Research paper

# Combustion characteristics of $N_2O$/GAP hybrid rocket —Effects of zirconium and magnesium—

Koutarou Matsumoto*† and Takuo Kuwahara*

*Department of Aerospace Engineering, College of Science and Technology, Nihon University,
7–24–1 Narashinodai, Funabashi, Chiba, 274–8501, JAPAN
Phone : +81–47–469–5317
†Corresponding author : csko12002@g.nihon–u.ac.jp

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## Abstract

To clarify the heat transfer effects of metal particle combustion on gas hybrid rocket combustion characteristics, we elucidated metal particle ignition characteristics and gas hybrid rocket combustion characteristics. The ignition delay time of metal particles decreases concomitantly with increasing $N_2O$ temperature. Moreover, the ratio of the chemical ignition delay time is about 20% at 1100 K, which indicates that metal particles can ignite rapidly in the secondary combustor. The $C^*$ combustion efficiency for GAP/AP is about 87%. That for GAP/AP/Mg is about 99%. That for GAP/AP/Zr is about 94%. In all cases, the gas hybrid rocket combustion efficiency is improved by adding metal particles, but the $C^*$ combustion efficiency is improved more by Mg particle addition. The addition of gas-phase combustion metal particles is more effective to improve gas hybrid rocket combustion characteristics.

***Keywords*** : gas hybrid rocket, combustion, nitrous oxide, zirconium, magnesium

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## 1. Introduction

A gas hybrid rocket is a two-stage combustion system that operates similarly to a ducted rocket[1)−3)]. Figure 1 portrays the fundamental structure of a gas hybrid rocket.

A gas hybrid rocket comprises a liquid oxidizer feeding system, a primary combustor, a secondary combustor, a primary nozzle, and a secondary nozzle. The gas generator is burned in the primary combustor to generate fuel-rich hot gas, which is then injected into the secondary combustor through the primary nozzle. The liquid oxidizer is fed into the secondary combustor through the liquid oxidizer feeding system. The mixture gas comprising the fuel-rich hot gas and the liquid oxidizer is then burned in the secondary combustor. This system mixes the high-temperature fuel gas and low-temperature oxidizer rapidly. Therefore, two-stage combustion systems present difficulties such as degradation of the combustion stability and combustion efficiency by cooling of the mixture gas[4)]. To compensate for these shortcomings, a flame holder that produces a hot spot is attached in the combustor. However, it is difficult to attach a mechanical flame holder in the rocket chamber because the combustion gas is extremely hot. Therefore, these rockets

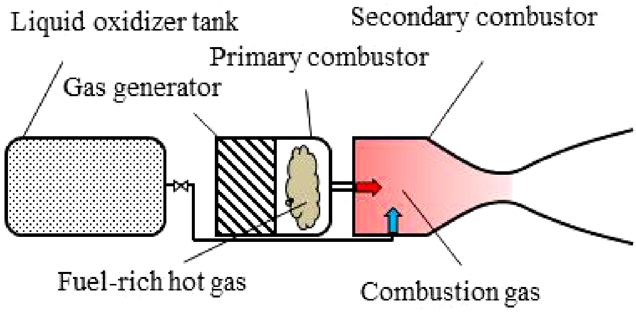



Figure 1 Structure of the gas hybrid rocket.

incorporate solid particles such as metal particles into the gas generator. The metal particles are heated in the fuel-rich hot gas and are injected into the secondary combustor, where they do not cool easily because the heat capacity of metals is higher than that of the mixture gas. For that reason, the heated metal particles can be an ignition source of the mixture gas. Moreover, the heated metal particles react easily with the oxidizer and ignite in the secondary combustor. Typical metals generate a high-temperature flame when burned. The burning metal particles transfer the combustion heat to the surrounding gas. A high-temperature region is generated around the metal particles, thereby increasing the chemical reaction rate of the mixture gas. Consequently, the ignition and combustion in the secondary combustor are improved[5),6)]. Therefore, the addition of metal particles is effective to increase the combustion efficiency of the gas hybrid rocket. The combustion heat of metals is transferred by three modes: heat conduction, heat convection, and heat radiation. The method of heat transfer affects the combustion efficiency in the secondary combustor, but the effects of these types have not been clarified.

