HiSST: 3rd International Conference on High-Speed Vehicle Science Technology
14 -19 April 2024, Busan, Korea

Conceptual Design of Hypersonic Combined Cycle Engines

Hideyuki Taguchi, Hidemi Takahashi, Shunsuke Imamura, Sadatake Tomioka (JAXA)

Abstract

Conceptual design of hypersonic combined cycle engines is investigated. A pre-cooled turbojet engine and a scramjet engine are combined to a turbine-based combined cycle (TBCC) engine. The pre-cooled turbojet engine is assumed to be operated from Mach 0 to Mach 5. The scramjet engine is assumed to be operated from Mach 5 to Mach 6. The operating condition of the pre-cooled turbojet engine is confirmed using the results of propulsion wind tunnel test at Mach 4 flight simulating condition. A light weight mode change mechanism is proposed to change the engine cycle from the pre-cooled turbojet engine to the scramjet engine. A waverider shape airframe is designed and the flight performance is calculated for a hypersonic transport aircraft using the TBCC engine.

Keywords: *Propulsion, Air-Breathing, Hypersonic*

1. Introduction

Currently, studies are underway on hypersonic transport aircraft that can transport passengers and cargo at high speed between two points on earth. Virgin Galactic has announced that it will develop its suborbital spacecraft technology to create a high-speed point-to-point transport aircraft [1]. Hermeus has announced a development concept for a hypersonic transport aircraft that can fly at around Mach 5, and is proceeding with demonstration tests of a pre-cooled turbo ramjet engine [2]. Destinus has announced a development concept for a hydrogen-fueled hypersonic transport aircraft, and is proceeding with engine combustion tests, takeoff and landing flight tests, etc. [3]. Reaction Engines is developing the SABRE engine, which cools air with liquid hydrogen, with the aim of realizing winged space transportation vehicles [4].

JAXA has been conducting research on systems for hypersonic transport aircraft [5,6]. In this study, conceptual design of a hypersonic combined engine that combines a pre-cooled turbojet and a scramjet is conducted, and the performance is estimated. System study of a hypersonic transport aircraft equipped with a hypersonic combined engine is conducted and the performance is estimated.

Figure 1 shows a conceptual drawing of the hypersonic transport aircraft obtained as a result of the system study. In order to fly through the atmosphere at high speeds of around Mach 5, it uses a waverider shape that utilizes the pressure increase caused by shock waves as lift. In addition, the layout is such that a hypersonic combined engine is mounted on the underside of the fuselage, where pressure has increased due to the waverider effect.

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Fig 1. Conceptual drawing of hypersonic transport aircraft

2. Propulsion wind tunnel test of pre-cooled turbojet

Research and development of a pre-cooled turbojet using liquid hydrogen fuel has been conducted toward realization of air-breathing engines for hypersonic transport aircraft.

Figure 2 shows the pre-cooled turbojet (PCTJ) [7] demonstration engine. A pre-cooled turbojet is an engine that can expand the upper limit of the operating speed of a jet engine from about Mach 2 to about Mach 5 by cooling the inlet air using cryogenic liquid hydrogen. Propulsion wind tunnel experiments [8] at Mach 4 flight simulating environment using a subscale engine has been conducted.

Fig 2. Pre-Cooled Turbojet Engine (PCTJ)

Figure 3 shows a picture of the PCTJ propulsion wind tunnel experiment. This experiment was conducted at the ramjet engine test facility at JAXA Kakuda Space Center. In this experiment, the engine was installed in a high-speed airflow under Mach 4 flight simulating conditions, and liquid hydrogen was supplied to the engine to evaluate the overall propulsive performance of the engine and the intake, precooler, core engine, ram combustor, etc. The performance of the engine components was obtained. In addition, the shock waves generated around and inside the intake has been visualized using Schlieren images. The afterburner structure temperature was visualized using an infrared camera. The exhaust temperature field was visualized using an infrared dichroic camera. The exhaust flow was visualized using the BOS (Background-oriented Schlieren) method.

