Research paper

Ignition characteristics of metal particles for gas hybrid rockets

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 address : csko12002@g.nihon-u.ac.jp

Received : November 29, 2011 Accepted : July 17, 2012

Abstract

Gas hybrid rockets burn a fuel rich hot gas and a liquid oxidizer. We selected N_2O for the liquid oxidizer and Glycidyl Azide Polymer (GAP) propellant for the gas generator. Nitrous oxide has high enough vapor pressure to use self-pressurized liquid oxidizer. GAP is high energy material. The burning rate of the GAP propellant is high. However, the temperature of the mixture gas is low, because the fuel rich hot gas mixed with the liquid oxidizer. Therefore, it is thought that the combustion efficiency of the gas hybrid rocket is decreased. A method to increase the temperature of the mixture gas is the addition of metal particles to the GAP propellant. The addition of the metal particles increases the temperature of the fuel rich hot gas and mixture gas. The metal particles should ignite in the mixture gas. However, it is considered that the metal particles cannot ignite in the mixture gas because the metal particles are cooled by mixture gas. Therefore, we investigated ignition characteristics of the metal particles using two combustion type particles, which have gas-phase combustion and surface combustion. In the results, ignition delay time of the metal particles was shortened with increasing the temperature of N_2O atmosphere, and the metal particles could ignite in the mixture gas.

Keywords : gas hybrid rocket, nitrous oxide, ignition, zirconium, magnesium

1. Introduction

Hybrid rockets burn a solid fuel and a liquid oxidizer. Therefore, hybrid rockets obtain their thrust. The main advantage of hybrid rockets is safety during fabrication, storage, and operation without any possibility of explosion or detonation.

Figure 1 shows the general structures of hybrid rockets. Conventional hybrid rockets burn solid fuel and liquid oxidizer in the combustion chamber. Decreasing the combustion efficiency is a problem with conventional hybrid rockets.

A new concept for hybrid rockets is the gas hybrid rocket. Unlike conventional hybrid rockets, the gas hybrid rocket has a two-stage combustion system[1),2)]. The liquid oxidizer is injected into the secondary combustor. The fuel rich hot gas is generated in the primary combustor, which is injected into the secondary combustor. The fuel rich hot gas reacts with the liquid oxidizer. We selected nitrous oxide (N_2O) for the liquid oxidizer and Glycidyl Azide Polymer (GAP) propellant for the gas generator. Nitrous oxide has enough vapor pressure to use self pressurized liquid oxidizer. Glycidyl azide polymer is a high energetic material. The burning rate of GAP propellants is high[3),4)]. Therefore, we use a GAP propellant for the gas generator.

The temperature of the mixture gas is low, because the fuel rich hot gas mixed with the liquid oxidizer. Therefore, it is thought that combustion efficiency of the gas hybrid rocket is decreased. A solution to this problem is the addition of metal particles to the GAP propellant. The metal particles can be heated enough in the fuel rich hot gas and injected into the secondary combustor. Then, the metal particles ignite and burn in the secondary combustor. Therefore, the temperature of the mixture gas increases.

2. Metal particles

The metal particles should ignite in the mixture gas. We selected Zirconium (Zr) particle and Magnesium (Mg)