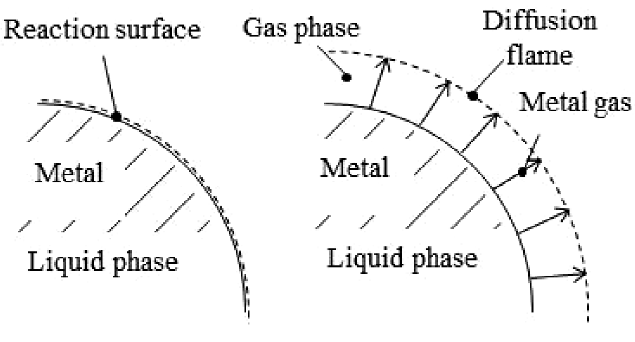
To ascertain the effects of heat transfer by the combustion of metals, the metal particles must ignite rapidly in the mixture gas. For that reason, the ignition delay time of metal particles in the oxidizer gas is important. The metal particles are heated in the primary combustor. They react with the liquid oxidizer in the secondary combustor. When the solid oxidizer is incorporated into the gas generator, the temperature of heated metal particles that depend on the mixture quantity of solid oxidizer is increased. The heated metal particles ignite rapidly in the secondary combustor when its temperature is high. Moreover, the physical processes and chemical processes must be evaluated. Physical processes include the temperature increment and the metal particle phase transition. Chemical processes include the reaction of metals with the oxidizer.

This study examined the ignition delay time of the metal particles and evaluated the chemical ignition delay time and physical ignition delay time. Then the effects of metal particle combustion on the gas hybrid rocket combustion characteristics were obtained.

## 2. Metal particle combustion

Metal combustion is divisible into two types: surface combustion and gas-phase combustion[7),8)]. Figure 2 portrays the metal particle combustion types.

Figures 2(a) and 2(b) respectively show the surface combustion (burning on the metal surface) and gas-phase combustion (burning in the vapor phase). The vaporized metal is burned around the metal particles, forming a diffusion flame. Each has different modes of heat transfer to the surrounding gas. Surface combustion transfers heat by heat conduction to the surrounding gas. Gas-phase combustion transfers heat by mass transport, which is transportation of the combustion products to the surrounding gas. This study examined the surface combustion metal particles and gas-phase combustion metal particles to evaluate the effects of the heat transfer modes. The metal particles must ignite rapidly in the secondary combustor. Therefore, this study used magnesium (Mg) as the gas-phase combustion type and zirconium (Zr) as the surface combustion type. These metal particles can ignite easily in the oxidizer gas.




(a) Surface combustion (b) Gas−phase combustion

Figure 2 Combustion types of metal particles.

## 3. Experiments

The gas generator must generate the fuel-rich hot gas and heat the metal particles. This study used a gas generator with glycidyl azide polymer (GAP) propellant. This highly energetic material can incorporate many metal particles. Moreover, GAP generates much fuel-rich gas[9),10)]. The liquid oxidizer feeding system is changed by the liquid oxidizer characteristics[1)]. Gas hybrid rockets can cut down on the structural mass using a self-pressurized system that pressurizes the oxidizer tank using the oxidizer vapor pressure. The optimum liquid oxidizer for a self-pressurized system is nitrous oxide ($N_2O$), which has sufficient vapor pressure for use in a self-pressurized type. Therefore, the liquid oxidizer uses $N_2O$.

Figure 3 shows the electric furnace used to obtain the ignition delay time of the metal particles. The gas in the furnace atmosphere is $N_2O$. Different temperatures were used: 900, 950, 1000, 1050, and 1100 K. The furnace inner dimensions are 100 mm height and 27 mm width. Metal particles (about 1 mg) were dropped from the upper side of the furnace. The ignition delay time is the time from contact with the high-temperature gas to the appearance of the luminous flame. The experiment was repeated 20 times per condition. To evaluate the ignition characteristics, we used Zr and Mg mean diameters of 45 $\mu$m. Moreover, the chemical ignition delay time ($\tau_c$) and physical ignition delay time ($\tau_p$) were calculated using the

