Non-Toxic Post Boost Stage Demonstration

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Abstract

A non-toxic Post Boost Stage (PBS) with LOX/Ethanol engine was successfully demonstrated at the Tomioka Facility of IHI Aerospace. IHI Aerospace has researched and developed the non-toxic propulsion systems and the LOX/Ethanol is one of the most attractive non-toxic bipropellant candidates. ρISP of LOX/Ethanol is higher than ρISP of the other non-toxic bipropellants as LOX/HC or LOX/LH_2.

The authors studied the combustion characteristics of LOX/Ethanol propellant with the engine designed for LOX/LNG propellant. Also the injector with a built-in igniter was designed and examined its feasibility, ignition and combustion characteristics.

We have demonstrated Post Boost Stage with future LOX/Ethanol engines. This propulsion system is targeted for expandable vehicle upper stage to accelerate delta-V to reach the required orbit.

PBS Demonstration Model is designed as a test stand to evaluate feed system for integrated propulsion system and also to demonstrate Integrated Vehicle Health Management (IVHM) technique using local valve control and also valve behavior-monitoring capability.

Feature of LOX/Ethanol

Figure 1 shows the relations between specific impulse (Isp) and mixture ratio (MR) and between the bulk density of propellant and MR. Instead of highest ISP, the bulk density of LOX/LH_2 is lowest in the figure. Figure 2 shows the relations between density ISP (ρISP) and MR. This figure shows that the ρISP of LOX/Ethanol (3.55E5 [kg・s/m^3] at MR=2) is higher than that of LOX/LCH_4 (3.19E5 [kg・s/m^3] at MR=4) and of LOX/LH_2 (1.69E5 [kg・s/m^3] at MR=6), except MMH/N_2H_4 as toxic propellant. The boiling point of Ethanol is 351K at 1atm and the melting point of Ethanol is 159K. These characteristics of Ethanol are very suitable and effective for storable propellant system, in particular for PBS or upper propulsion systems those installing volumetric capacities are limited[1].

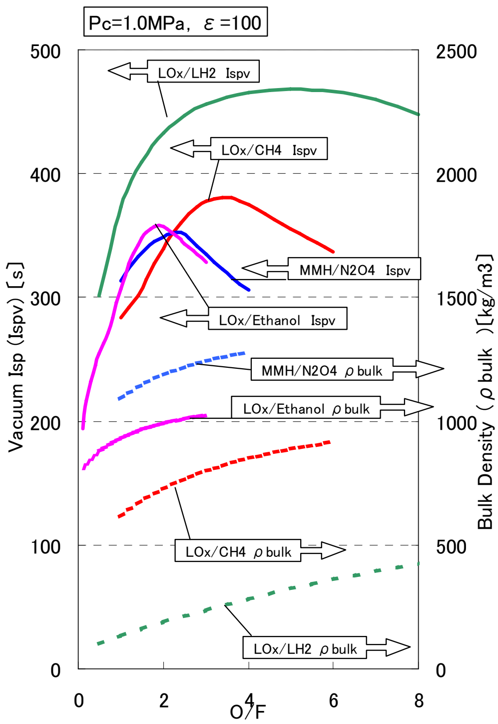

Figure 1 ISP and Bulk density vs. MR

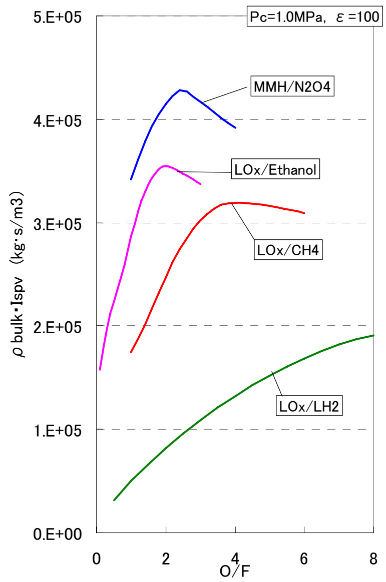

Figure 2 ρISP vs. MR

Combustion characteristic of LOX/ethanol

The combustion characteristic of LOX/Ethanol was examined based on the LOX/LNG sub-scale engine developed and researched by IHI Aerospace. Figure 3 shows the engine configuration. The injectors have like impingement elements with film cooling orifices with fuel. Two injectors with 12 and 36 elements were tested to evaluated the effects of c*efficiency. The GOX/GCH4 igniter and water-cooled chambers are same as for LOX/LNG. The distribution of heat flux was measured by the water-cooled chambers. The normal operating conditions at the normal thrust level are determined as MR of 1.7 and chamber pressure of 1.0 [MPa].