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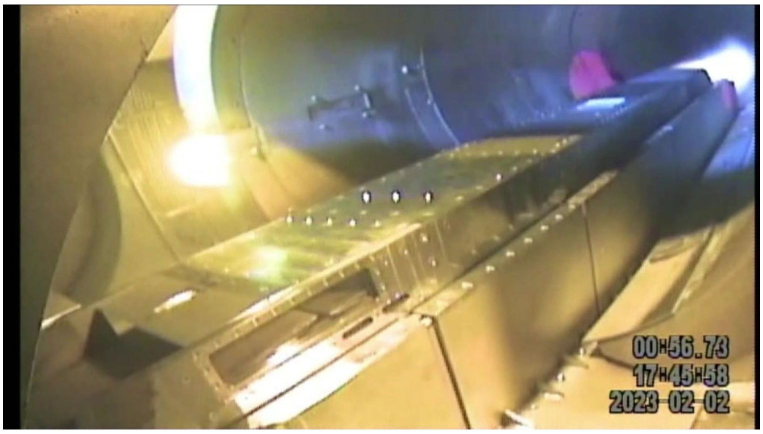

Fig 3. Propulsion Wind Tunnel Test of PCTJ

Figure 4 shows the PCTJ intake performance map obtained in the propulsion wind tunnel experiment (Mach 4). Total Pressure Recovery (TPR) is the ratio of intake outlet total pressure to airflow total pressure. Mass Capture Ratio (MCR) is the ratio of the intake outlet flow rate to the air flow rate flowing into the intake front area. The highest value of TPR is about 0.44 and the highest value of MCR is about 0.56. These values are achieved in the starting condition, where oblique shock waves are formed inside the intake and the air is moderately compressed. To create this starting condition, a bypass door is installed upstream of the core engine to maintain the intake air flow rate even when the core engine air flow rate is low. It is known that when the intake air flow rate is small, a vertical shock wave is formed at the intake inlet, resulting in a non-starting condition, and TPR drops to about 0.15.

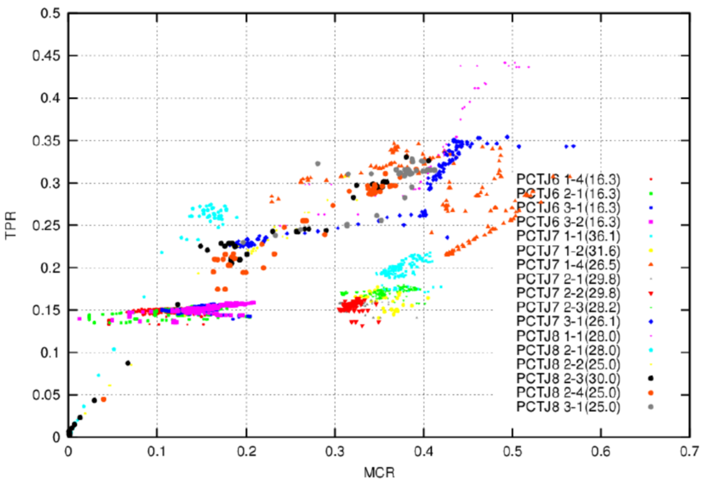

Fig 4. Intake Performance Map of PCTJ

In the propulsion wind tunnel experiments, ram combustion using liquid hydrogen fuel was achieved. Figure 5 shows the PCTJ ram combustion temperature with fuel rich combustion. This data was obtained during the 8th Pre-Cooled Turbojet Engine Experiment (PCTJ-8) [8,9]. TAB-2 was measured at 160mm downstream of the injector, and TAB-3 was measured at 75mm downstream of the injector and 10mm away from the wall. In this experiment, in order to ensure the cooling performance of the pre-cooler that cools the air with liquid hydrogen, fuel was supplied at equivalence ratio of about 2, resulting in a combustion temperature of about 2000 K with fuel rich combustion.

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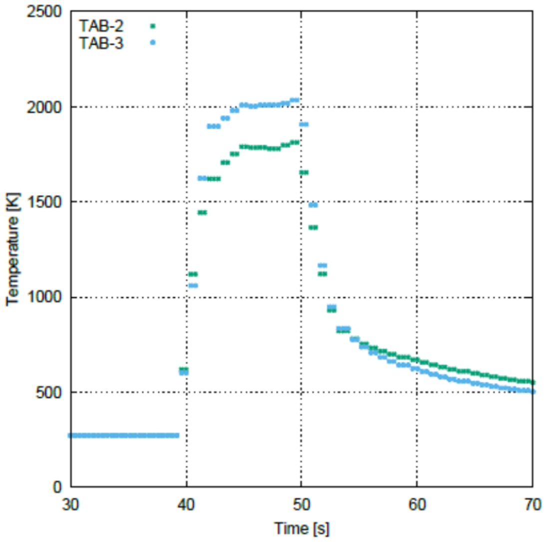

