Scramjet Engine Research of KARI : Ground Tests of Engines and Components

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1 Introduction

As a hypersonic engine for the future transport systems, the scramjet engine is attracting great interests due to its high speed and specific impulse [1]. Even though a combined-cycle rocket engine or gas turbine would be more practical for transportation [2-3], the realization of scramjet mode is still a critical aspect of hypersonic air-breathing engine development. Especially, flame holding methods in supersonic flow and the control of drag and aerodynamic heating are the most important part of the scramjet engine technology.

Since 2005, KARI (Korea Aerospace Research Institute) has been studied the core technology of the scramjet engine to prepare for the scramjet engine development and international collaboration research in the future. In spite of the short period of investigation, KARI has built the supersonic wind tunnel and performed a few tests of the engine and its components to obtain the core technology of hydrogen fuel scramjet engine. In this paper, KARI's fundamental and applied research results about the scramjet engine are summarized. The engine and its major components design and ground test results are explained. And engine performance enhancement skills are also addressed.

2 The ground test of the prototype engine model

The first scramjet engine test model of KARI, S1 was designed to observe the fundamental physics and characteristics of the scramjet engine. The supersonic combustion characteristics of various component configurations were also investigated, using free jet tests of the model scramjet engine in the T4 free-piston shock tunnel. Figure 1 is a picture of the S1 model. In the model, a rectangular intake with a four-shock-wave system was employed for a high total pressure recovery and robust combustion. The intake ramp angles were determined using Levenberg-Marqurdt's optimization method and Korkegi's criteria [4, 5]. As in figure 2, the W-shape cowl and the cavity are also employed in the model. With the installation of the W-shaped cowl, intake start-ability was enhanced. In the combustor, the cavity was installed for mixing enhancement and flame holding. For the combustor design, the Rayleigh line theory [6] and the Perfectly Stirred Reactor (PSR) model [7, 8] were used. In the cavity design, the flow residence time in the cavity was predicted by the Davis and Bowersox's relation [7].

For the test, the free-stream conditions are fixed at a Mach number 7.6 and an altitude of 31km. With the fixed free-stream condition, the effects of fuel equivalence ratios and varying component configurations were investigated.

In figure 3, pressure distributions within the model for reacting flow cases are presented. When φ=0.11 and 0.18, the measured pressure levels of the fuel-into-air test start to rise above those for the fuel-into-nitrogen test at approximately 700mm from the leading edge indicating a combustion phenomenon. However, for the case in which φ=0.40, pressure levels start to rise upstream of the fuel injection point. The pressure distribution suggests that the boundary layer has separated and that there are subsonic regions within the combustor.

In figure 4, effects of cavity and cowl shape were presented. As in the figure, the presence of the cavity and the W-shaped cowl resulted in greater combustion-induced pressure increases. Numerically, the cavity in the combustor was predicted to generate a hot static temperature region that acted as an ignition source, improving the mixing characteristics. With the W-shaped cowl, the static pressure showed transverse directional fluctuations and resulted in improved mixing. Via the combined effects of the cavity and the W-shaped cowl, earlier ignition and more active combustion were observed.

