreases with the increase of oxygen content in the air flow composition. However, the influence of the oxygen content of the air flow composition on the ignition delay time has a certain threshold range. When the oxygen content increases from 10% to 14%, the ignition delay time almost no change. When the oxygen content increases from 14% to 21% (pure air condition), the ignition delay time was significantly reduced. When the oxygen content continues to increase from 21% to 30%, the ignition delay time decreased less obviously.
Figure 5. The effect of the flow component on ignition delay time.

4. Conclusion

This paper mainly studies the effects of tangential air flow rates and tangential air flow components on ignition and combustion characteristics of Al-Mg-depleted propellant. Air flow rate affects the shape and brightness of the propellant burning flame, with the brightest flame and clear outline at the air flow rate of 0.8 L/min. With the increase of air flow rate, the erosion combustion effect of the propellant burning surface becomes more obvious. Air flow rate also affects the diffusion rate and convective heat transfer of propellant burning surface. As the air flow rate increases, the ignition delay time gradually decreases. When the air flow rate is 0.8L/min, the ignition delay time is reduced to a minimum. Afterwards, as the air flow rate continues to increase, the ignition delay time increases. With the increase of oxygen content in the air flow component, the combustion reaction of propellant is more sufficient, which makes the flame brightness increase and the flame is more robust. The ignition delay time of the propellant increases with the increase of oxygen content in the airflow component.

Acknowledgments

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