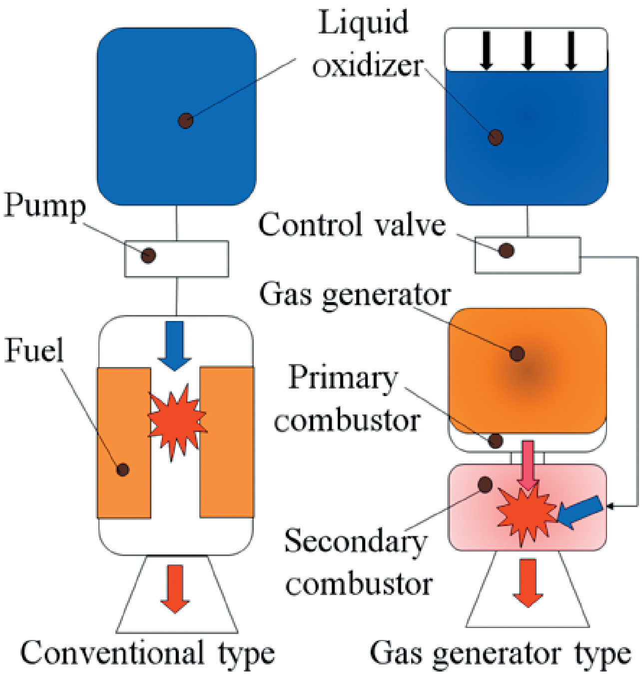

Figure 1 Structures of hybrid rockets.

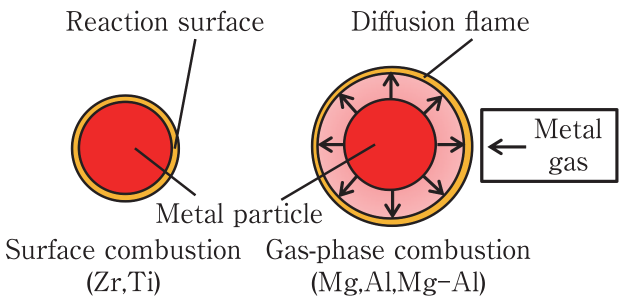

Figure 2 Combustion types of the metal particles.

particle because Zr particle and Mg particle ignite easily, compared with other metal particles.

There are two types of the metal particles, which are a gas-phase combustion type and a surface combustion type. It is thought that the combustion characteristics of the gas hybrid rocket containing the metal particles are changed by the combustion types of the metal particles. The combustion characteristics of the gas hybrid rocket containing the metal particles are not investigated. Therefore, we used two combustion types of the metal particles. Figure 2 shows combustion types of the metal particles.

Zr particle is the surface combustion metal particle. Mg particle is the gas-phase combustion metal particle. Gas-phase combustion metal particles generate the gas over the surface[5]. The metal particles are cooled in the mixture gas. Gas-phase combustion metal particles are easier to cool than surface combustion metal particles because gas-phase combustion metal particles generate the metal gas. It is considered that gas-phase combustion metal particles are more difficult to ignite than surface combustion metal particles in the mixture gas.

3. Experimental

3.1 Ignition delay time of the metal particles in N_2O atmosphere

Metal particles should ignite and burn in the secondary combustor. However, ignition characteristics of metal particles in N_2O atmosphere have not been studied. We investigate ignition delay time of metal particles in N_2O atmosphere. Figure 3 shows the experimental apparatus.

Ignition delay time is composed of physical ignition delay time τ_p and chemical ignition delay time τ_c. Physical ignition delay time includes the physical process in the temperature increase of the metal particle. Chemical ignition delay time includes the time from glow to burn. Ignition delay time τ_{ig} is defined as follows

$$\tau_{ig} = \tau_p + \tau_c \tag{1}$$

Therefore, chemical ignition delay time is defined as follows

$$\tau_c = \tau_{ig} - \tau_p \tag{2}$$

There is no probability of the ignition in the physical process[6]. Physical ignition delay time is shown in Figure 4.

