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Research Activity on Rocket-Ramjet Combined-cycle Engine in JAXA

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Abstract

Recent activities on the scramjet and rocket-ramjet combined-cycle engine of Japan Aerospace Exploration Agency (JAXA) are herein presented. The scramjet engines and combined-cycle engines have been studied in the world and JAXA has also studied such the engines experimentally, numerically and conceptually. Based on the studies, 2 to 3 m long, hydrogen-fueled engine models were designed and tested at the Ramjet Engine Test Facility (RJTF) and the High Enthalpy Shock Tunnel (HIEST).

A scramjet engine model was tested in Mach 10 to 14 flight condition at HIEST. A 3 m long scramjet engine model was designed to reduce a dissociation energy loss in a high temperature condition. Drag reduction by a tangential injection and two ways of a transverse fuel injection were examined. Combustor model tests at three operating modes of the combined-cycle engine were conducted, demonstrating the combustor operation and producing data for the engine design at each mode. Aerodynamic engine model tests were conducted in a transonic wind tunnel, demonstrating the engine operation in the ejector-jet mode. A 3 m long combined-cycle engine model has been tested in the ejector-jet mode and the ramjet mode since March 2007. Carbon composite material was examined for application to the engines. Production of the cooling channel on a nickel alloy plate succeeded by the electro-chemical etching.

Introduction

For more economical space activities and new business, for example, space tourism, a new space transportation system is required. Reuse of the transportation vehicle is one of the ways for the economical transportation system. At the same time, for the next generation transportation system, high reliability and abort-ability are required for credible and safety transportation of payload, including tourists.

To carry out such requirements, weight margin for supplemental redundant system is necessary. Since a required velocity increment is specified by a target orbit, the specific impulse of the booster stage should be increased to realize the margin. However, present conventional liquid rocket engines produce almost an ideal specific impulse. To attain such a larger specific impulse, use of an air-breathing engine has been studied in the booster stage, e.g., the turbo-ram jet engine,[1] the scramjet engine.[2] Figure 1 shows an artist image of a space transportation system with the air-breathing engine in the booster stage. The kinetic energy is proportional to a square of the velocity, so the use of the air-breathing engines in supersonic or hypersonic regime is effective to attain the energy for suppression of propellant consumption.

Although the scramjet engine has superior performance in the hypersonic region, another engine is required to accelerate the vehicle from take-off to supersonic speed. When the vehicle with the scramjet flies up to a high altitude where the atmosphere is too sparse, a rocket engine is further required. An engine that can operate in these different cycles was thus introduced and is called "a combined-cycle engine." The rocket-ramjet combined cycle engine, i.e., the rocket based combined cycle engine (RBCC),[3-5] is a combination of a rocket engine and a ramjet engine/a scramjet engine. The engine also enhances an average specific impulse, comparing to the conventional rocket engines, and can operate from take-off to hypersonic speed.

Japan Aerospace Exploration Agency (JAXA) has been studying the scramjet and the combined cycle engine.[6-9] Figure 2 shows history of the research activities on these engines. Herein, recent activities of JAXA on them are presented.

Scramjet Engine

Scramjet Engine Model Studies

The scramjet engine has been studied in the world and JAXA has also studied the engine as a booster experimentally, numerically and conceptually. Based on the studies, 2 to 3 m long, hydrogen-fueled engine models were designed and tested at the Ramjet Engine Test Facility (RJTF)[10] and the High Enthalpy Shock Tunnel (HIEST).[11] Recently a scramjet engine model was tested over Mach 10 flight condition at HIEST.[12,13] The objective of the tests was suppression

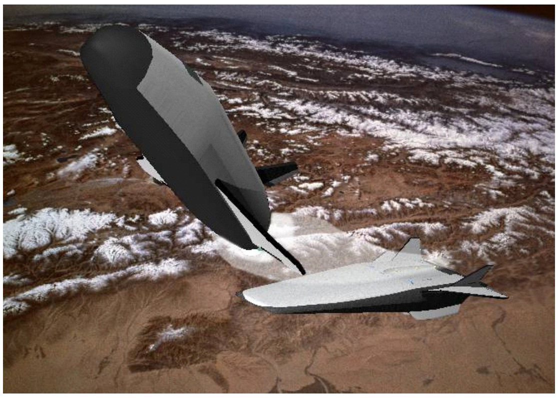


Figure 1 An artist image of a space transportation system.