Figure 4 shows the hot firing test of LOX/Ethanol. MR was varied from 1.4 to 2.1 and chamber pressure (Pc) was varied from 0.6 to 1. The ignition and combustion was very stable through the all test MR and Pc range. The ignition characteristic of LOX/Ethanol confirmed and the responses of LOX/Ethanol engine are better than that of LOX/LNG.

Figure 5 shows the c*efficiency versus MR with two injectors at Pc = 1.0 [MPa]. It shows that c* efficiency increase with increase of MR slightly. c* efficiency of the injector with 36 elements is about 8% higher than that of the injector with 12 elements. Compared with c* efficiency of LOX/LNG with same engine, c*efficiency of LOX/Ethanol is several % low.

The distribution of heat flux was measured by water-cooled chamber. Heat flux is lowest at the injector side and highest at the area just upstream of throat as well as the LOX/LNG propellant. A remarkable coking was not confirmed on the surface of water-cooled chamber.

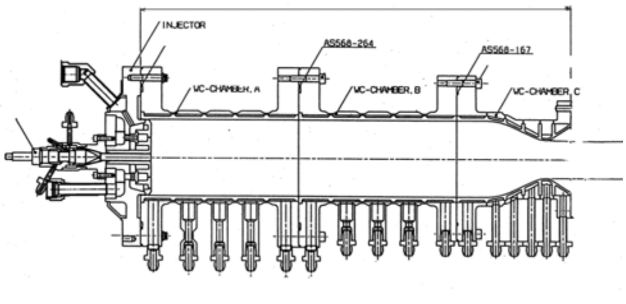

Figure 3 Engine configuration

Figure 4 LOX/Ethanol hot firing test

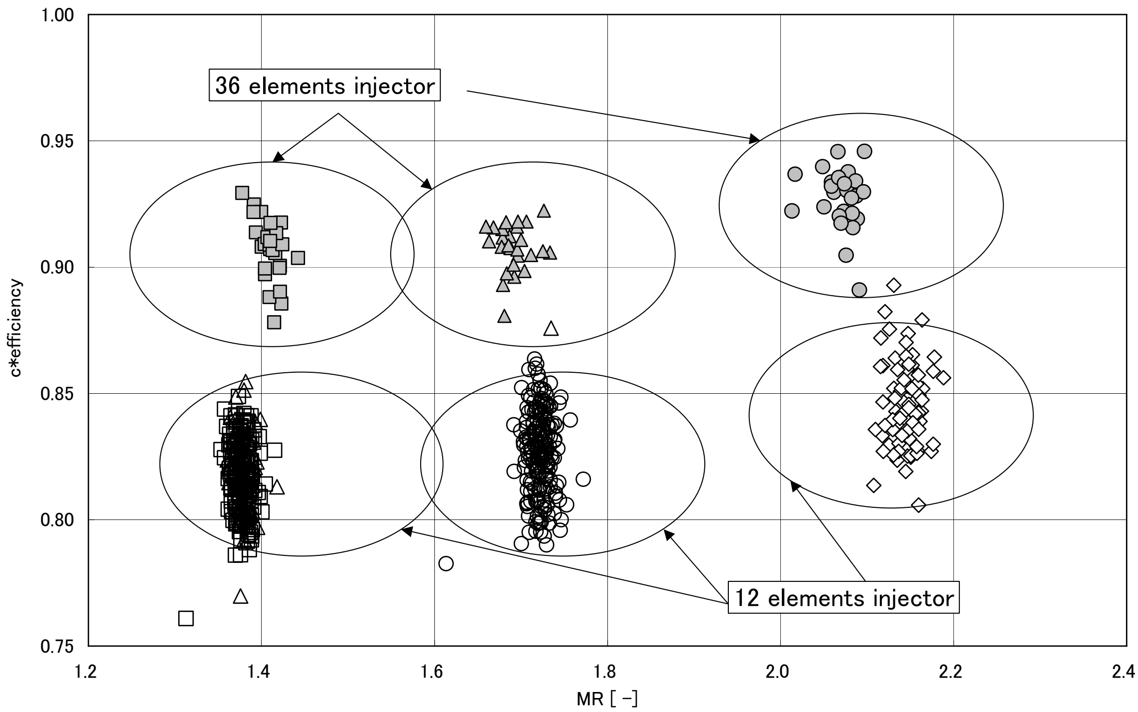

Figure 5 c*efficiency vs. MR

Engine for LOX/Ethanol

The injector with a built-in igniter was designed and examined based on the LOX/Ethanol hot firing test results with the LOX/LNG engine. Figure 6 shows the outline of the injector with a built-in igniter. The element type of this injector is like impingement basically. Igniter designed as built-in type and the fuel and oxidizer for ignition are supplied from injector manifolds respectively. With this injector, the propulsion system can omit the propellant bottles or heat exchange devices, the