Fig 5. Temperature of Ramjet Combustor (Fuel Rich Combustion)

Figure 6 shows the PCTJ ram combustion temperature with fuel lean combustion. This data was obtained during the 12th Pre-Cooled Turbojet Engine Experiment (PCTJ-12). In this experiment, liquid hydrogen fuel was supplied with an equivalence ratio of about 0.5, and the combustion temperature was about 2000 K with fuel lean combustion. It was confirmed that the same injector can be used for both fuel rich combustion and fuel lean combustion.

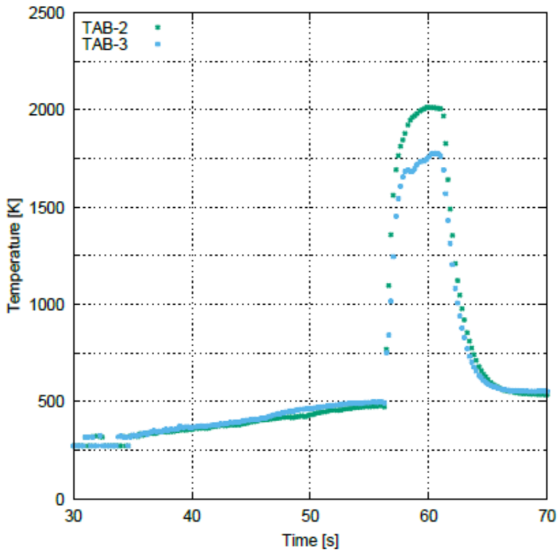

Fig 6. Temperature of Ramjet Combustor (Fuel Lean Combustion)

3. Conceptual design of hypersonic combined engine

Pre-cooled turbojet engines generate a large amount of thrust during initial acceleration, but it is known that for a long-distance cruising, lean-burn ramjet consume less fuel. In addition, thrust generation with a scramjet has been demonstrated at Mach 4 to Mach 8 at the previous experiments in JAXA.

Therefore, conceptual design of a hypersonic combined engine with a pre-cooled turbojet engine and a scramjet engine [10] has been conducted. This engine is a kind of Turbine-based Combined Cycle

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(TBCC) engine.

Figure 7 shows the system diagram of the hypersonic combined engine. Liquid hydrogen fuel is supplied to each engine from the fuel tank via a fuel pump. When operating the pre-cooled turbojet engine, liquid hydrogen fuel is supplied to the pre-cooler and the core engine. The liquid hydrogen fuel supplied to the pre-cooler is used for combustion in the afterburner after cooling the air. The liquid hydrogen fuel supplied to the core engine is used for combustion in the core engine. When operating the scramjet, liquid hydrogen fuel is supplied to the scramjet injector. The afterburner wall and scramjet combustion wall are assumed to be cooled by regenerative cooling using liquid hydrogen fuel. The liquid hydrogen fuel receives heat on the combustion wall and rises in temperature before being supplied to the fuel injector.