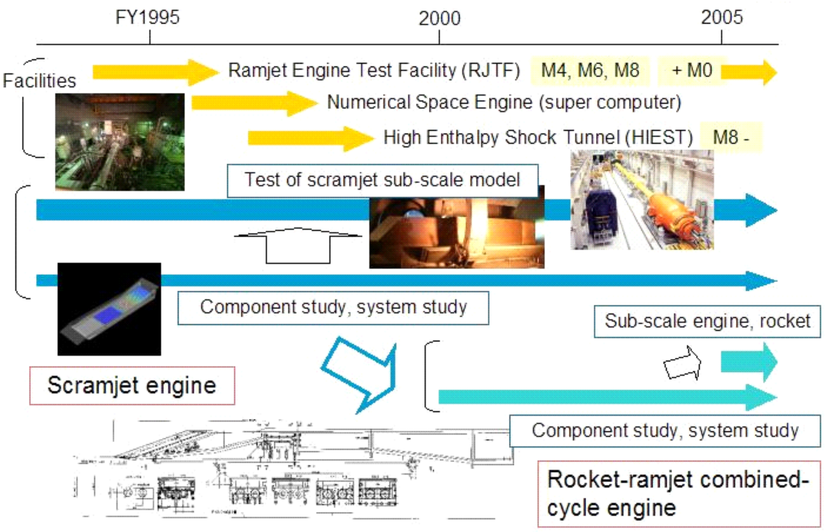
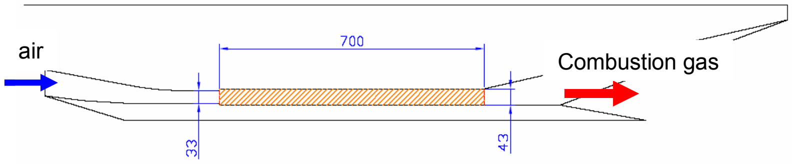
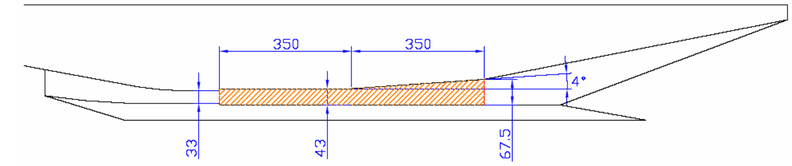


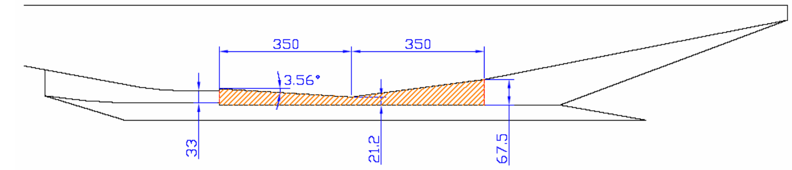
Figure 2 History of research activities on scramjet and rocket-ramjet combined-cycle engine.



(a) The parallel combustor (PC)



(b) The diverging combustor (DC)



(c) The converging–diverging combustor (CDC)

Figure 3 Combustor geometries of the scramjet engine model.

of dissociation of combustion gas in high temperature condition for efficient use of the combustion energy. Flow conditions of three combustor geometries were examined. Figure 3 shows schematic geometries of the tested engine combustors. Figure 4 shows estimated thrust by the wall pressure integration. In 7 to 9 MJ·kg^{-1} stagnation enthalpy conditions of the air, which correspond to fight Mach number of 12 to 14, the combustor performance was insensitive to the combustor geometry. It was caused by the short ignition delay at the high static temperature condition.