valves and the feed lines etc for igniter. And it would be great help to achieve high reliability propulsion system by the reduction of parts for ignition system. Additionally, it is effective to the engine that required multi burn such as RCS or PBS engines. However, with exciter plug, there is a necessity that gasification of LOX from LOX manifold certainly. Therefore, a special mechanism to gasify LOX was designed. The manifold of oxidizer for the igniter was installed around the exciter plug, and the heat exchange achieved through the acoustic cavity sufficiently.

The stable ignition and combustion were confirmed through the range of MR 0.9 to 2.2 and Pc 0.6 to 1.0 [MPa]. Figure 7 shows the hot firing test results. Multi burn or second burn after long duration firing the ignition characteristics are same as first burn and the temperature of oxidizer manifold is stable at higher than LOX boiling point.

The spectrum of plum at the nozzle exit was measured by the spectroscope as part of the health monitor method with this engine. Figure 8 shows the typical luminous intensity distribution. The luminescence such as OH, CH, and C_2 typically found in the combustion of a hydrocarbon fuels[2] were confirmed. Luminous intensity of OH at 310[nm] and CH at 431[nm] are recognized clearly, and the relation between the burn-time averaged luminous intensity and the mixture ratio is shown in figure 9. This figure shows that both of OH and CH luminous intensity increase with decreasing of MR.

The relation between the MR and luminous intensity will be one of the monitor items of IVHM that confirms the health of engine combustion status from the outside.