3.2 Theoretical analysis

We calculate the temperature of the mixture gas T_m by

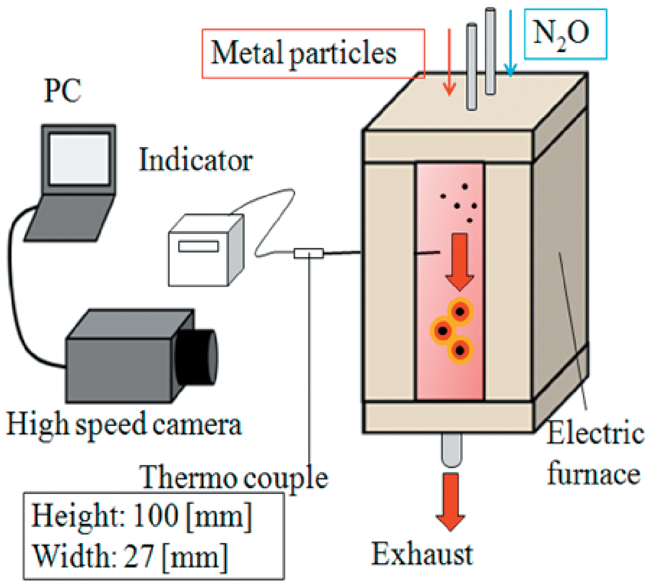

Figure 3 Experimental apparatus for ignition delay time.

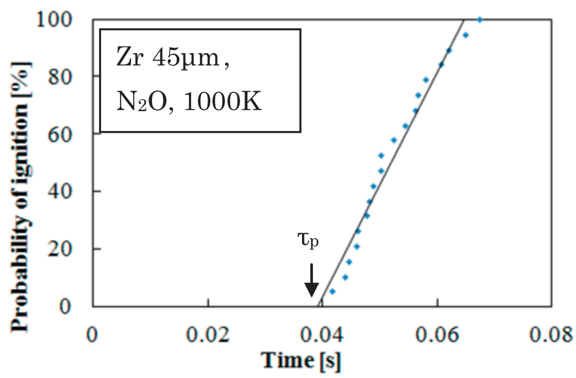

Figure 4 The definition of physical ignition delay time.

Table 1 Calculation conditions.

Pressure P [MPa]	0.1
Temperature T_{N2O} [K]	298.15
Particle size D [μm]	45

using Chemical Equilibrium with Applications[7] (CEA). The temperature T_m was defined as follows

$$T_m = \frac{C_{pg} T_g + \varepsilon C_{pN_2O} T_{N_2O}}{C_{pg} + \varepsilon C_{pN_2O}} \quad (3)$$

where the C_p was isopiestic specific heat, and suffixes g and N_2O were the fuel rich hot gas and nitrous oxide. Temperature T_g was the fuel rich hot gas temperature. Temperature T_{N2O} was the temperature of N_2O. The ε was the mixture ratio of the mixture gas. The surface temperature of the metal particles T_s was calculated by using the energy balance equation. The energy balance equation is defined as follows

$$h\pi D^2 (T_m - T_s) = \frac{\pi}{6} D^3 C_{pmetal} \rho \frac{dT_s}{dt} \quad (4)$$

where the t was time. The h was coefficient of heat transfer of the metal particles. The constant D was the diameter of the metal particles. The constant ρ was density of the metal particles. The suffix metal was the metal particle. Thermal conductively λ is defined as follows

$$\lambda = \frac{hD}{Nu} \quad (5)$$

where the Nu was Nusselt number. We assumed $Nu = 2$ because the metal particle size is small. The λ was thermal conductivity. Equation (4) can be expressed as follows using Equation (5).

$$T_s(t) = T_m + \{T_s(0) - T_m\} e^{-\left(\frac{12\lambda}{C_{pmetal} D^2 \rho}\right)t} \quad (t \geqq 0) \quad (6)$$

The metal particles should ignite and burn in the secondary combustor. The surface temperature of the metal particles decreases with the decrease of the temperature of the mixture gas. Therefore, the metal particles cannot ignite and they are exhausted to the outside of the secondary combustor.

Figure 5 shows the theoretical temperature history of the metal particles T_s in the mixture gas. Table 1 shows the calculation conditions. The thermal conductivity λ, isopiestic specific heat C_p, and density ρ was the value of the metal particles at 298.15 K.

From Figure 5, the surface temperature of the surface combustion metal particles was cooled slowly in the mixture gas. Gas-phase combustion metal particles are easier to cool than surface combustion metal particles because the isopiestic specific heat of the metal gas is low. Therefore, we investigated the ignition characteristics of the metal particles in the mixture gas.

