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Flame Structure Measurement of Burning Boron Particles in High Temperature Air

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Abstract: Ducted rockets are one kind of ramjet engines which are air-breathing propulsion systems. Boron is the most suitable material for the fuel of ducted rockets in terms of its high combustion heat. In this study, flame structure of burning boron particles was measured by schlieren photography to obtain combustion characteristic in high temperature air. Boron particles burned in two stages separately. Flame front was appeared around the particles, and temperature distribution in the flame front was calculated.

1. Introduction

Ducted rocket engines are one kind of ramjet engines. Figure 1 shows fundamental structure of a ducted rocket engine. When a ducted rocket operates at supersonic flight, supersonic air is compressed by shockwaves at air-intakes, and becomes ram air. In parallel, the gas generator which is composed of solid propellant generates fuel-rich hot gas in the primary combustor. The fuel-rich hot gas is fed to the secondary combustor in which combustion process occurs with the ram air. The combustion gas is ejected through the secondary nozzle, and the ducted rocket engine propels in the atmosphere.

The ducted rocket can obtain high specific impulse with using fuel materials which evolve high combustion heat per unit mass in the air. Boron is the most suitable material with the exception of beryllium which produces toxic compounds and lithium which has high reactivity. The ducted rockets obtain over 1000 seconds of specific impulse with boron-added gas generator in theory.

Boron particles added in the gas generator are heated and injected to the secondary combustor with fuel-rich hot gas, and they ignite with touching the air. The air becomes high temperature by combustion of fuel-rich gas. It is necessary to obtain combustion characteristics of boron particles in the high temperature air. In this study, flame structure of burning boron particles was measured by schlieren photography.

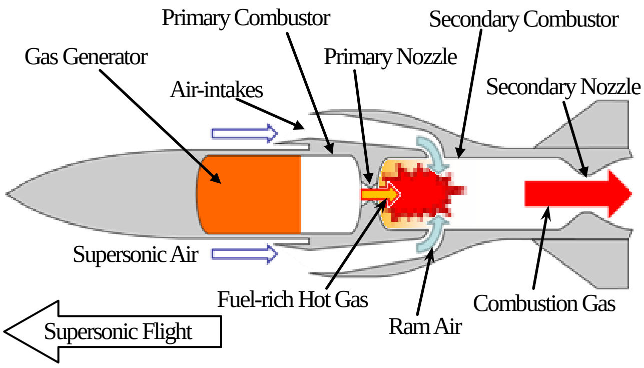

Figure 1. Fundamental structure of a ducted rocket

2. Experiment

Figure 2 shows the experimental apparatus for measuring flame structure of burning boron particles. It consisted of a schlieren optical system, a high speed camera and an electric furnace. The electric furnace had two tube-shaped heating elements on upside and downside of an observation zone. The observation zone was visualized with two horizontally-mounted quartz windows. The temperature in the observation zone had kept constant at 1120 K. This temperature simulated mixed gas of fuel-rich hot gas and ram air. Boron particles were set on the mesh fixed on the bottom of the plastic bottle. With vibrating and pushing the bottle, particles were injected to the observation zone with the air instantaneously at room temperature. Combustion behavior was recorded by a high speed camera at 600 fps. The specimen was amorphous boron particles with an initial average diameter of 2 μm.

3. Results and discussion

3.1 Combustion behavior of boron particles

During combustion, flame front appeared around the luminous flame of burning boron particles. The flame front diameter is