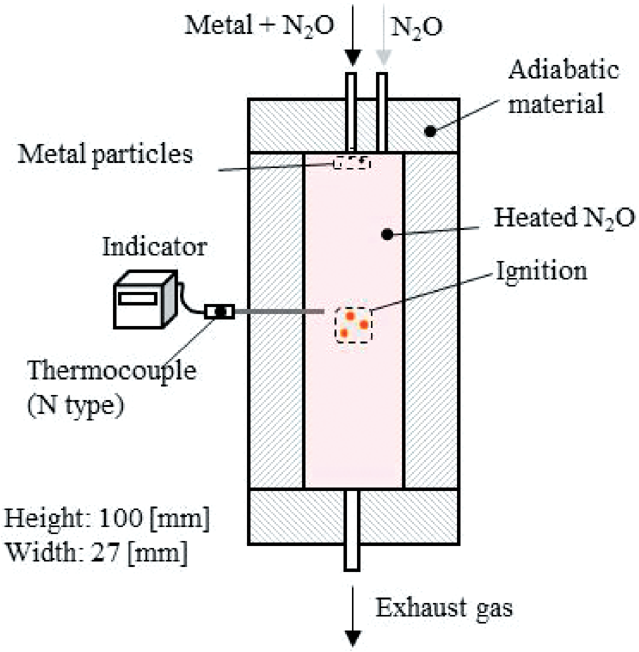



Figure 3 Electric furnace.

**Table 1** Compositions of gas generators and theoretical performance of gas hybrid rockets at1 MPa.

| Name | GAP [mass%] | AP [mass%] | Metals [mass%] | Ispth [s] | $O/F_{th}$ [−] |
|---|---|---|---|---|---|
| GAP/AP | 60 | 40 | 0 | 307 | 1.81 |
| GAP/AP/Zr | 54 | 36 | 10 | 306 | 1.73 |
| GAP/AP/Mg | 54 | 36 | 10 | 309 | 1.81 |

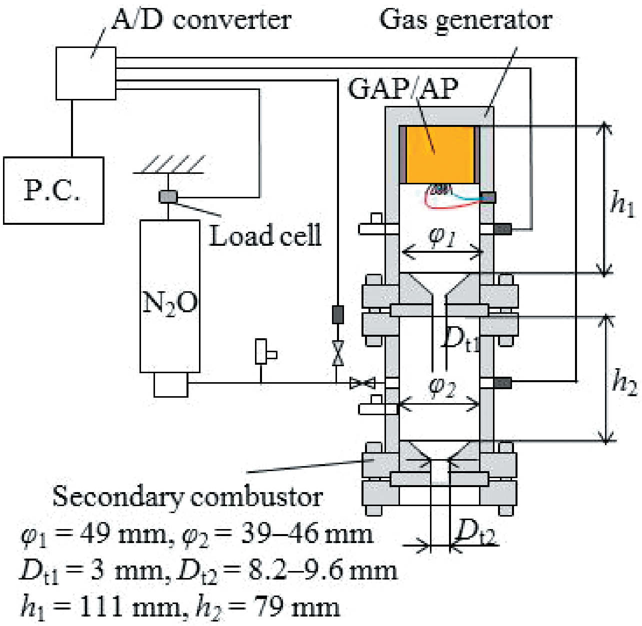



**Figure 4** Experimental apparatus of the gas hybrid rocket.

ignition delay time to investigate the ignition characteristics in the secondary combustor. The physical process is the temperature increment and phase transition of the metal particles. No probability of ignition exists in the physical process. Consequently, the physical ignition delay time is defined as the time for which the probability of no ignition is 100%[11),12)].

The gas hybrid rocket combustion characteristics were measured using a small combustion chamber, as presented in Figure 4. The secondary combustor is 79-mm long with 39-46-mm diameter. The primary combustor nozzle throat diameter is 3 mm. The secondary nozzle throat diameter is 8.2-9.6 mm. The characteristic length of the secondary combustor is 2 m. To change the fuel-rich hot gas and liquid oxidizer mixture ratio, the mass flow rate of fuel-rich hot gas is controlled. The mass flow rate was changed by the gas generator diameter so that the mixture ratio was 1.3-2.3. The gas generator used the GAP propellants. Table 1 presents gas generator compositions and the theoretical performance of the gas hybrid rockets. The combustion products of GAP include much carbonaceous residue[9), 13)]. To investigate the effects of metal particles clearly, the solid and liquid products must decrease. Moreover, the pressure exponent of burning rate of GAP/metal propellants is higher than 1. To decrease the pressure exponent and carbonaceous residue generation, AP was incorporated into the GAP propellant. Theoretical calculations show that the GAP generates 30% carbon graphite as a mole fraction and show that the GAP propellant that incorporates 40 mass% AP generates no carbon graphite[14)]. The combustion of the GAP/AP propellants generated large amounts of fuel gas. The amount of added metal particles was 10 mass%. The metal particles were expected to burn out in the secondary combustor. Therefore, the average diameters of the metal particles were used for assessments.