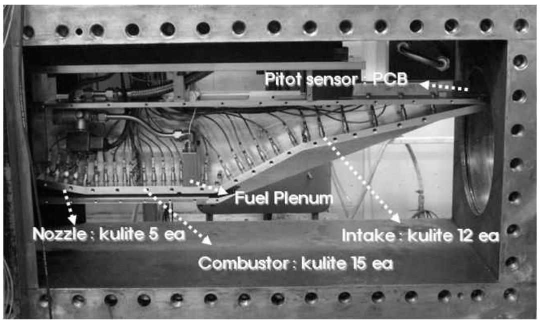


Figure 1. Scramjet engine test model, S1

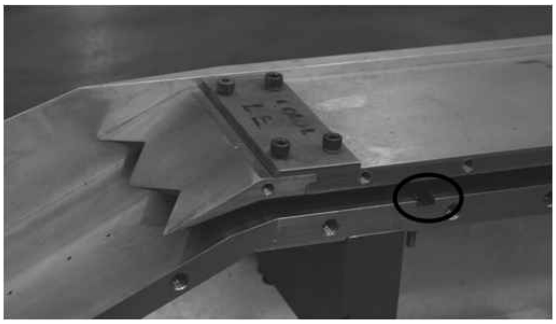


Figure 2. W-shape cowl and cavity flame holder

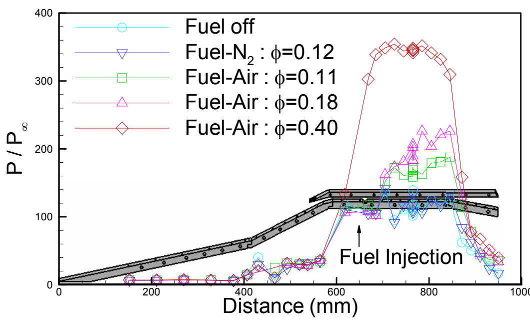


Figure 3. Normalized pressure distribution within the scramjet engine test model

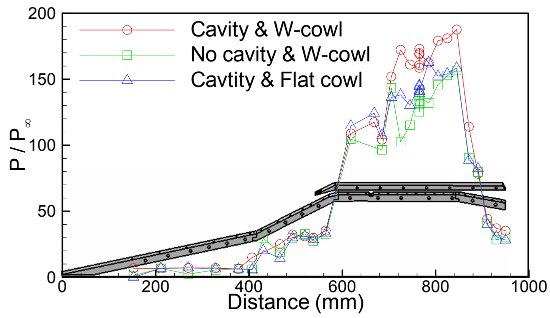


Figure 4. Effects of component variations on the normalized pressure distribution

3 Scramjet engine combustor tests

In the scramjet engine combustor, flame should be generated and sustained in supersonic flow to prevent thermal dissociation of the combustion product. Therefore, the way of fuel-air mixing and flame holding within the combustor have been the most important technique for scramjet engine development. For better performance of the scramjet engine combustors, various kinds of mixing and flame holding devices such as struts, cavities, ramp injectors, etc. have been suggested [9-13]. Cavity flame holders have fewer problems in aerodynamic heating and drag. But with a cavity and fuel injection from walls, fuel-air mixing is localized and rather ineffective [12, 13].

In the previous section, effects of cavity flame holders and shape of cowls on combustion within the model scramjet engine were shown. In the results, the W-shape cowl generated transverse directional pressure nonuniformity and enhanced fuel-air mixing. With the same idea of the W-shape cowl, combustion characteristics variations with different type of flame holders are investigated by the model scramjet combustor testing and quasi-one-dimensional analysis.

For the experiment, blow down wind tunnel with a hydrogen-fueled vitiation air heater was used. The facility provides Mach 2.5 flow with total pressure of 1.2 MPa and total temperature of 2000 K. With the fixed flow condition, effects of fuel equivalence ratio and component variations were investigated by measuring pressure distribution and exhaust gas sampling. Figure 5 shows the schematic of the scramjet engine combustor test model. The combustor test model is composed of an isolator section, a fuel injection section and a diverging combustor section. The model is 1015 mm in length and its entrance area is 147.3 × 32 mm^2. The lengths of the isolator section and the fuel injection section are 342 mm and 121 mm respectively, and their cross sectional areas are constant.

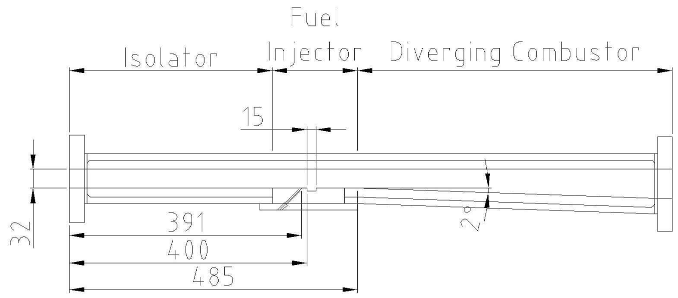
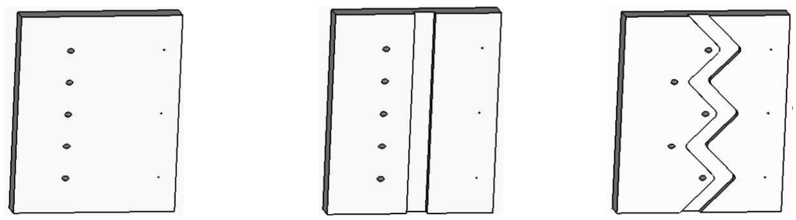