Scramjet Engine Component Studies

The scramjet engine performance can be further improved, for example, by reduction of drag or mixing and combustion enhancements. In a tangential injection of fuel for reduction of drag, insufficient

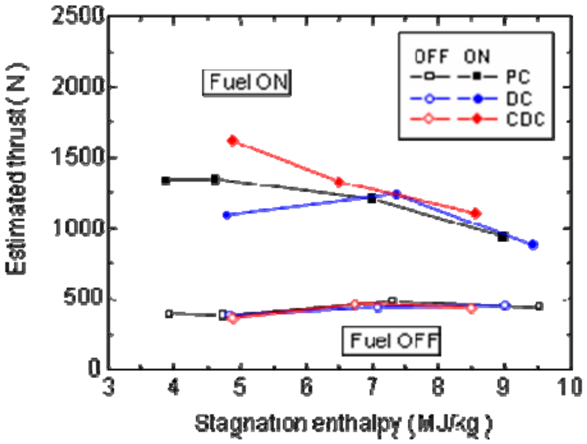


Figure 4 Estimated thrust of scramjet engine models by wall pressure integration.

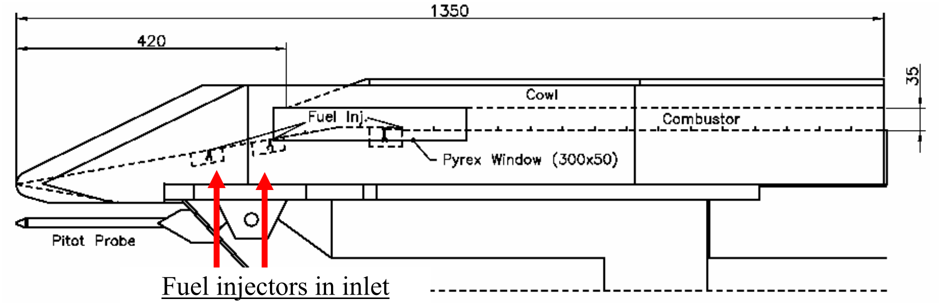


Figure 5 Schematic of scramjet engine model with inlet fuel injection ports.

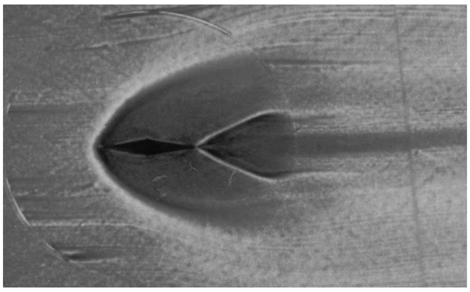


Figure 6 Streak lines around the diamond-shaped orifice.

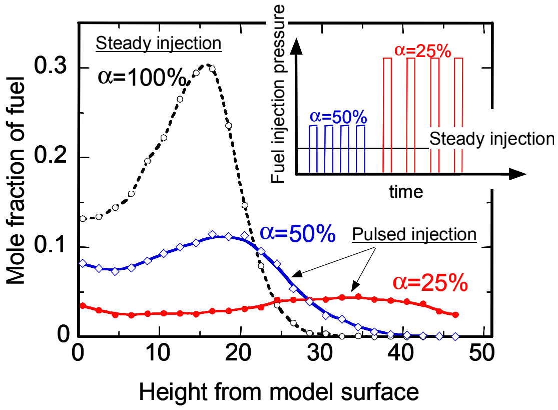


Figure 7 Distributions of mole fraction of pulsed-injection fuel.

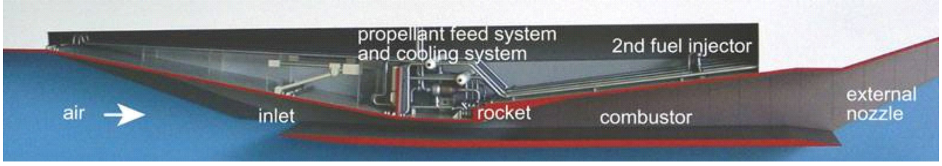


Figure 8 Photo of a display model of the rocket-ramjet combined-cycle engine.

mixing of fuel with the air is a serious problem and sufficient mixing cannot be attained by conventional ways of the injection. To enhance the mixing efficiency and keep the reduction effect of the drag, a tangential fuel injection from the inlet has been examined.[14] Figure 5 shows an engine model tested at HIEST. By the fuel injection from the inlet, higher pressure in the combustor was measured with no increase of pressure in the inlet section.