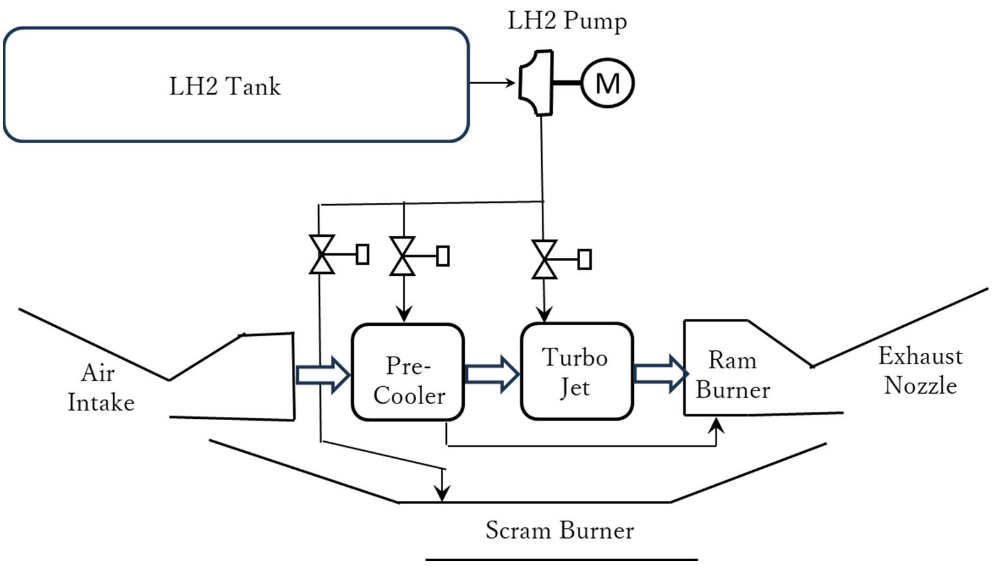
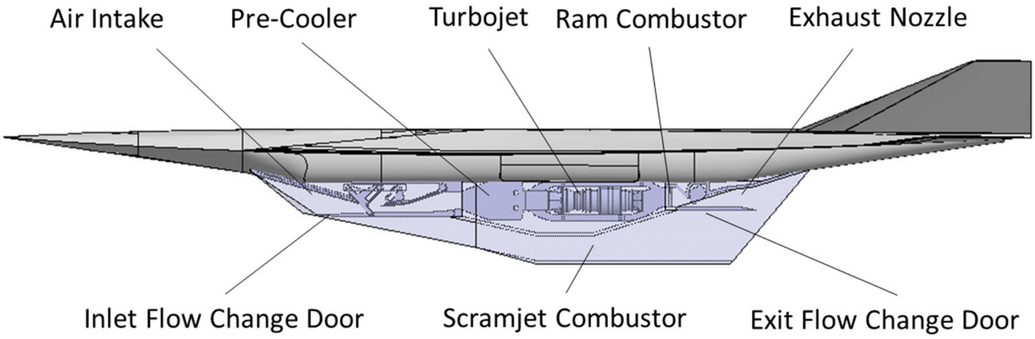


Fig 7. System diagram of Hypersonic Combined Engine

Figure 8 shows a cross-sectional view of the hypersonic combined engine. When the pre-cooled turbojet engine is operating, the inlet flow change door and the outlet flow change door are opened to introduce airflow into the pre-cooled turbojet engine. At this condition, air also flows into the scramjet flow path, but it passes through the inside and is exhausted without combustion. During scramjet operation, the inlet flow change door and outlet flow change door are closed, and their outer surfaces form the walls of the scramjet intake and scramjet nozzle. At this condition, air flow is not formed in the pre-cooled turbojet engine.



a) Pre-Cooled Turbojet Operation

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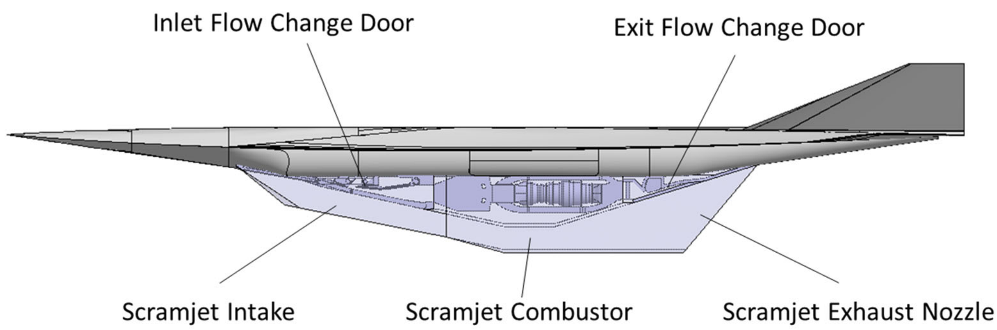

b) Scramjet Operation

Fig 8. Cross Section of Hypersonic Combined Engine

When designing a hypersonic combined engine, it is important to reduce the weight of the flow change door. This design allows the actuator driving force to be reduced by linking the variable mechanism inside the intake and the inlet flow change door to balance the pressure. In addition, the variable mechanism inside the exhaust nozzle and the outlet flow change door are similarly linked to balance the pressure, making it possible to reduce the driving force of the actuator.

