Ground Test of Model SCRamjet Engine with Free-Piston Shock Tunnel

Sang Hun Kang,[1] Yang Ji Lee,*[2] Soo Seok Yang,*[3] Michael Smart,*[4] Milinda Suraweera*[5]*

*[1~3]*Advanced Propulsion System Department, Korea Aerospace Research Institute*
45 Eoeun-Dong, Youseong-Gu, Daejeon, 305-333, Korea
E-mail: aeroksh@kari.re.kr

*[4,5]*HyShot Group, Division of Mechanical Engineering, University of Queensland*
Brisbane QLD 4072, Australia

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Abstract

Model Scramjet engine is tested with T4 free-piston shock tunnel at University of Queensland, Australia. Basically, test condition is fixed as Mach 7.6 at 31 km altitude. With this condition, variation effects of fuel equivalence ratio, cavity, cowl setting and angle of attack were investigated.

In the results, supersonic combustion was observed with low and middle fuel equivalence ratio. At high equivalence ratio, thermal choking was occurred due to the intensive reaction. Cavity and W-shape cowl showed early ignition and enhanced mixing respectively.

Introduction

Recently, as a promising candidate for the future transport system, scramjet engines are attaining national and international attention. It can be operated with hypersonic speed without any oxidizer storage tank which was one of the heaviest parts in rocket engines. With an advantage of its light weight, scramjet engine can be applied to reusable launch vehicle for satellites or hypersonic airplane which can realize 2 hours trips around whole world.

Many countries, such as Australia, Japan, UK and USA, are working on the scramjet engine development. Flight tests of HyShot series of Australia's consortium and X-43A of United States are recent accomplishments. Keeping pace with these world research trends, KARI (Korea Aerospace Research Institute) has been continuously doing research on the high speed propulsion system for years. Especially in 2007, KARI performed the ground test of the model scramjet engine, designed by itself, with T4 shock tunnel at University of Queensland in Australia.

In this research, test procedures and results of the ground test of model scramjet engine with T4 shock tunnel will be explained.

Experimental Apparatus

T4 shock tunnel

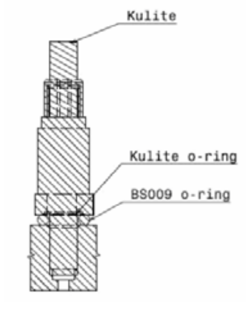
T4 is a free-piston type shock tunnel of University of Queensland and has been used for the ground test of the HyShot II and III. Results of their ground tests were validated by the flight test data comparison twice. Specification of T4 is summarized in Table 1[1)].

Table 1 Specifications of T4 shock tunnel

Description	Quantity
Piston Mass	92 kg
Compression Tube	229mm ID, 26m long
Shock Tube	76mm ID, 10m long
Nozzles	Mach 4, 6, 7, 7.6, 8, 10
Enthalpy Range	2.5 – 15 MJ/kg
Supply Pressure Range	10-50 MPa

Pressure sensors

Kulite™ and PCB™ piezoelectric pressure transducers were used to measure pressure levels within the test model. Static pressure was measured on the test surface using Kulite™ XTEL-190M piezoelectric pressure transducers. The pressure transducers had an excitation voltage of 10 V and had pressure ranges of 0-70kPa, 0-170kPa, and 0-700 kPa. High pressure levels such as pitot pressures and plenum chamber pressures are measured by PCB™ type 111A26 piezoelectric pressure transducers. The transducers sensing faces were thermally protected from the flow by attaching 25 μm cellophane discs to the sensing faces.



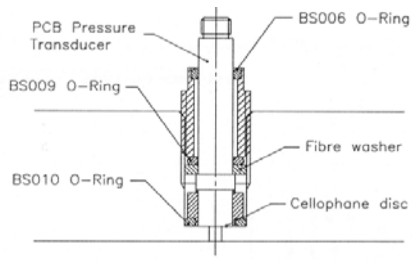


Fig. 1 Piezoelectric pressure transducers, Kulite (UP) and PCB (Down)

Fuel System

Gaseous hydrogen was injected on the scramjet engine combustor through a row of 4 holes. Fig. 2 shows the layout of the fuel system within the test model. The fuel was injected from a room temperature reservoir through a fast-acting solenoid valve. The fuel reservoir was a coiled Ludwieg tube which kept the temperature of the fuel approximately constant at 300K during injection[2)]. The injection flow was initiated at least 8 ms prior to test flow arrival. The fuel injection was sonic at an angle downstream of 45° to the local flow. The injector holes were 2 mm in diameter and were spaced laterally at 25mm intervals[3)].