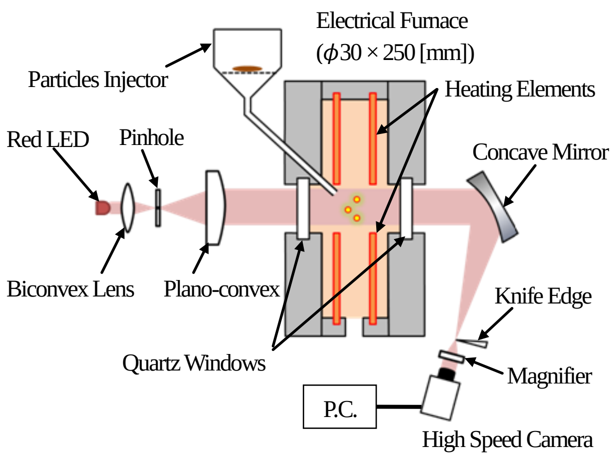

Figure 2. Experimental apparatus

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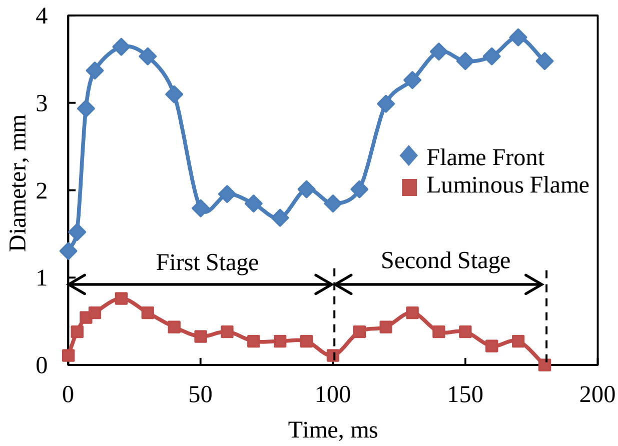

Figure 3. Typical Series of Time History of Flame Front Diameter and Luminous Flame Diameter

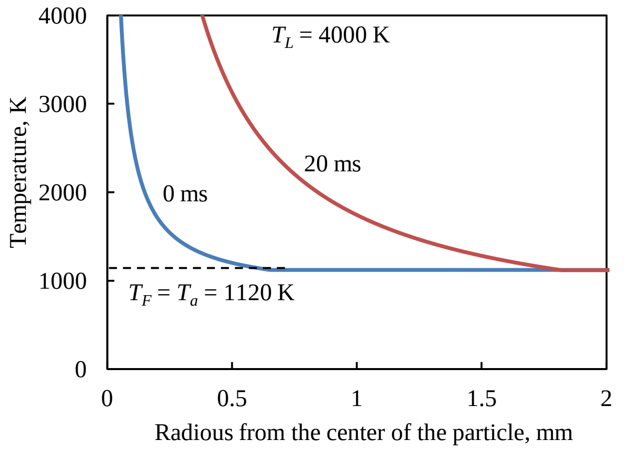

Figure 4. Temperature Distribution around the Burning Boron Particles

defined as horizontal width of the flame fronts through the center of a particle. Figure 3 shows a typical time history of flame front diameter and luminous flame diameter. Combustion of boron particles can divide in two stages at the local minimum of luminous flame diameter.

In the first stage, it is believed that boron particles were covered with oxide layer. In contrast, the particles were bare in the second stage. The boron particles burn in gas phase through overall combustion process because the luminous flame diameter is very large despite initial average diameter.

The change of flame front diameter seems to link with the change of luminous flame diameter. However the flame front diameter was approximately constant at the end of boron particle combustion even through the luminous flame diameter decreased. The inside of flame front became shadow gradually with low luminescence intensity area. The low intensity area shows condensed and diffused boron oxide(B_2O_3).

3.2 Temperature distribution around boron particles

Figure 4 shows the temperature distribution around boron particles at each time. The spherical temperature distribution was obtained with one-dimensional heat equation as follows:

$$\frac{d}{dr}\left(\lambda r^2 \frac{dT}{dr}\right) = 0 \qquad (1)$$

, where r was the radius from the center of the particle, λ was thermal conductivity, T was temperature. The boundary conditions at the radius of luminous flame r_L and flame front r_F were assumed as follows. The temperature T_L at r_L was the adiabatic flame temperature of boron combustion, and T_L was 4000 K. The temperature T_F at r_F was equal the ambient temperature T_a.

The temperature distribution around the particle spread gradually with time. When the time is 20 ms, high temperature region over 2000 K is approximately 0.8 mm in radius. This is two times larger than a half of the luminous flame diameter. Boron particles can form high temperature region in the secondary combustor.

4. Conclusion

1) Boron particles burn in two stages. The flame front which is going to be B_2O_3 appears around the particles during the combustion.
2) High temperature region distributes widely around the burning boron particles.

5. References

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