4. Performance Analysis of Hypersonic Combined Engine

Performance analysis of a pre-cooled turbojet engine was conducted as an initial acceleration engine for a hypersonic combined engine. A thermodynamic analysis model was composed for the intake, pre-cooler, turbojet, ram combustor and exhaust nozzle. The internal state quantities such as pressure, temperature and velocity were analyzed. Liquid hydrogen is used because it has a high cooling capacity. Fuel-rich combustion with an equivalence ratio of about 2 is selected to attain enough cooling capacity. The analysis was conducted assuming the flight range with Mach 0 to 6 and altitude 0 to 30 km.

Figure 9 shows the analysis results of net thrust / frontal area corresponding to changes in Mach number and altitude. As the Mach number increases, the net thrust / frontal area tends to decrease. Additionally, as the flight altitude increases, the net thrust / frontal area decreases. This is caused by the effect of a decrease in air density.

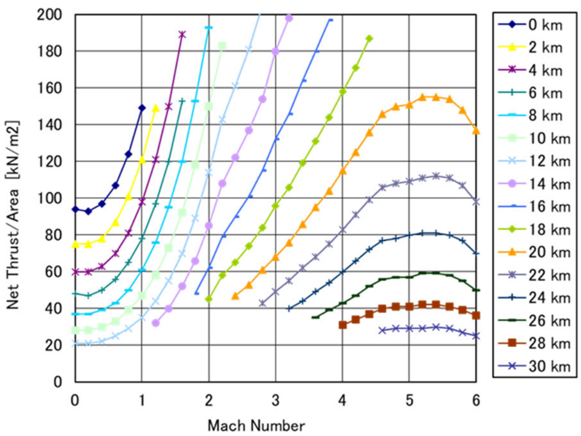

Fig 9. Thrust Map (PCTJ)

Figure 10 shows the relation between Mach number and specific impulse. As the Mach number

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increases, the specific impulse tends to decrease. On the other hand, even if the flight altitude increases, the change in specific impulse is small. This is because even if the air density changes, the analysis is performed to match the upper limit of the combustion temperature by adjusting the equivalence ratio, and the change in the engine cycle is small.

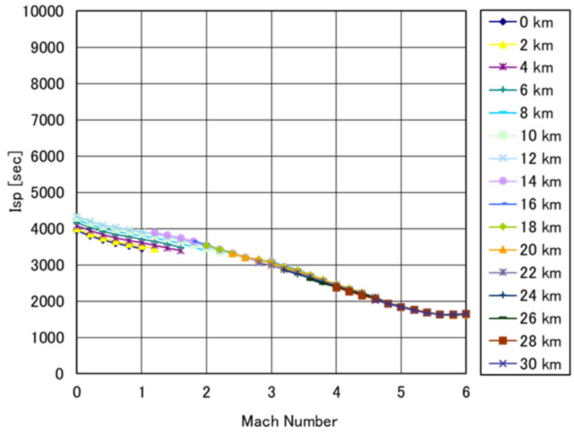

Fig 10. Specific Impulse Map (PCTJ)

Another candidate for air-breathing engines that can be applied to hypersonic transport aircraft is the turbo-ramjet, which combines a turbojet and a ramjet.

Therefore, engine performance analysis for a hydrogen-fueled turbo-ramjet is also conducted. Assuming that the turbojet operates at Mach 0 to 2 and the ramjet operates at Mach 2 to 5, the size of the ramjet was adjusted so that there would be no change in thrust when switching from turbojet to ramjet. Since there is no need to cool the air in a turbo-ramjet, furl lean combustion with an equivalence ratio of less than 1 is selected.

Figure 11 shows the net thrust / frontal area of a turbo-ramjet with hydrogen fuel. The net thrust / frontal area decreases as the Mach number increases. The net thrust / frontal area at Mach 5 and an altitude of 30 km is approximately 3 kN/m^2, which is approximately 1/10 of the 30 kN/m^2 of the pre-cooled turbojet shown in Fig. 9. The reason for this is that in a pre-cooled turbojet engine, the air density increases due to pre-cooling, which increases the air flow rate for the same engine size. Another effect is that the flow rate of hydrogen fuel as a propellant increases due to fuel rich combustion.

Figure 12 shows the analysis results of the specific impulse of a turbo-ramjet with hydrogen fuel. The value is higher than that of the pre-cooled turbojet engine shown in Fig. 10 because it assumes fuel lean combustion that reduces fuel consumption. The specific impulse at Mach 4 is about 2500s for a pre-cooled turbojet, while it is about 5000s for a turbo-ramjet. Therefore, switching to ramjet operation can reduce the fuel consumption in cruise flights that do not require large thrust.