## 4. Results and discussion

### 4.1 Ignition characteristics of metals

Figure 5 portrays the relation between the $N_2O$ temperature and metal particle ignition characteristics. Figures 5 (a) and 5 (b) respectively present the Zr particle and Mg particle ignition characteristics. The figures show the ignition delay time $\tau_{ig}$, chemical ignition delay time $\tau_c$, and physical ignition delay time $\tau_p$.

These fractions are expressed by $\eta_c = \tau_c/\tau_{ig}$ and $\eta_p = \tau_p/\tau_{ig}$. The ignition delay time of Zr is 0.05 s at 1000 K, but that of Mg is 0.09 s. Zirconium is readily ignited in the $N_2O$ atmosphere. The ratio of chemical ignition delay time $\eta_c$ of each metal is about 20%. Therefore, Zr particles and Mg particles that are heated in the primary combustor react rapidly with $N_2O$ and ignite in the secondary combustor.



### 4.2 Combustion efficiency with a gas hybrid rocket

Results of combustion experiments are presented in Figure 6. The burning rate of GAP/AP was about 9.2 mm/s at 2MPa. That of GAP/AP/Zr was about 10.1 mm/s and

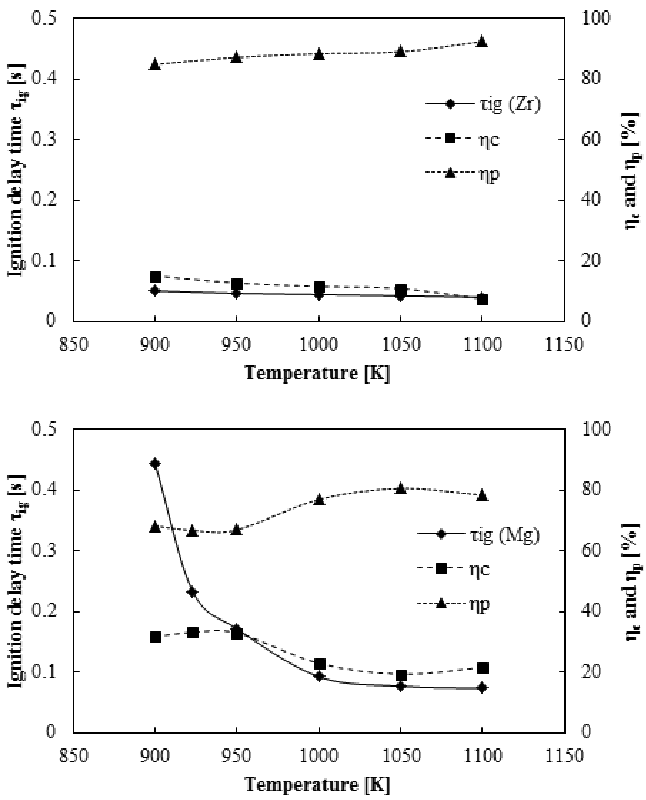



**Figure 5** Relation between the electric furnace temperature and ignition delay time or the ratio of $\tau_c$ to $\tau_p$ to the ignition delay time at 0.1 MPa : (a) zirconium 45 μm and (b) magnesium 45 μm.

