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Effects of nitrogen film cooling on flame structures in ignition transition

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Abstract

The objective of this paper is to observe the effects of nitrogen film cooling on flame structures in ignition transition. Gaseous oxygen and liquid kerosene were used as propellants, and the shear coaxial injector was used to inject propellants. In order to study effects of the nitrogen film cooling on the flame structures, the dynamic pressure transducer is established to detect over-peak pressure and pressure rise time, and the high-speed camera is set up to obtain visualized flame structures. The over-peak pressure and pressure rise time were detected in cases with film cooling. With the increase in the differential pressure between the combustion chamber pressure and injection pressure of the film coolant, the over-peak pressure decreased. Also, the pressure rise time increased as the differential pressure increased. In this paper, these phenomena are explained by the interruption of normal propellant injection in the propellant mixing zone. Flame structures were recorded to confirm the unstable flame structures in cases of injected the film coolant.

1 Introduction

Ignition is one of the important processes in the liquid-fueled rocket launches because unstable ignition processes, such as overshoots and ignition delay, may damage rocket systems (Manski et al. 1998, Sutton, 2003). Over-peak pressure at the initial ignition could damage the propellant injection system and combustion chamber, thus deteriorating the performance of the liquid rocket engine. Ariane V18 had problems at initial ignition and the ignition process was shut down soon after ignition starts (Gastal et al., 1988). The unsteady heat release due to unstable ignition causes an unsteady pressure in the combustion chamber, and affects the vibration of the rocket structure and oscillation of the reactant flow rate. In other words, the unsteady heat release at the initiation moment in a combustion reaction induces a pressure fluctuation (Anderson et al., 1998, Sliphorst et al., 2011). Consequently, combustion instability could be occurred and impedes the rocket engine system. The combustion instability phenomenon such as ignition, propellant mixing, and chemical kinetics during the combustion has been observed in numerous researches of liquid-fueled rocket engines and has been studied from many years. However, the cause of the unstable ignition has not been clearly understood because of the complex relationships.
In addition, the combustion chamber undergoes numerous hot fire tests in laboratory scale tests. Therefore, it should be protected from the combustion gases, which are at high pressure and temperature. For the cooling system of the liquid rocket engine, film cooling with a regenerative cooling channel has been used in the first stage engine in that it helps in reducing the convective heat transfer on the surface of the combustion chamber wall (Arnold et al., 2010, Hessam et al., 2014).

2 Experimental Setup

The combustion chamber was established as Fig. 1. In this study, the shear coaxial injector was used for injection, and the gaseous oxygen and liquid kerosene was injected for propellants. The gaseous oxygen was sprayed through the annular gap between the outer diameter and inner diameter of injector. The outer and inner diameters of the liquid injector are 3 and 1.5 mm, respectively. The combustion chamber diameter is 22 mm: its length is 182 mm: and the diameter at the nozzle throat is 6.4 mm. Also, the spark plug (NGK CR9EIX) was used to supply ignition energy with 90 mJ, and its value was fixed in all cases. Pressurant tank was used to supply the liquid fuel. The gaseous oxygen was injected directly from the oxidizer tank, and its mass flow rate was controlled by the orifice, which is located right before the injection. For the injection of the film cooling, gaseous nitrogen was sprayed between the outer body of the injector and the combustor with a gap of 0.75 mm.
Check valves in supply lines were established to prevent flame backfire from the combustion chamber to the propellant lines. The mass flow rate of propellants was calculated by the data from the volumetric turbine flow rate and density, which in turn were estimated from the temperature and static pressure.
Chemiluminescence is related to the phenomenon of spontaneous photon emission. In order to observe the effects of the film cooling on the flame structures, the CH* chemiluminescence images were recorded using the high-speed camera with a 430 nm band pass filter.
The experiments in this study were performed to obtain the effects of film coolant on the ignition transition. This study was focused on the comparison between the presence and absence of film cooling. Gaseous nitrogen for film cooling gas was injected with the different pressures during the combustion. In all cases, the propellant injection pressure was maintained with the same pressure. The combustion chamber pressure was approximately 1.7 MPa, and the oxygen and fuel injection pressures were approximately 2.0 MPa during the steady state condition. The film cooling gas was injected by varying the pressure from 1.89 MPa to 2.39 MPa, thus the differential pressure between the combustion chamber and injected film cooling gas was calculated from 0.19 MPa to 0.69 MPa.