In the scramjet engine, sufficient mixing and subsequent combustion in a supersonic airflow in a restricted length of a combustor is a difficult and important problem. To enhance the mixing of fuel with the supersonic air, a fuel injection from a diamond-shaped orifice[15] and a pulsed transverse injection[16] were investigated. In the study of the diamond shaped orifice, an aspect ratio of the orifice was a parameter. Figure 6 shows surface streak lines around the diamond-shaped orifice. Larger penetration was attained with a longer orifice in an airflow direction. In another study of the pulsed fuel injection, combination of an interval time and an injection pressure was a parameter. A higher injection pressure with a longer interval time attained a longer penetration length (Figure 7).

Rocket-ramjet Combined Cycle Engine

Operating Condition of Rocket-Ramjet Combined-Cycle Engine

Figure 8 shows a picture of a display model of the rocket-ramjet combined-cycle engine and Figure 9 shows a schematic diagram of the engine operating conditions. The engine has several rocket engines in an airflow/combustion gas duct.

The engine operates in an ejector-jet mode from take-off to flight Mach number 3. From Mach 3 to 7, the engine operates in a ramjet-mode. From Mach 7 to 10, the engine does in a scramjet-mode. In a higher speed range or at a higher altitude, the engine operates in a rocket mode.

In the ejector-jet mode, air is breathed by the ejector effect of the rocket engine exhaust. The air is mixed with the rocket exhaust and pressure of the mixture increased in the divergent duct by deceleration. Fuel is injected into the subsonic mixture in the downstream combustor. Heat addition by combustion accelerates the subsonic combustion gas and the gas chokes at the engine exit. In the ramjet mode, the rocket exhaust is reduced and works for ignition and flame-holding. A supersonic airflow from the inlet decelerates to subsonic speed with an increase of static pressure in the divergent section. Fuel is injected into the subsonic airflow and the combustion gas chokes at the engine exit. In the scramjet mode, residual fuel in the rocket exhaust reacts with the supersonic air. The supersonic combustion gas flows out from the engine.

Combined-Cycle Engine Component Studies

Component level studies of the rocket-ramjet combined-cycle engine have been conducted to make clear physical/chemical mechanisms in the engine operation, to enhance the engine performances, and to establish deign technologies. The studies have been conducted experimentally, conceptually, and numerically.

The ejector system used in the low-speed, ejector-jet mode was investigated experimentally and the test results were compared with simple numerical model results.[17] Figure 10 shows a schlieren picture and an example of the comparison. The supersonic primary airflow simulated a rocket exhaust and the N2 secondary flow simulated a breathed air in an actual engine. The estimated values by the models agreed well with the experimental values.

Combustor model tests were conducted at each operating mode, that is, the ejector-jet mode,[18] the ramjet mode,[19] and the scramjet mode.[20] Figure 11 shows a combustor model used in the ejector-jet mode tests and measured pressure distributions at the sea-level static air condition. Air was breathed and choked at the entrance. The rocket exhaust and the air were in the supersonic condition at the entrance of the divergent section. The exhaust and the air were decelerated, and their mixture increased its pressure level gradually. Fuel was injected to the subsonic mixture in the downstream parallel section and the combustion gas choked at the exit throat. The ejector jet mode operation was demonstrated.