Figure 5. Schematic of the scramjet engine combustor test model

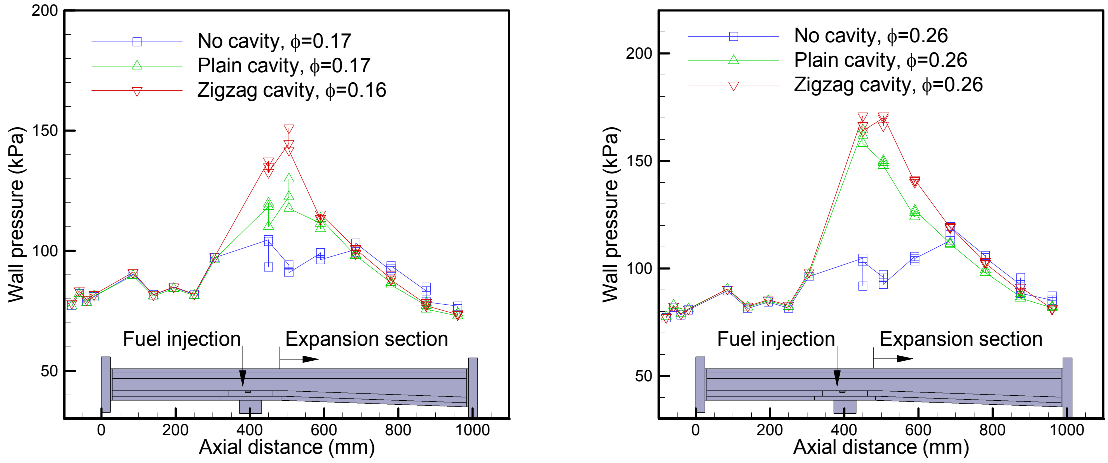


(a) No cavity (b) Plain cavity (c) Zigzag cavity

Figure 6. Fuel injector plates

In order to investigate the effects of the flame holder configuration, three different exchangeable fuel injection plates are made. Three plates are shown in figure 6. The first fuel injection plate has five sonic injectors with the diameter of 3.5 mm but has no cavity flame holder. Those sonic injectors are connected to a single hydrogen plenum chamber and inject gaseous hydrogen at 45° to the local flow. In the second fuel injection plate, a 5 mm deep and 15 mm long cavity was placed. The sonic injector has the same configuration with the first one. In the third fuel injection plate, zigzag cavity is installed. The zigzag cavity is inclined at 45° to the air inflow direction in upstream and downstream way by turns. Five inclined sonic injectors are placed on this plate, also in a zigzag pattern. The zigzag cavity and fuel injector configuration are expected to generate transverse directional pressure nonuniformity and enhance the fuel-air mixing. Following the fuel injector section, the 530mm long, diverging combustor section is connected. The expansion angle of the section is 2°.

In figure 7, pressure levels of three various flame holder configurations are compared. In figure 7-(a), combustor wall pressure distributions with fuel equivalence ratio around 0.17 are shown. As in the figure, the case with a plain cavity shows higher combustion pressure than the case without a cavity. Furthermore, the combustion pressure showed its highest value with zigzag cavity. Based on the maximum wall pressure, the case with zigzag cavity shows 17% higher than the case with the plain cavity indicating more active combustion. Figure 7-(b) shows the test results with fuel equivalence ratio of 0.26. Even in the different fuel setting, the zigzag cavity showed the best performance among all the cases, whereas pressure rise is rather small in the case without a cavity. As mentioned in the section 2, transverse directional nonuniformity of breathed air to the scramjet engine combustor is effective in air-fuel mixing and supersonic combustion. Zigzag cavity is expected to generate transverse directional flow within the cavity and stimulate the mixing. As a result, zigzag cavity is shown to be effective in combustion in scramjet engine combustor.



(a) φ = 0.16~0.17 (b) φ = 0.26

Figure 7. Wall pressure distribution comparison for various flame holder configurations

4 Scramjet engine intake tests

The intake and isolator of a scramjet engine should provide the combustor with properly conditioned air. Furthermore, the isolator should prevent the intake unstart from sudden combustion pressure rise in the combustor. To inspect the intake and isolator performance, the scramjet engine intake test model was tested. Figure 8 is a photograph of SETF (Scramjet engine test facility) of KARI which is used for the test of the intake. SETF is a blowdown windtunnel with a storage air heater. Maximum total temperature and pressure of the test facility is 1300K and 30bar, respectively. Detailed specifications of the facility are summarized in Table 1. The test conditions are fixed at a Mach number of Mach 6.7 and an altitude of 30km. However, supply pressure and temperature conditions are transformed to be within the facility limit by Reynolds analogy. The test model is composed of a two-stage compression ramp, an isolator and the nozzle with a plug. In the model, several sidewalls and isolators configurations are made for exchange. In figure 9, the test models with different side wall configuration are shown.