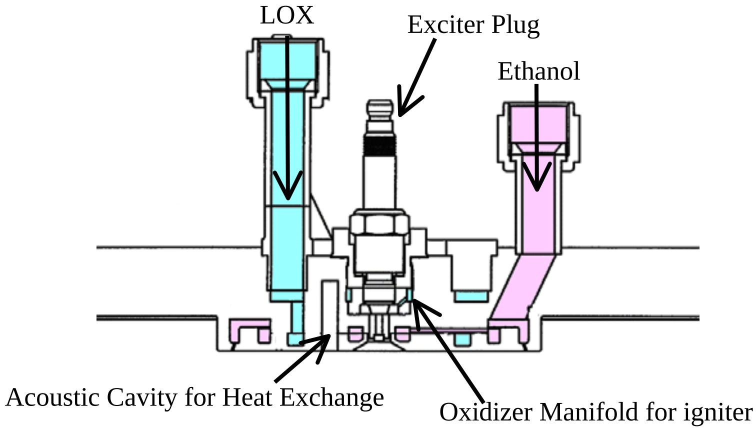

Figure 6 Injector with a Built-in Igniter

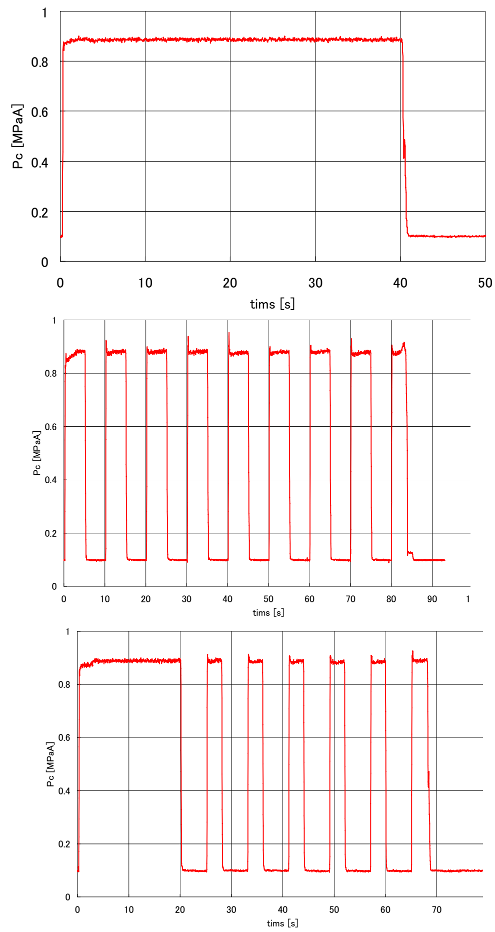

Figure 7 Hot firing test results by Injector with a Built-in Igniter

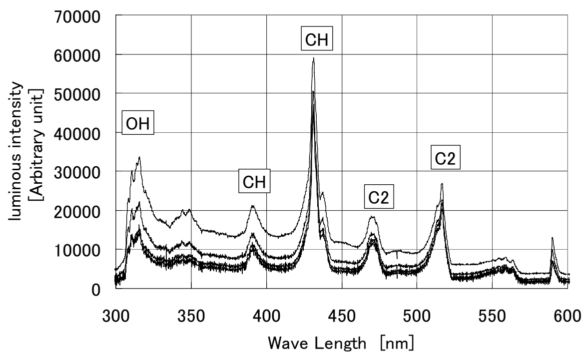

Figure 8 Luminous Intensity at the nozzle exit

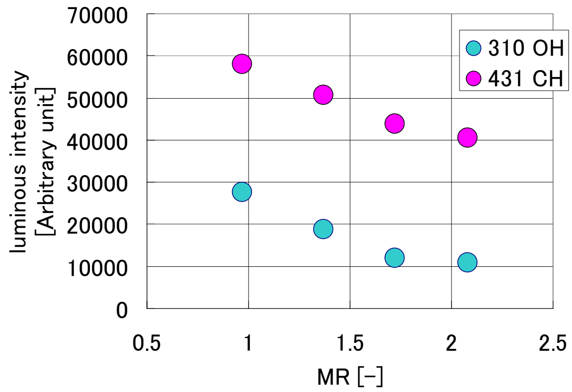

Figure 9 OH and CH Intensity vs. MR

PBS Demonstration

PBS demonstration model (shown in Figure 10) was designed as a test stand to evaluate feed system for integrated LOX/Ethanol propulsion system described above and also to demonstrate IVHM technique[3] using local valve control and also valve behavior-monitoring capability.

Demonstration Model has been developed and settled on Tomioka Facility of IHI Aerospace.

The normal operating conditions of the engine for PBS stage at the normal thrust level are determined as MR of 1.7, chamber pressure of 0.9 [MPa] and vacuum thrust of 2 [kN].

As for the valve control, we have applied Bang-Bang Control for regulated tank pressure control for LOX tank and also Ethanol tank individually by measuring the actual tank pressure and controlling the open/close of latch valve upstream each tanks for demonstration.

Cold flow test with LOX and ethanol were performed to evaluate the feed back control parameters and then firing test has been conducted.

During the cold flow, control system worked well as shown in Figure 11 for Bang Bang Control of the latch valve and also measuring the valve behavior. But at firing test level, due to the dielectric discharge of the ignition fuse, local data acquisition node network bus reset occurred and could not fully control or monitor. This was a kind of known problem for engines but new to this system as the network bus and power supply was not intended for such discharge using commercial products.