Figure 12 shows an aerodynamic test model and the measured pressure.[21] The tests were conducted in a transonic wind tunnel. Rocket exhaust in an actual engine was simulated with nitrogen gas. Suction and pressure recovery performances were examined in Mach 0 to 1.1 conditions. The pressure of nitrogen gas and the cowl geometry were parameters. The breathed air was choked at the exit of the inlet. The pressure recovered in the combustor section. CFD simulation was also conducted, showing insufficient mixing in the combustor section (Figure 13).[22]

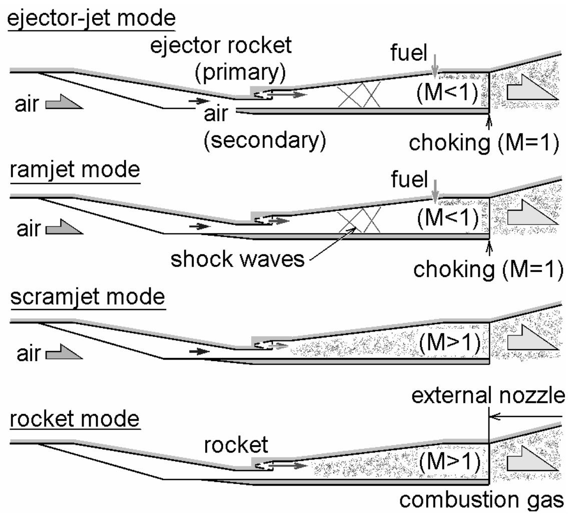
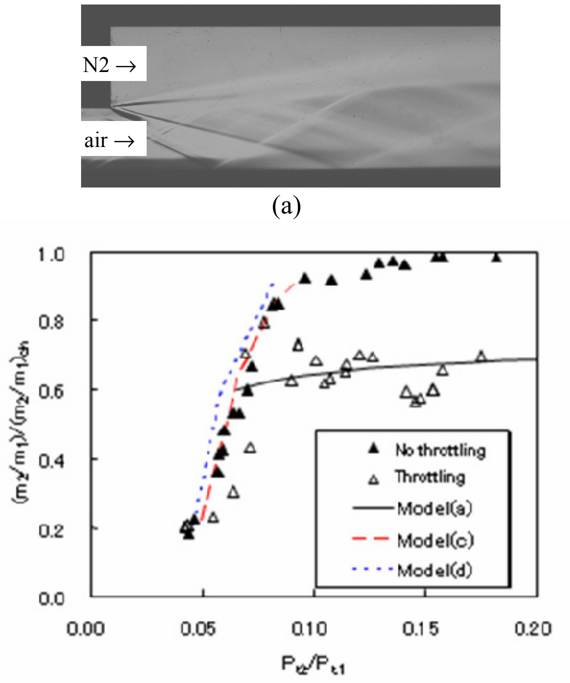


Figure 9 Schematic diagram of the rocket-ramjet combined-cycle engine operation.



(a)

(b)

Figure 10 (a) Schlieren picture of the ejector experiment and (b) suction performance. Mach number of primary flow is 2.4. A cross sectional area ratio of the secondary flow to the primary flow is 0.57.

Combine-Cycle Engine Model Study

Based on the results, an engine model was designed in 2004[23] and tests of the ejector-jet and ramjet modes have started. Figure 14 shows a schematic of the rocket-ramjet combined-cycle engine model for tests at RJTF. Its length was 3 m. Fuel is hydrogen gas. Oxidizer is oxygen gas, because RJTF does not have a supply system of liquid oxygen. The model is cooled by water. The engine is composed of panels for easy parametrical replacement of the components.