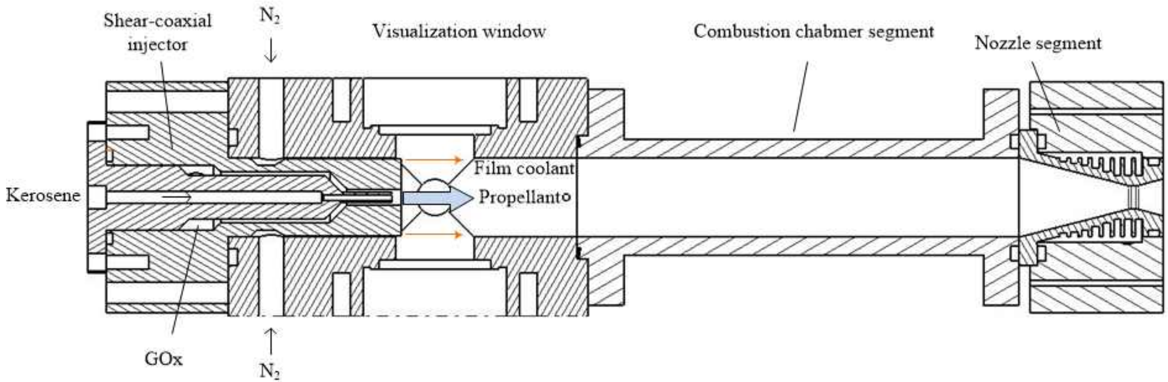


Figure 1: Schematic of combustion chamber

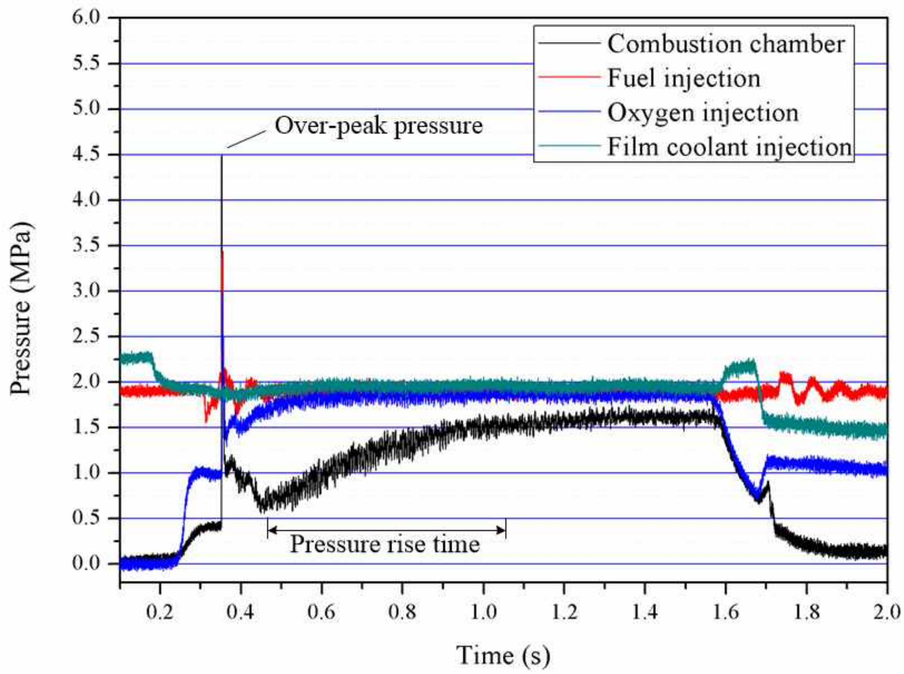


Figure 2: Calculation methods of over-peak pressure and pressure rise time

3 Results and Discussion

Fig. 2 represents the calculation method of over-peak pressure and pressure rise time. The pressure rise time was defined as time from the initial ignition to steady state condition. The over-peak pressure at the initial ignition process is one of the most important situations because it causes the problem such as the structural destruction. Fig 3 shows the over-peak pressure with respect to the differential pressure between the combustion chamber and film cooling injection pressure. There is no over-peak pressure in the case of absence film cooling gas. The over-peak pressure decreased with increases of the differential pressure as shown in Fig. 3. At low differential pressure, the over-peak pressure was measured to be approximately 4.0 MPa. Its value converged to the combustion chamber pressure as the differential pressure increased.

Fig. 4 shows the pressure rise time with respect to the differential pressure. The pressure rise time increases with the increase in the differential pressure. The pressure rise time in the case of the low differential pressure was calculated to be 674 ms, whereas It was 1110 ms at high differential pressure. However, the case in the absence of film cooling was calculated to be 218 ms.

The reason of these phenomena is that nitrogen film cooling injection affects the mixing and atomization of the injected propellant at initial ignition. In order to obtain stable ignition, an appropriate mixing and atomization conditions are necessary. However, the injected propellant was disturbed to mix and atomize well by the injected film cooling gas. In other words, the injected film cooling gas was coexisted in the mixing zone of propellant at initial ignition. As results, the unstable ignition was occurred with over-peak pressure and pressure rise time. The differential pressure between the combustion chamber and injected film cooling gas pressure increased to increase the momentum flux of film cooling gas. The high momentum flux of film cooling gas allows the propellant to be mixed and atomized well. Additionally, the high differential pressure disturbs the flame development during the ignition transition, thereby increasing the pressure rise time until the steady state condition.