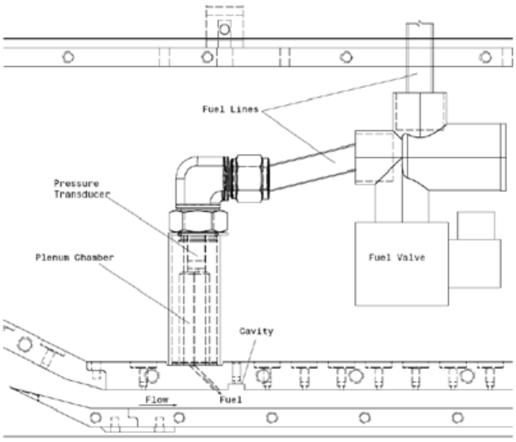


Fig. 2 Layout of Fuel supply system

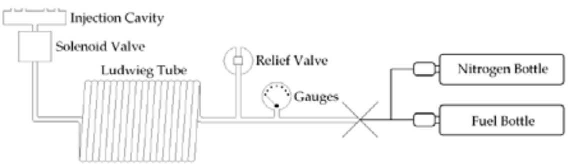


Fig. 3 Schematic of fuel delivery system[2)]

The fuel system was calibrated prior to testing to determine the mass flow rate of hydrogen as a function of the reservoir pressure. The calibration procedure for the shock tunnel fuel system is described by Robinson et al. (2003)[4)]. The instantaneous mass flow rate of the fuel is given by

$$\dot{m}_f = \frac{1}{\alpha} P_{o,i}^{\frac{\gamma-1}{2\gamma}} P_f^{\frac{\gamma+1}{2\gamma}} \tag{1}$$

Where α is the experimentally determined fuel calibration constant given by,

$$\alpha = \frac{R_f T_{o,i}}{V_o (P_{o,f} - P_{o,i})} P_{o,i}^{\frac{\gamma-1}{2\gamma}} \int_i^f P_f^{\frac{\gamma+1}{2\gamma}} \tag{2}$$

And $P_{o,i}$ = initial pressure in the fuel reservoir,

$P_{o,f}$ =final pressure in the fuel reservoir,

P_f =measured pressure in the plenum chamber,

V_o = Volume of fuel reservoir (1.66×10^{-3} m^3)

$T_{o,i}$ =initial temperature in fuel reservoir (300K)

R_f = ideal gas constant of the fuel

t_i =initial time

t_f =final time

Test model

Scramjet engine test model was composed of 4 shock wave intake, W-shape cowl and a cavity flame holder. In the test program, flat cowl and no-cavity combustors were also tested to find out their effects. By 4 shock system intake, Mach 7.6 free stream became compressed and slowed down to Mach 2.0 ~ 2.3 levels to be provided to the supersonic combustor. In the combustor, 3mm deep and 9mm long cavity was installed. Gaseous hydrogen was injected to the downstream direction at 45° through a row of 4 sonic injectors. In the test model, static pressures are measured at 32 points. More detailed design procedures and specifications can be found in Kang et al. (2007)[3)].