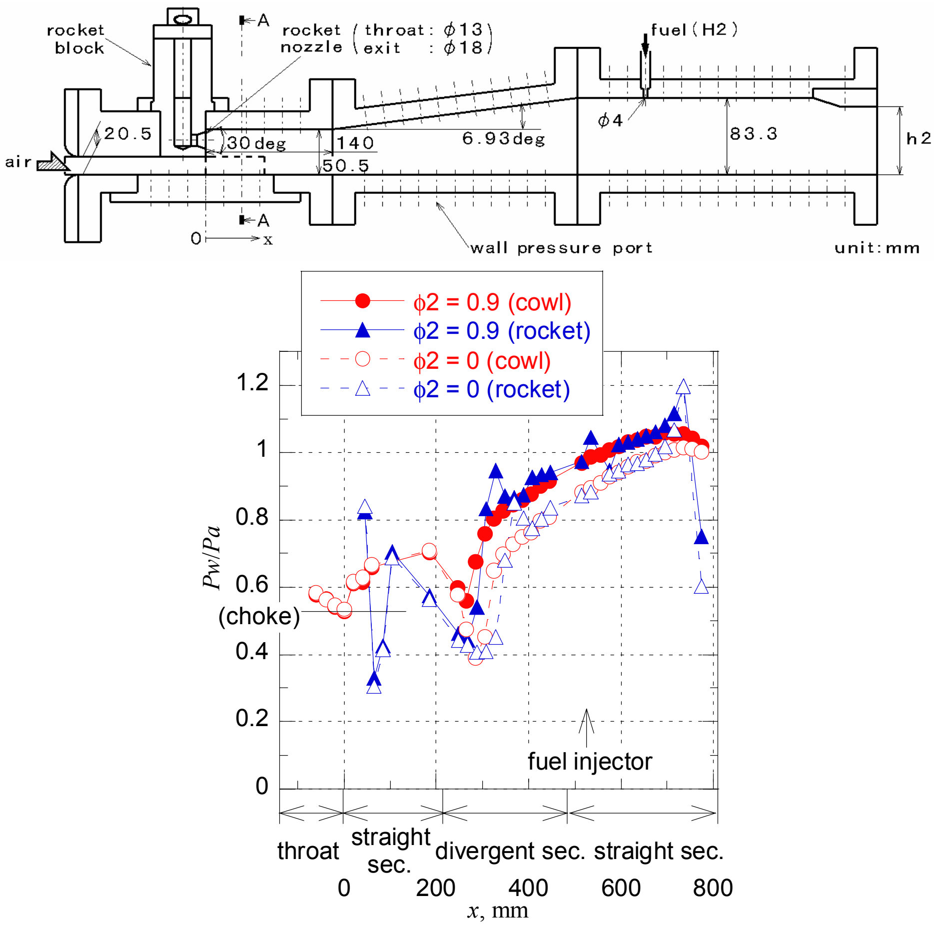


Figure 11 Combustor model tested in the ejector-jet mode and wall pressure distributions.

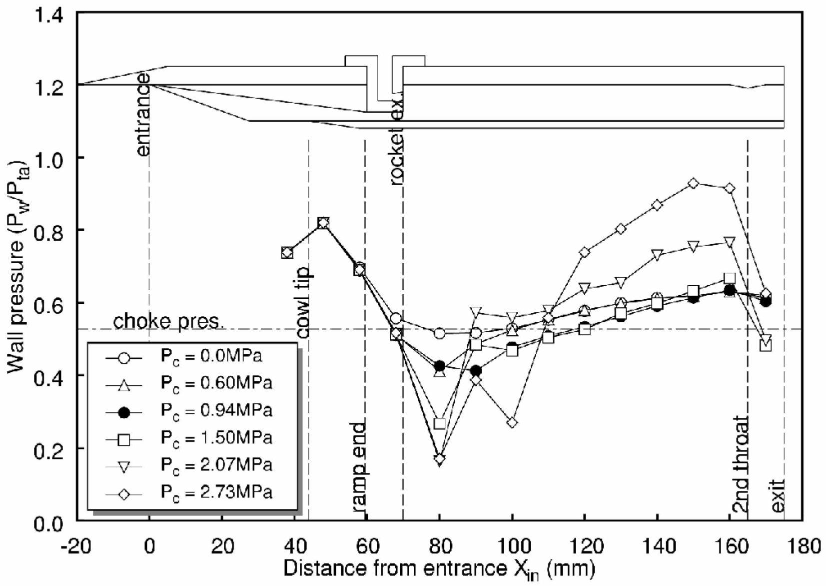


Figure 12 Aerodynamic engine model and measured pressure at Mach 0.8 condition.

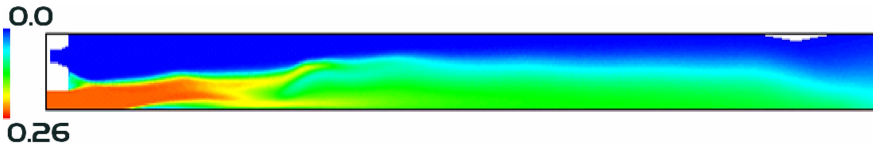


Figure 13 CFD simulation. Distributions of O2 mole fraction.