The cross section of the flame recorded using the high-speed camera to visualize the effects of film cooling on the flame structure. The inverse Abel transform was performed to obtain the boundary layer of

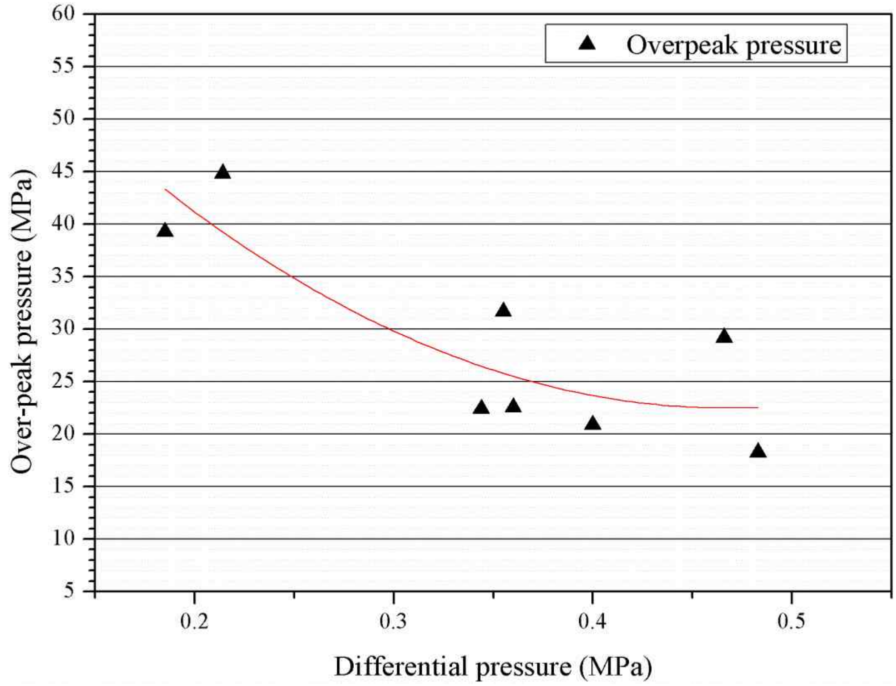


Figure 3: Over-peak pressure with respect to the differential pressure.