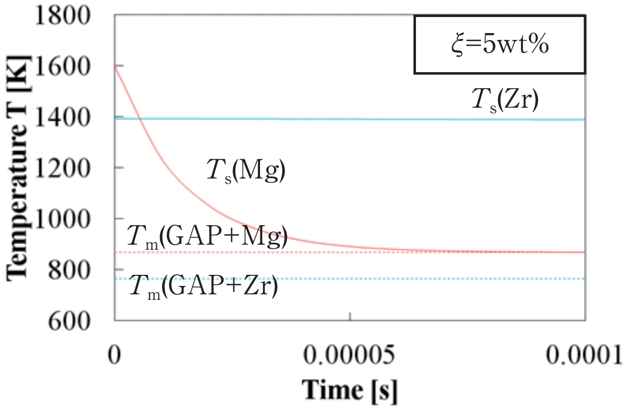

Figure 5 Relationship between the surface temperature of metal particles and residence time.

4. Results and discussion

Figure 6 shows the experimental results of ignition delay time in N_2O atmosphere. The metal particles were used Mg and Zr. Average particle diameters were 45 μm. The experiment was repeated 20 times per each condition. The ambient pressure was the atmosphere pressure.

From Figure 6, ignition delay time of the metal particles was shortened with increasing the temperature of N_2O atmosphere.

Figure 7 shows chemical ignition delay time in N_2O atmosphere. From Figure 7, chemical ignition delay time of the metal particles is shortened with increasing temperature of N_2O atmosphere.

Ignition delay time of the metal particles was related to the surface temperature of the metal particles. Because

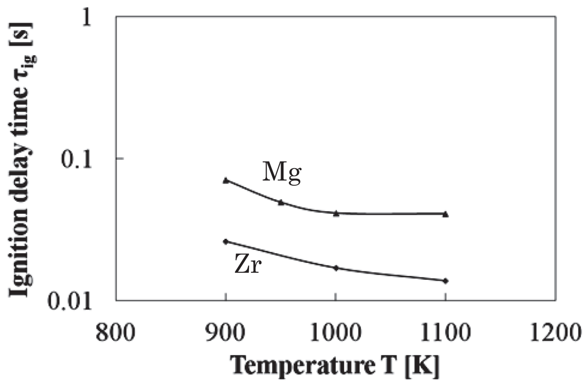

Figure 6 Ignition delay time in N_2O atmosphere.

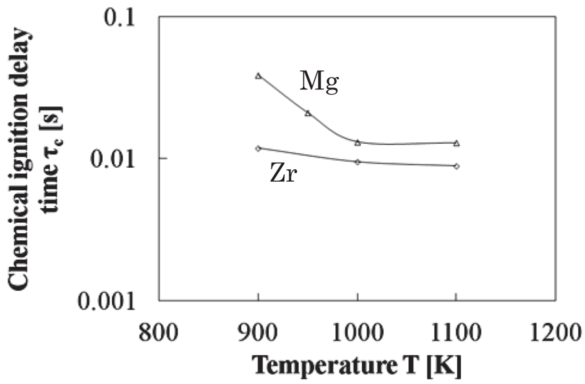

Figure 7 Chemical ignition delay time in N_2O atmosphere.

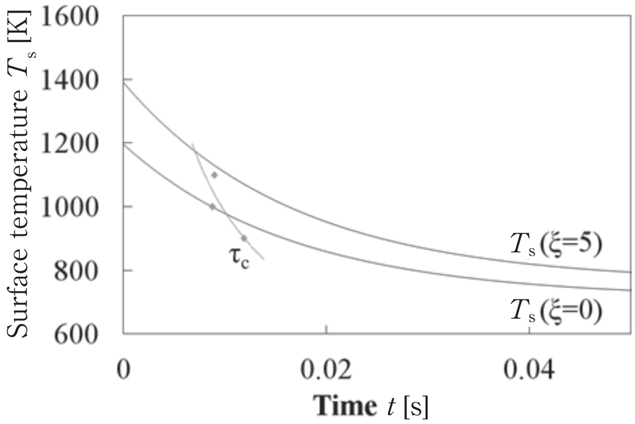

Figure 8 Relationship between surface temperature and τ_c of Zr particle (45 μm).