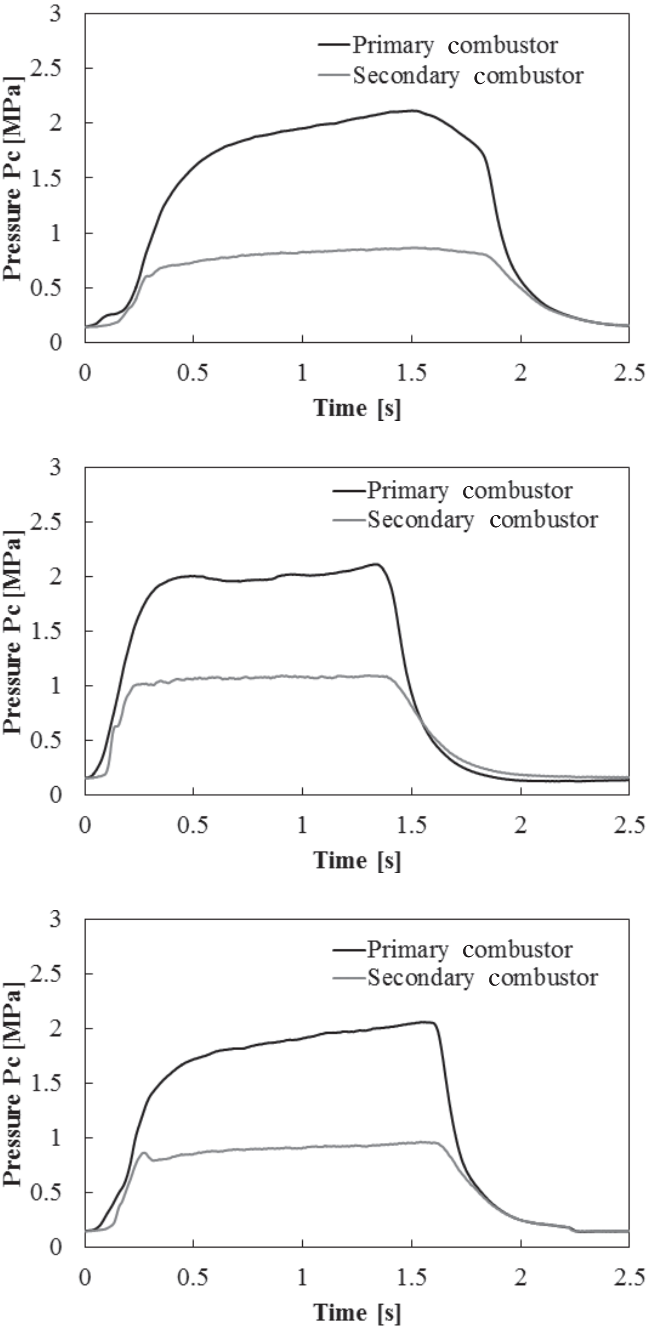



**Figure 6** Pressure histories of the gas hybrid rocket chamber : (a) GAP/AP, (b) GAP/AP/Zr, and (c) GAP/AP/Mg.

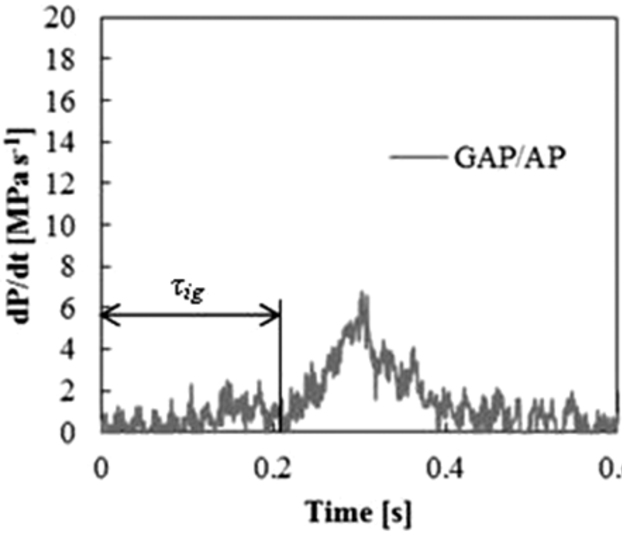



**Figure 7** Temporal differentiations of the pressure in the secondary combustor.

GAP/AP/Mg was about 9.3 mm/s at 2MPa. The pressure curves of the primary combustor and the secondary combustor are portrayed respectively in Figure 6(a) at GAP/AP, GAP/AP/Zr in Figure 6(b), and GAP/AP/Mg in Figure 6 (c). The pressure curves are stable and constant.