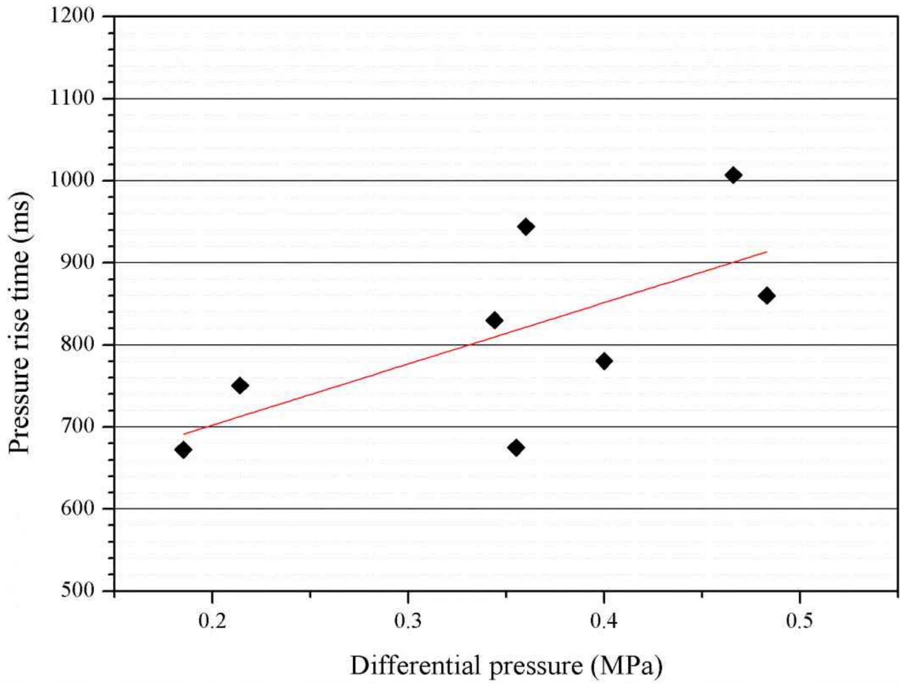
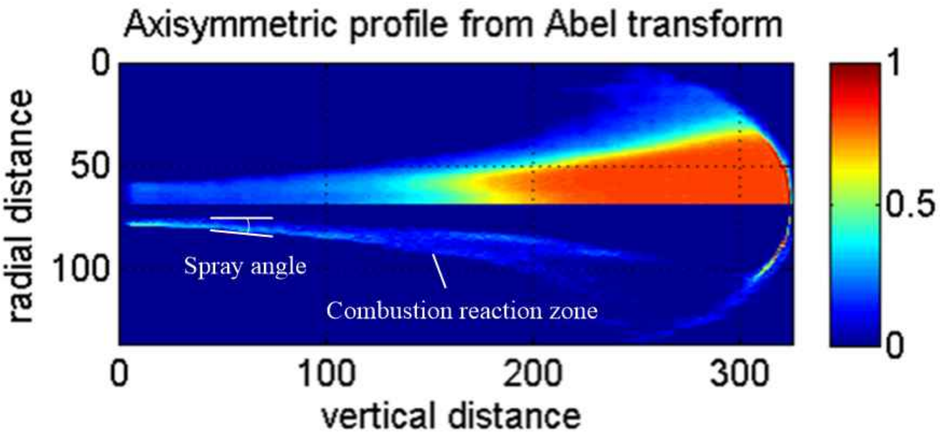
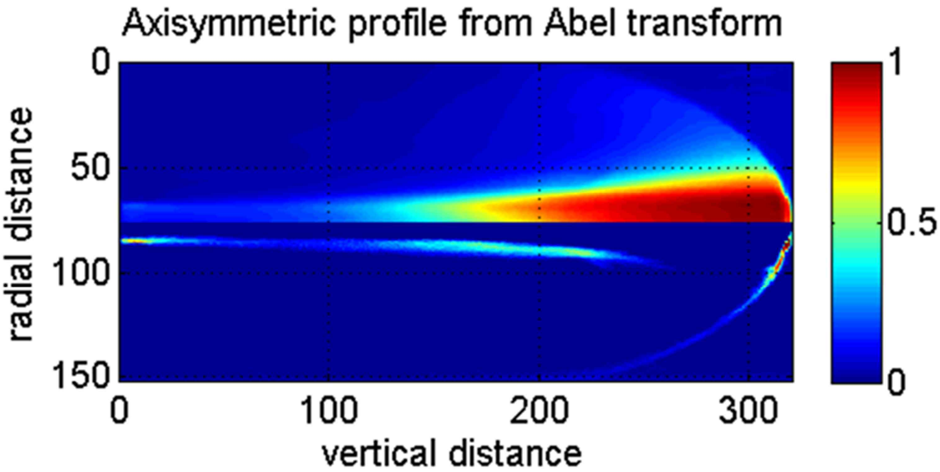


Figure 4: Pressure rise time with respect to the differential pressure



(a)



(b)

Figure 5:Visualized images of CH* chemiluminescence under different conditions: (a) without film cooling, (b) with film cooling

sprayed propellant. Fig. 5(a) represents the case without the film cooling gas, and Fig. 5(b) shows the image in the case with the film cooling gas. The difference by the film cooling gas is intensity and spray angle. Chemiluminescence intensity at the vicinity of injector in the case with the film cooling gas shown in Fig. 5(b) is higher than the case without the film cooling gas shown in Fig. 5(a). Also, compared to the case of absence the film cooling gas, the spray angle decreased with film cooling gas injection.

4 Conclusion

A stable ignition at initial combustion process is important in terms of the safety of liquid-fueled rocket systems. In order to protect the combustion chamber wall, the film cooling system was used in this study. The gaseous nitrogen was selected as the film cooling gas. In this study, an experiment was designed to observe the effects of the nitrogen film cooling on flame structures in ignition transition. To confirm the film coolant effects, injection conditions of the propellant was the same in all cases, and the injection pressure of the film cooling gas was varied. The analysis was performed with the data of over-peak pressure, pressure rise time and visualized flame images. The over-peak pressure was detected, and a pressure rise time was observed in the case with the injection of film cooling gas. The injected film cooling gas affected the propellant mixing zone, as a result, the over-peak pressure decreased with the increase in the differential pressure. Also, the pressure rise time increased with the increase in the differential pressure. Therefore, the flame structure was visualized to observe effects of the film cooling gas. Chemiluminescence intensity at the vicinity of injector was confirmed to increase in the case with the injection of film cooling gas. In addition, the spray angle in the case of presence film cooling gas decreased compared to the case of absence film cooling gas. In order to avoid unstable ignition, such as the occurrence of over-peak pressure, it is better to inject the film cooling gas with a high differential pressure.

Acknowledgements

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