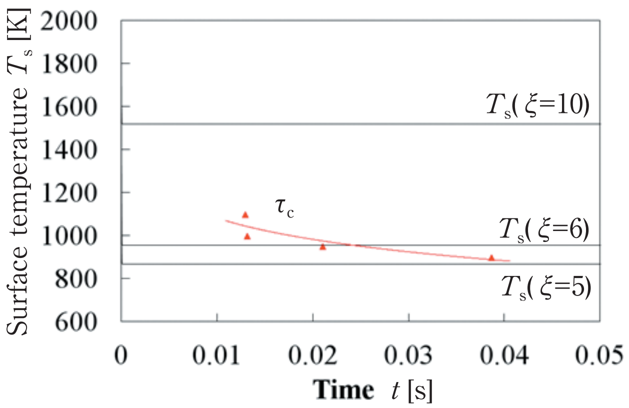

Figure 9 Relationship between surface temperature and τ_c of Mg particle (45 μm).

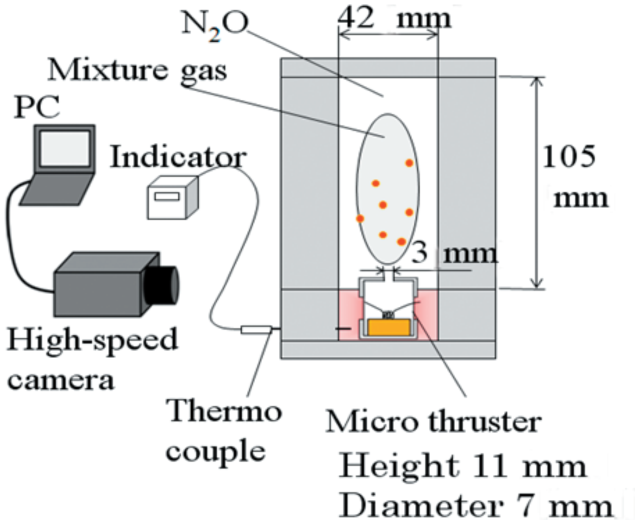

Figure 10 Experimental apparatus of the micro thruster.

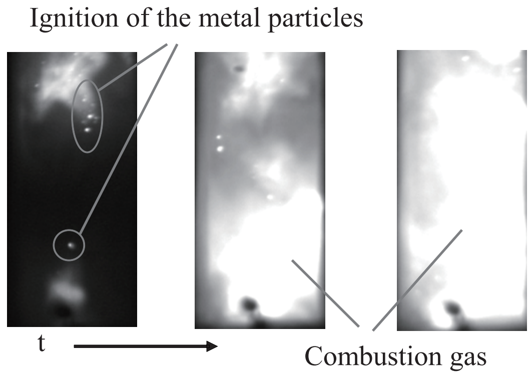

Figure 11 Photograph of the ignition of the metal particles and combustion of the mixture gas.

the mixture gas temperature decreases, we investigated refrigeration of the surface temperature of the metal particles. Therefore, we calculated the surface temperature of the metal particles by using Equation (6).

The metal particles could ignite in the mixture gas when the following was realized.

$$T_s(\tau_c) < T_s(\xi = a) \tag{7}$$

where the temperature $T_s(\tau_c)$ was the temperature when chemical ignition delay time was measured. The a was the constant, and ξ was the additive amount of the metal particles. When Equation (7) was not satisfied, the metal particles could not ignite in the mixture gas. When Equation (7) was satisfied, chemical ignition delay time was completed before the metal particles was cooled. Therefore, the metal particles could ignite in the mixture gas.