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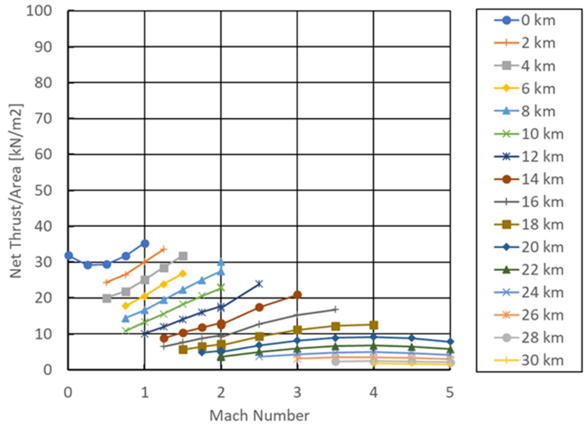

Fig 11. Thrust (Turbo-Ramjet)

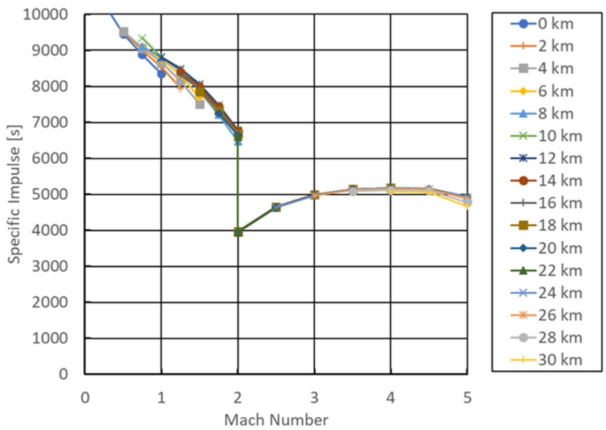

Fig 12. Specific Impulse Map (Turbo-Ramjet)

5. System design of Hypersonic Transport Aircraft

Figure 13 shows a conceptual drawing of a hypersonic transport aircraft. This fuselage shape was derived using a design program for simultaneous optimization of fuselage shape and trajectory [11]. Regarding the shape of the waverider, which uses shock waves to increase the pressure at the lower side of the fuselage to increase the lift. The fuselage shape is obtained using design variables. The aerodynamic coefficient maps are created for various shapes. Afterwards, flight trajectory analysis was conducted and an optimum shape to minimize the total weight was obtained.

Table 1 shows the specifications of the hypersonic transport aircraft obtained through the optimization design analysis. Assuming a business jet, the number of passengers including crew was set at 14. The flight distance was 8,800 km, assuming a route between Tokyo and Los Angeles across the Pacific Ocean. The optimal solution obtained through design analysis had a takeoff mass of 93 Mg and a total fuselage length of 49 m.

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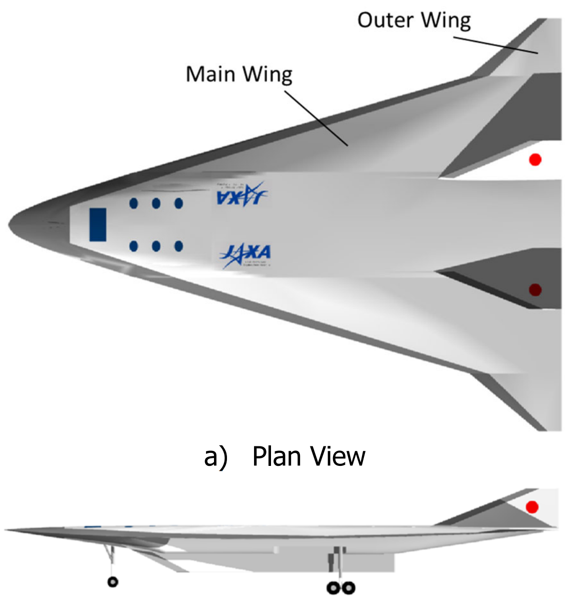

a) Plan View

b) Side View

Fig 13. Conceptual drawing of Hypersonic Transport Aircraft

Table 1. Specifications of Hypersonic Transport Aircraft

Number of passengers	14 people
Flight distance	8800 km
Takeoff mass	93 Mg
Dry mass	48 Mg
Fuel mass	45 Mg
Overall length of the aircraft	49 m
Overall width of the aircraft	36 m
PCTJ side length	1.32 m
Take-off distance	1000 m
Maximum dynamic pressure	30 kPa