After mixing, the reaction is controlled under an Arrhenius equation. The mixed gas reaction rate is

$$\dot{\omega} = z \exp\left(\frac{-E}{RT}\right). \quad (1)$$

In that equation, $z$ is a constant, $E$ denotes the activation energy, $R$ is the gas constant, and $T$ represents temperature. The reaction rate multiplies the reaction heat. Then we obtain the reaction heat, which is the reaction enthalpy $h$. The change of the reaction enthalpy $h$ is proportional to the temperature change, as in the following equation.

$$\dot{\omega} \times q = \frac{\partial h}{\partial t} = C_p \frac{\partial T}{\partial t} \quad (2)$$

Therein, $C_p$ denotes the heat capacity at constant pressure. When ignition in the secondary combustor occurs, the pressure increases. Ignition marked a change of $\partial T/\partial t$. The equation of state shows that $T$ is proportional to $P$. Therefore, the following equation is formed.

$$\frac{\partial T}{\partial t} \propto \frac{\partial P}{\partial t} \quad (3)$$

The change of the first point of $\partial P/\partial t$ is chosen as the ignition point[15]. The relation between $\partial P/\partial t$ and time is presented in Figure 7.

The mean ignition delay time GAP/AP is 0.21 s. That of GAP/AP/Zr is 0.21 s. That of GAP/AP/Mg is 0.28 s. Ignition delay times of GAP/AP and GAP/AP/metals are nearly equal values because the theoretical adiabatic flame temperature of fuel-rich hot gas is higher than 1300 K[14]. Therefore $N_2O$ decomposes easily.

The combustion efficiency $\eta_{c^*}$ of the gas hybrid rocket is obtained using the following equation.

$$\eta_{c^*} = \frac{C^*_{\exp}}{C^*_{th}} \times 100 \quad (4)$$

Subscript exp denotes ***experiment***, ***th*** stands for ***theoretical***, and $C^*_{\exp}$ is obtained as shown below[16].

$$C^*_{\exp} = \frac{A_t P_c}{\dot{m}} \quad (5)$$

In that equation, $A_t$ stands for the secondary nozzle throat area, $P_c$ denotes pressure in the secondary combustor, and $\dot{m}$ is the mass flow rate. The relation between $\eta_{c^*}$ and O/F ($N_2O$/fuel ratio) is depicted in Figure 8.

The combustion efficiency $\eta_{c^*}$ of GAP/AP is about 87%. That of GAP/AP/Zr is about 94%. That of GAP/AP/Mg is about 99%. The $\eta_{c^*}$ increased with addition of the metal

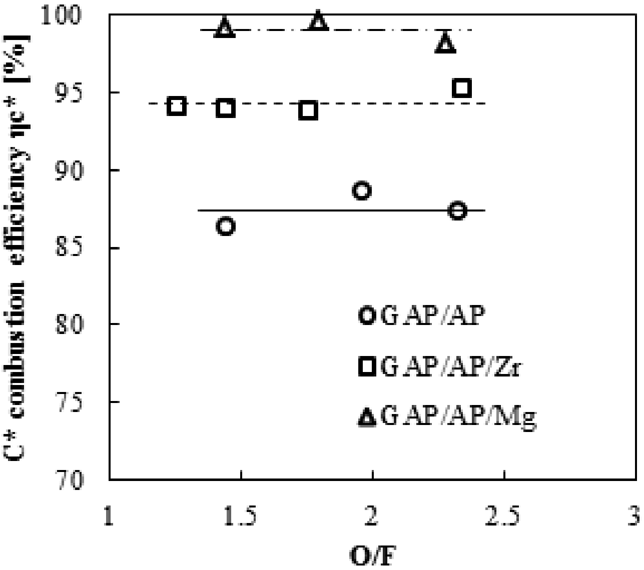



Figure 8 Relation between O/F ($N_2O$/fuel) and $C^*$ combustion efficiency.

particles. Moreover, the $\eta_{c^*}$ was increased more by the addition of Mg than by the addition of Zr. Therefore, the metal particle combustion improved combustion in the secondary combustor. Result shows that the addition of gas-phase combustion metal particles presents the benefit of decreasing the secondary combustor length. The addition of the gas-phase combustion metal particles is more effective to improve gas hybrid rocket combustion characteristics.

## 5. Conclusions

(1) The ignition delay time of Zr particles is shorter than that of Mg particles. The ignition delay time decreases concomitantly with decreasing $N_2O$ temperature. The chemical ignition delay time is shorter than the physical ignition delay time. The ratio of the chemical ignition delay time is about 20% at 1100 K. Consequently, Zr and Mg particles can ignite rapidly in the secondary combustor.

(2) The $C^*$ combustion efficiency of the gas hybrid rocket is improved by the addition of metal particles. The effects of Mg particles are greater than those of Zr particles. The addition of the gas-phase combustion metal particles is more effective to improve the gas hybrid rocket combustion characteristics.

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