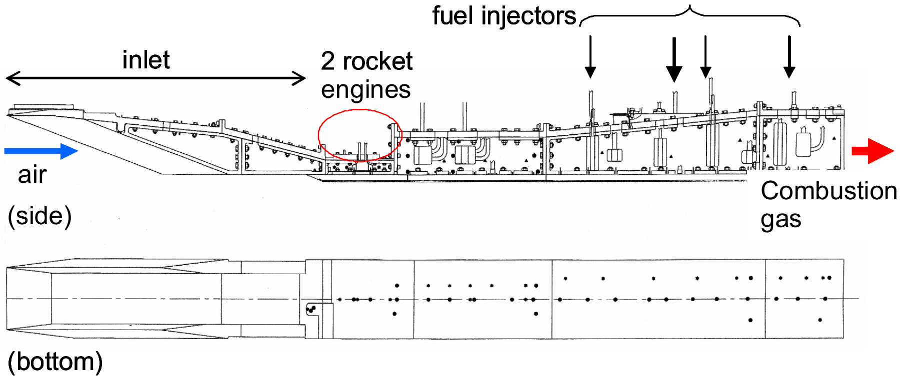


Figure 14 Schematic of rocket-ramjet combined-cycle engine model.

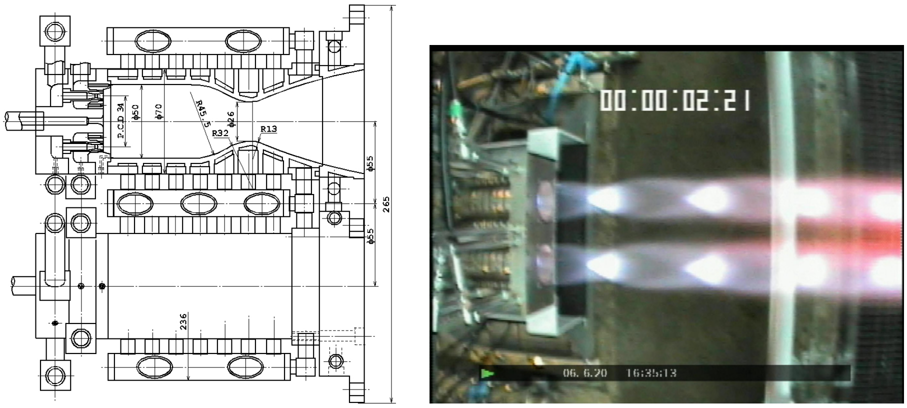


Figure 15 Schematic of twin rocket engines for integration to the combined-cycle engine and a picture of the rocket engine test.

The rocket engines mounted in the engine model were examined prior to the integration.[24] It was designed for wide range in operating conditions of pressure from 0.5 to 3 MPa and a mixture ratio O/F from 0.5 to 8. Figure 15 shows a schematic of the twin rocket engines and a picture in the experiment.

The first series of tests of the ejector-jet mode[25] and ramjet-mode[26] were conducted in 2007, respectively. Figure 16 shows photos of the engine model. Modifications have been conducted, based on the test results. Another series of both mode tests will be conduct in autumn to winter 2007.

Engine Materials and Structures

Pressure levels in the scramjet engine and the combined-cycle engine except the core rocket engines are lower than that of the conventional rocket engine, whereas sizes of the engines are larger than that of the rocket engine in a similar thrust level. Application of the light weight material is greatly effective for mass reduction in the scramjet and the combined-cycle engines due to their large size. The two engines require cooling in their air/combustion gas ducts for hypersonic flight, as well as their leading edges. Since the duct sizes of the engines are large, an efficient light-weight cooling system is required, which is different from a regenerative cooling system of the conventional rocket engines. JAXA has also conducted researches on the engine material and the engine cooling structure.

Engine Materials

Carbon/Carbon (C/C) composite material can be used

Figure 16 The engine model in the ejector-jet mode at sea-level static air condition.