Figure 14 shows the flight trajectory of a hypersonic transport aircraft. The altitude reaches 30 to 35 km during cruising after takeoff and climbing flight. The cruising altitude increases to reduce drag of the aircraft, which has become lighter due to fuel consumption. After cruising, the altitude is lowered by descending flight. In this analysis, the performance of a pre-cooled turbojet engine was used for takeoff to climb phase. The performance of a ramjet was used for cruising phase. Mach number is about Mach 5.3 during the cruise flight.

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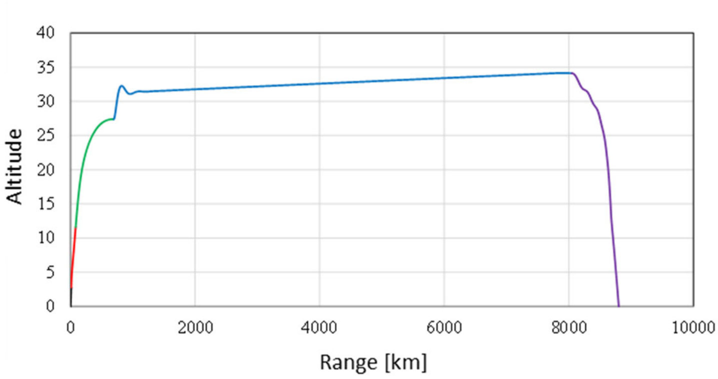
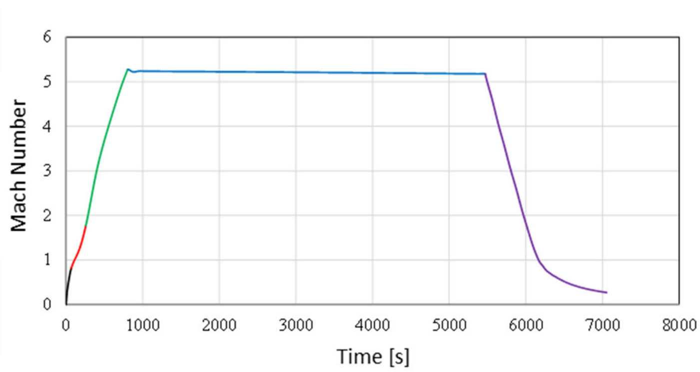


a) Altitude



b) Mach Number

Fig 14. Flight Trajectory of Hypersonic Transport Aircraft

6. Conclusion

The following knowledge was obtained regarding the conceptual design of a hypersonic combined engine applied to hypersonic transport aircraft.

- Propulsion wind tunnel experiment of a pre-cooled turbojet engine (PCTJ) using liquid hydrogen fuel were conducted in a Mach 4 flight simulating environment.

- The intake performance map of PCTJ was obtained by varying the angle of the variable mechanism.

- The design temperature of 2000K can be achieved with fuel rich combustion and with fuel lean combustion using the same injector.

- Conceptual design of a hypersonic combined engine that combines a pre-cooled turbojet engine and a scramjet engine was conducted.

- As a result of performance analysis of a hypersonic combined engine, the net thrust / frontal area of the ramjet at Mach 5 was about 1/10 that of a pre-cooled turbojet engine. The specific impulse of turbo-ramjet was about twice that of a pre-cooled turbojet engine.

- Simultaneous optimization analysis of the aircraft shape and trajectory using the performance analysis results of the hypersonic combined engine was conducted and a fuselage shape that can fly across the Pacific Ocean was derived.

- Switching to ramjet operation can reduce the fuel consumption in cruise flights that do not require large thrust.

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Acknowledgment

The authors acknowledge the contribution of researchers at Ramjet Engine Test Facility in JAXA Kakuda Space Center and JAXA technical interns in carrying out the propulsion wind tunnel experiments. The authors also acknowledge the contribution of Dr. Junichi Oki, Dr. Shunsuke Nishida and Mr. Iba in conducting the engine performance analysis. The conceptual design of the hypersonic transport aircraft was carried out as part of joint research with the Tsuchiya Laboratory at the University of Tokyo.

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