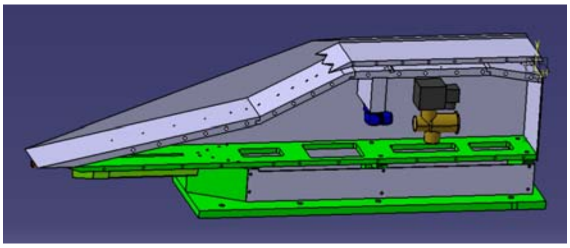


Fig. 4 Model Scramjet engine drawing

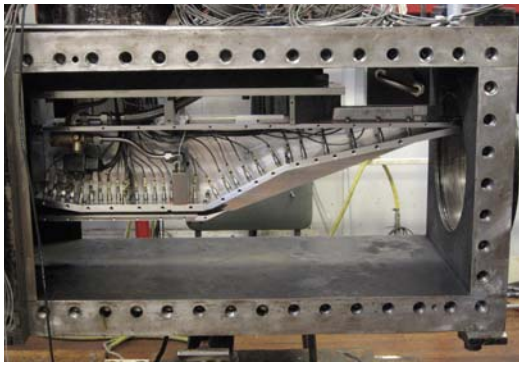


Fig. 5 Test model installation to T4 shock tunnel

Test condition

Basically, test condition is fixed as Mach 7.6 at 31 km altitude ($P_\infty = 1.04kPa$, $T_\infty = 224K$). With this condition, variation effects of fuel equivalence ratio, cavity, cowl setting and angle of attack are investigated.

Table 2 Engine test condition summary

Shot No.		Comment	Test gas	AOA$^{(o)}$	ϕ
1	9481	0^o AOA	Air	0	0
2	9486	ϕ=0.11	Air	0	0.11
3	9487	ϕ=0.183	Air	0	0.183
4	9483	ϕ=0.4	Air	0	0.4
5	9489	N_2, f	N_2	0	0.11
6	9492	N_2, f	N_2	0	0.4

7	9497	Visual.(BOS)	Air	0	0
8	9498	Visual2.(BOS)	Air	0	0
9	9493	No cavity	Air	0	0
10	9494	No cavity, f	Air	0	0.11
11	9495	No cavity, f	Air	0	0.4
12	9496	N_2, f	N_2	0	0.11
13	9499	Neg.° AOA	Air	-2	0
14	9503	ϕ=0.11	Air	-2	0.11
15	9500	ϕ=0.4	Air	-2	0.4
16	9502	N_2, f	N_2	-2	0.11
17	9504	Pos.° AOA	Air	2	0
18	9507	ϕ=0.11	Air	2	0.11
19	9505	ϕ=0.4	Air	2	0.4
20	9506	N_2, f	N_2	2	0.11
21	9508	Flat cowl ϕ=0.0	Air	0	0
22	9509	Flat cowl ϕ=0.11	Air	0	0.11

Test results

Baseline case

The results of baseline cases (AOA=0°, Cavity, W-shape cowl) are summarized in Fig. 6. In the figure, a separation bubble was observed at the first deflection point of the intake ramp. However, the size of the separation bubble is too small to affect the flow at the second ramp and the combustor.

In the figure, circle symbols are showing the pressure levels of the case without fuel injection. At the combustor part, pressure fluctuations were observed due to the shock reflections and expansion waves. But the overall pressure levels are remaining constant. The case with fuel injection into N_2 stream was expressed in delta symbol. As in the figure, these two cases showed almost the same pressure level because no reaction occurred.

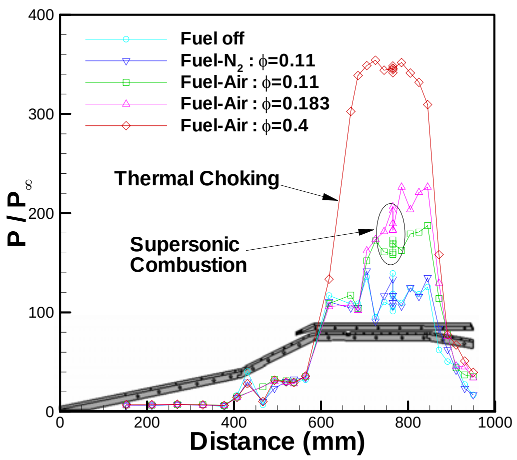


Fig. 6 Static pressure distributions; Baseline case

However, in the cases with fuel injection into the air stream, pressure levels started to rise from around 700mm location and increased rapidly. Furthermore, these pressure rising patterns did not propagate to the upstream. Therefore, those pressure increases can be regarded as a proof of supersonic combustion. In higher fuel equivalence ratio, pressure rises became more remarkable due to the more active reaction. However, in the case with ϕ=0.4, there were pressure rises even before the fuel injection point. Furthermore, in this case, pressure decreasing part was observed in the middle of the combustor. Therefore, it confirms that thermal choking occurred in the combustor.