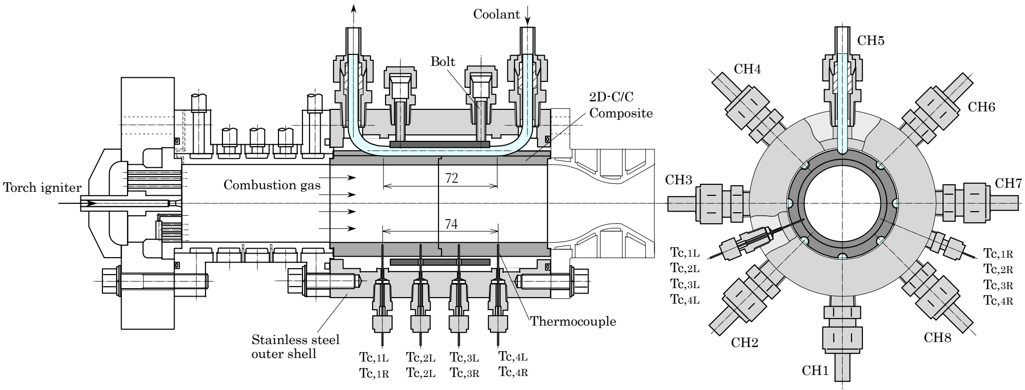


Figure 17 C/C composite rocket chamber with metal cooling tubes.

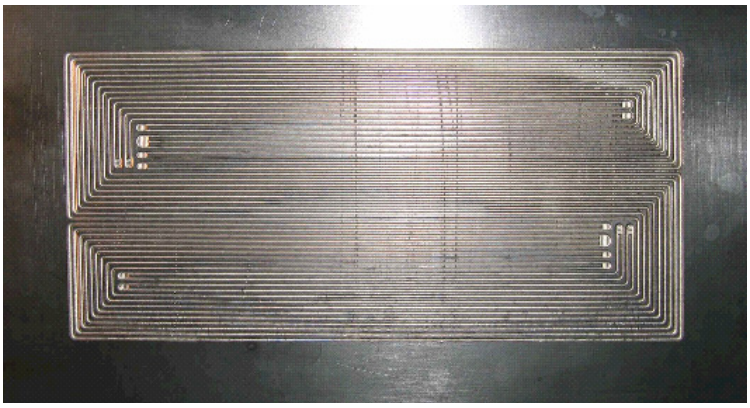


Figure 18 Sample plate with cooling channels by electro-chemical etching.

in high temperature, but its oxidation and permeability are problems for its application to the engines. SiC coating and silicon infiltration are tried to the material.[27]

In cooling of the C/C composite material structure, metal cooling tubes are applied to the structure against the permeability of the material. This idea was applied to a rocket chamber.[28] Figure 17 shows a schematic of the experimental model. The chamber material temperature could be controlled by change of a flow rate of cooling water.

Engine Cooling System Structure

Cooling channel production on a wide, thin plate needs another technique from that for the conventional rocket engines. Chemical etching is suitable for processing a thin plate. The scramjet and combined-cycle engines will be made of a nickel-based alloy from a viewpoint of the heatproof ability. However, conventional etching solutions cannot dissolve such alloys. To etch the channels to the alloy, electro-chemical etching was applied.[29] Figure 18 shows a sample plate with the channels formed by the electro-chemical etching.

Closing Remarks

The researches of the scramjet and rocket-ramjet combined-cycle engines have been conducted for a new space transportation system. In next 5-year program, the scramjet-mode of the combined-cycle engine will be tested and examined, based on the knowledge from the scramjet engine studies. With the outcomes, a modified combined-cycle engine model will be designed and constructed, applied with the C/C material and the cooling structure.

The engine operations and the design technologies should be demonstrated in flight conditions. Several kinds of the flight tests are planned, including a transition condition tests of an inflow air. For example, conversion of a small sounding rocket to an ejector-jet rocket is one of the options for the flight demonstration of the design technologies. They will be discussed and decided in the JAXA future space transportation program.

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