Figures 8 and 9 show the relationship between the surface temperature history and chemical ignition delay time. From Figure 8, Zr particles ignited in the mixture gas when the additive amount of Zr particles was small because the chemical reaction was completed before the surface temperature decreased. From Figure 9, when the additive amount of Mg particles was less than 5 wt%, Mg particles could not ignite in the mixture gas because they were cooled by the mixture gas. Additionally, Mg particles were exhausted from the secondary nozzle. When the additive amount of Mg particles was larger than 6 wt%, Mg particles ignited and burned in the mixture gas.

We investigated the ignition characteristics of the metal particles in the mixture gas. Figure 10 shows the experimental apparatus.

The fuel rich hot gas was injected into N_2O atmosphere by using a micro thruster. The micro thruster was heated to 473 K to burn the GAP propellant at atmosphere pressure. Figure 11 shows photographs of the combustion gas. In Figure 11, the gas generator used GAP+Zr10wt%.

From Figure 11, the metal particles ignited in the mixture gas. Therefore, the metal particles containing the GAP propellant were injected with the fuel rich hot gas into the secondary combustor and they ignited. When the metal particles burned in the secondary combustor, the temperature of the mixture gas increased. Therefore, it is thought that combustion efficiency increases by containing the metal particles in the GAP propellant.

5. Conclusions

(1) Ignition delay time of the metal particles is shortened by increasing N_2O temperature.

(2) Zirconium particles can ignite in the mixture gas when additive amount is low.

(3) Magnesium particles can ignite in the mixture gas when additive amount is larger than 6 wt%.

6. References

1) N. Kubota, "Propellant and explosives", WILEY-VCH, 430−437 (2007).
2) George P. Sutton, "Rocket Propulsion Elements", John Wiley & Sons, Inc., 502−506 (1992).
3) T. Kuwahara, M. Mitsuno, H. Odajima, S. Kubozuka, and N. Kubota, "Combustion Characteristics of Gas Hybrid Rockets", AIAA Paper 1994, 2880 (1994).
4) N. Kubota, et al, "Propellant handbook", Japan Explosives Society, 309−342 (2005), (in Japanese).
5) S. Yuasa, "Characteristics of Ignition and Combustion of Metals", Journal of the Combustion Society of Japan 45 152−163 (2003), (in Japanese).
6) S. Kumagai, "Combustion", Iwatani Syoten, 64−72 (1976), (in Japanese).
7) S. Gordon and B. J. McBride, "Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications," NASA Reference Publication 1311 (1996).

ガスハイブリッドロケット用金属粒子の着火特性

松本　幸太郎*†，桑原　卓雄*

ガスハイブリッドロケットは高温の燃料過剰ガスと液体酸化剤を燃焼させる。我々は，液体酸化剤に亜酸化窒素（N_2O）を，ガスジェネレーターにグリシジルアジ化ポリマー（GAP）推進薬を選定した。N_2Oは自己加圧方式を用いるのに十分な蒸気圧を持っている。GAPは高エネルギ物質であり，燃焼速度が大きい。ガスハイブリッドロケットは燃料過剰ガスと液体酸化剤を混合させるため，混合ガス温度が低下してしまう。よって，燃焼効率が低下すると考えられる。混合ガス温度を向上させる方法の一つに，GAP推進薬への金属粒子の添加が挙げられる。GAP推進薬に金属粒子を添加することで燃料過剰ガス温度及び混合ガス温度が上昇する。金属粒子は混合ガス中で着火し，燃焼しなければならない。しかし，金属粒子は混合ガス中で冷却されてしまう。そこで，我々は気相燃焼方式と表面燃焼方式の２つの燃焼方式の異なる粒子を用いて混合ガス中での金属粒子の着火特性を調べた。その結果，金属粒子の着火遅れ時間はN_2O雰囲気の温度が上昇すると短くなる。また，金属粒子は混合ガス中で着火することが得られた。

*日本大学理工学部航空宇宙工学科　〒274−8501　千葉県船橋市習志野台7−24−1
Phone : 047−469−5317
†Corresponding address : csko12002@g.nihon-u.ac.jp