Then the tank pressure was regulated by the regulator and hot firing test was demonstrated. Figure 12 and Figure 13 show PBS hot firing demonstration result. The stable ignition and combustion were confirmed.

We achieved all purposes to confirm the procedure of propellant feeding, the measurement and control system, health monitoring system, engine sequence and the combustion characteristics, except Bang Bang Control with firing.

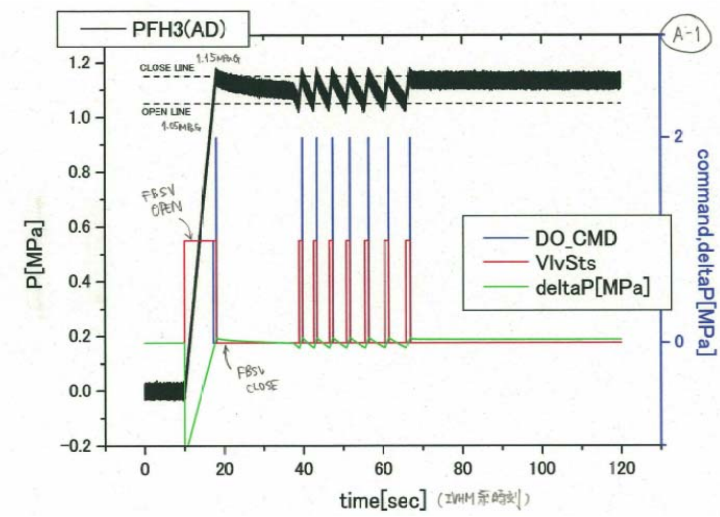

Figure 11 Bang Bang Control Result (Fuel Cold Flow Test)

Figure 12 PBS Hot Firing Demonstration

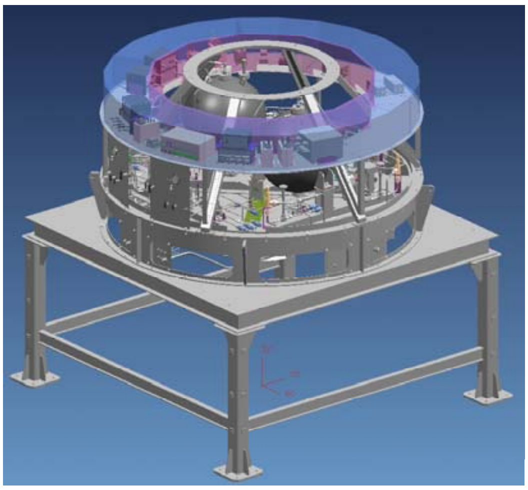

Figure 10 PBS Demonstration Model Design

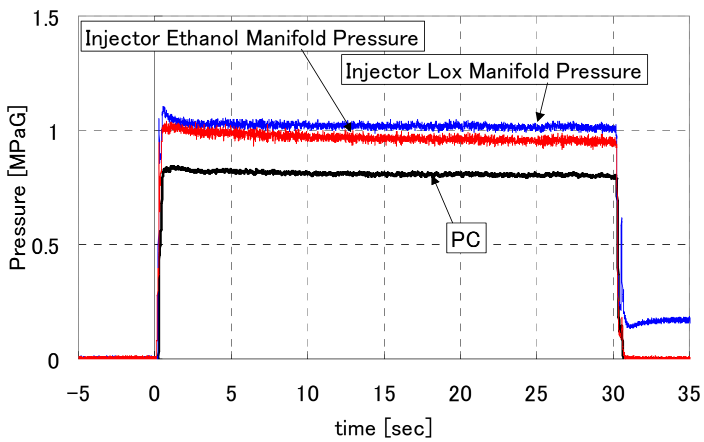

Figure 13 Hot Firing Demonstration Result

Nomenclature

PBS: Post Boost Stage
IVHM : Integrated Vehicle Health Management
MR: Mixture Ratio
ρISP: Density Specific Impulse

Conclusion

A non-toxic Post Boost Stage (PBS) with LOX/ethanol engine was successfully demonstrated at the Tomioka Facility of IHI Aerospace.

The injector with a built-in igniter was designed and examined its feasibility, ignition and combustion characteristics.

Acknowledgments

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