Effects of Angle of attack

Fig. 7 shows the effects of angle of attack on the no- fuel air shot. Positive angle of attack results in the smaller compression angle in 1st ramp of the intake. So, pressure levels became a little bit lower than the zero-AOA case. Negative angle of attack resulted in opposite effects. Pressure levels became a little bit higher than the zero-AOA case. Besides, theoretically predicted combustor entrance Mach numbers are 2.15, 2.25 and 2.03 for 0°, +2° and -2° AOA cases respectively.

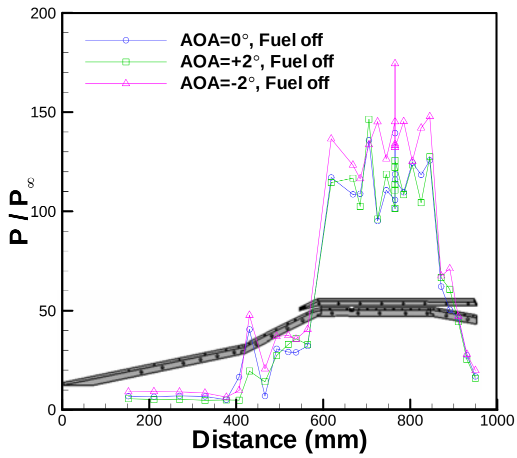


Fig. 7 Static pressure distributions; Angle of Attack variation effects on the non-reacting flow

Fig. 8 shows the AOA effects on the supersonic combustion. The case with zero and negative AOA showed similar pressure distribution. However, the case with positive AOA showed relatively lower pressure level. Especially, based on the pressure drop at 720mm point, we can presume that ignition delay time became longer than other cases due to the high combustor entrance Mach number or other worse condition for ignition.

Cavity and cowl shape effects

Fig. 9 shows effects of cavity and cowl shape on the supersonic combustion. The case without cavity showed lower pressure level than baseline case. Especially, pressure drop around 720mm point confirmed that it had longer ignition delay time. Flat cowl also showed lower pressure level than baseline case. However, in this case, pressure rise development patterns are similar with baseline case although its pressure rising slope is gentler. By this result, we can presume that W-shape cowl enhanced the fuel-air mixing.

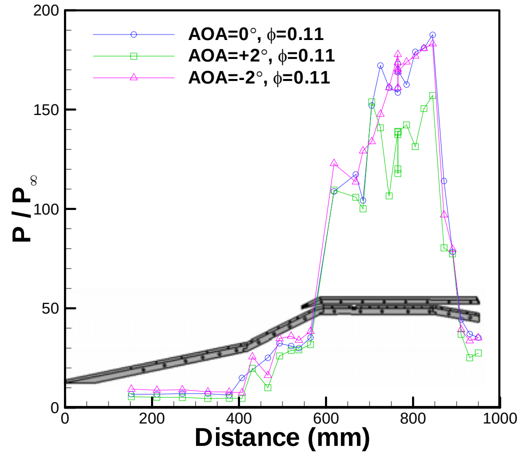


Fig. 8 Static pressure distributions; Angle of Attack variation effects on supersonic combustion

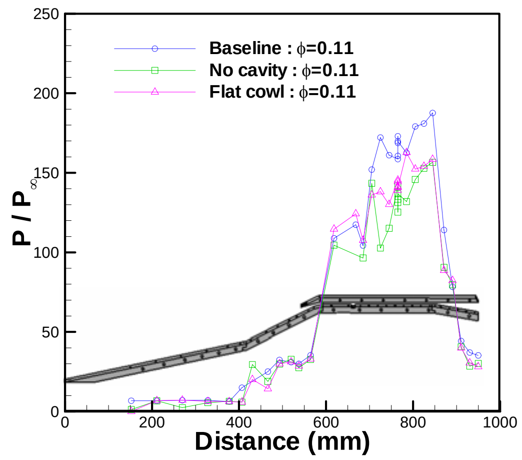


Fig. 9 Static pressure distributions; Component variation effects on supersonic combustion

Conclusion

In this study, model scramjet engine was tested with T4 free-piston shock tunnel. Test results showed supersonic combustion with the case of low and middle equivalence ratio. In high equivalence ratio case, thermal choking was observed. Variation of angle of attack changed the combustor entrance conditions and affected the combustion phenomenon. Cavity showed faster ignition and, W-shape cowl showed enhanced mixing effects.

References

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