In test results, the side wall has little effects on the pressure distribution of the model as shown in figure 10. In the case without sidewalls, compressed air pressure is slightly small. However, reduced drag due to the absence of sidewalls can be advantageous. Therefore, the sidewall effects are rather inconclusive in this case. In the isolator test, the intake is found to be capable of combustion pressure up to 5% of the total pressure of the free stream as in the figure 11.

Figure 8. Scramjet engine test facility of KARI

Table 1: Specification of the SETF

Description	Quantity
Mach nozzles	3.5, 6.7
Nozzle exit area	220x220 mm^2
Maximum total temperature	1300K
Maximum total pressure	30 bar
Maximum air mass flow rate	20kg/s
Typical test time	30 ~ 60 sec

(a) High and narrow side wall (b) No side wall

Figure 9. Scramjet engine intake test model

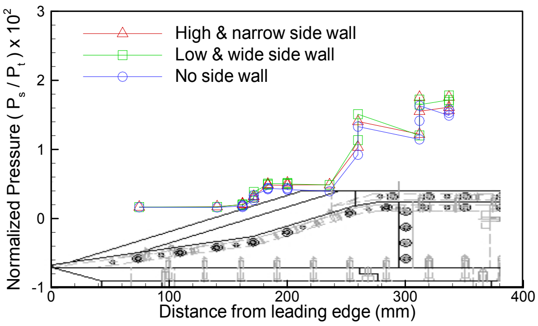


Figure 10. Side wall effects on the static pressure distribution within the intake

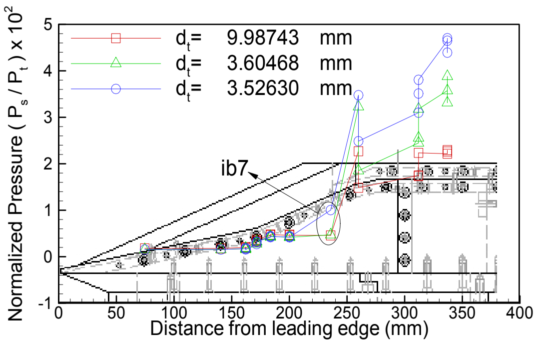


Figure 11. Back pressure limit for intake unstart

5 Improved engine tests

The first scramjet engine test model of KARI, the S1 model had several problems although it showed active combustion at Mach 7.6 flight condition. In the test results, upper limit of the fuel equivalence ratio was 0.4, which is too small to generate enough thrust. The intake buzz was also a serious problem in this case. Based on the test results of S1 and engine components, the S2 model is designed to remedy those problems. Figure 12 shows the improved scramjet engine test model, S2. The model is composed of a rectangular intake with four shock-wave system and a W-shaped cowl. Also, an expanding combustor is attached the constant area combustor with the zigzag cavity. For stable combustion with wide range of fuel amount, the speed of the inflow to the combustor is adjusted to be Mach 2.4~2.7.

Figure 12. Improved scramjet engine test model, S2

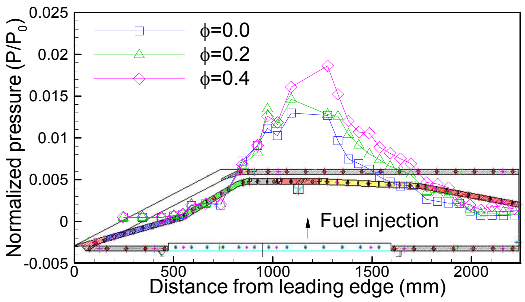


Figure 13. Pressure distribution within the S2 model

For the test of the S2 model, HIEST (High Enthalpy Shock Tunnel) at JAXA is used. The test conditions are fixed at a Mach number of Mach 7.7 and an altitude of 30km. Figure 13 shows the static pressure distribution of the S2 model with various fuel amount conditions. As in the figure, the S2 model showed stable combustion at φ=0.4, which was the condition of thermal choking in the S1 model. Based on the pressure force integral, the S2 model showed 409*N* of thrust increase by active combustion in this case.

6 Conclusions and future plan

Through the design and the ground test study of scramjet engines and components, the characteristics and the performances of the scramjet engine were investigated. The S1 model, the first trial of KARI, showed active combustion in the supersonic flow, but showed very limited operation range. By additional study of the engine components, some skills for performance enhancement are found. The W-shape cowl and the zigzag cavity turned out to be effective in supersonic combustion in the engine test model. After all, the improved model S2 showed more enhanced performance.

For future work, KARI is planning to apply multi-injection of the fuel in the combustor to produce more energy from large amount of fuel burning. The application of the hydrocarbon fuel is another theme of the plan. After revision of the scramjet engine test model, free falling flight test of the hydrogen scramjet engine is under consideration.

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