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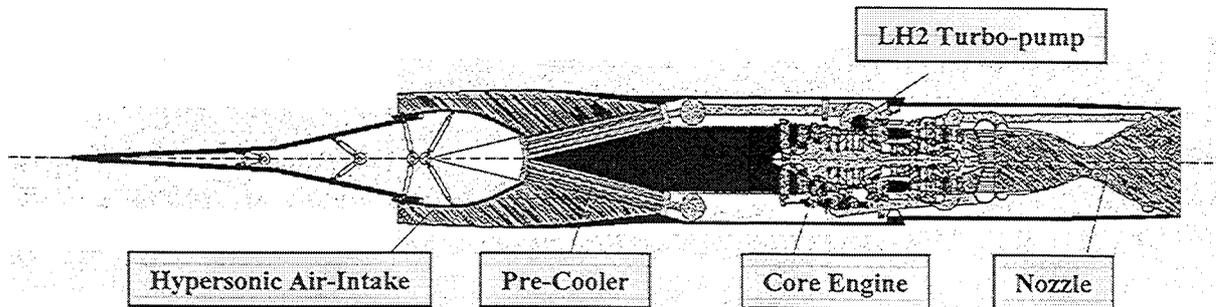
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LH2 Turbo-pump

Hypersonic Air-Intake   Pre-Cooler   Core Engine   Nozzle

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Analytical Study of Pre-Cooled Turbojet Engine for TSTO Spaceplane

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ABSTRACT

Authors are investigating a concept of pre-cooled turbojet engine for Two-Stage-To-Orbit (TSTO) spaceplane. In this study, the engine system is designed with some assumptions. Technological problems and operational limits of the engine are clarified by an engine performance analysis. Then, flight performance of the engine is compared with some air-breathing engines such as: pre-cooled air turbo ramjet, turbo-ramjet and rocket-ramjet. Sizes and mass of engines are estimated by analogical estimations with use of a database of existing engines. As a result, pre-cooled engines brought better payload performance than other engines.

INTRODUCTION

Various concepts of air-breathing propulsion system have been studied for next generation space launchers. The engines must operate from Mach 0 to about Mach 6. The weight of the engine should be light, because the weight is just a penalty for missions. The specific impulse of the engine should be large, because the propellant weight used at accelerating phase is also a penalty for missions. Recently, following accelerator engines are reported with realistic design features: Ejector Ramjet[1], Turbo Ramjet[2,3], Air Turbo Ramjet[4], Deep Cooled Turbojet[5,6], etc.

Authors selected pre-cooled turbojet as an accelerator engine. Figure 1 shows the concept drawing of proposed TSTO. First stage has air-breathing engines. Second stage has conventional rocket engine. Operating speed ranges of each engine mode are assumed as follows: pre-cooled turbojet engine is used between Mach 0

and Mach 6, rocket engine is used over Mach 6.

Figure 2 shows the cross section of the pre-cooled turbojet engine. The incoming air is cooled at pre-cooler by cryogenic fuels like liquid hydrogen. The air density increase by cooling brings larger airflow rate. The temperature drop brings less compressor load. Then, the engine produces larger power compared to normal turbojet engines. In this concept, liquid hydrogen fuel is supplied to the pre-cooler in order to attain low air temperature, and the fuel is injected into both main-burner and after-burner.

Variable shape nozzle is assumed. Gas flow rate is controlled by throat area. The engine also operates with lean combustion at landing phase to obtain high specific impulse. The pre-cooled turbojet engine can achieve high thrust to weight ratio and high specific impulse by controlling the equivalence ratio.

In the former study[7], general performance analysis of the pre-cooled turbojet was conducted. As results, it was confirmed that the pre-cooled turbojet engine with fuel rich operation produces high thrust to weight ratio and can be adopted to Single-Stage -To-Orbit (SSTO) spaceplane.

In this paper, conceptual design of "the

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Pre-cooled Turbojet Engine for TSTO spaceplane is mentioned. Shape and dimension of each component in the sub-scale engine are created in the conceptual design. Off-design performance analysis of the pre-cooled turbojet is carried out. Finally, flight analysis of the engine with an assumed mission was carried out.

CONCEPTUAL DESIGN

Engine System

The system diagram of pre-cooled turbojet combined engine is shown in Fig. 3. Liquid hydrogen is selected as a propellant. Liquid hydrogen is supplied to the engine through the pre-cooling heat exchanger. A part of liquid hydrogen is supplied to the after-burner wall. The hydrogen absorbs the heat, and drives the liquid hydrogen turbo pump.

Air Intake

Two-dimensional bifurcated intake is selected. Required capture area greatly changes, since the flight Mach number varies from 0 to 6. The capture area is adjusted by varying the angle of the cowl. Maximum capture area is decided by front face area of the pre-cooling heat exchanger.

Pre-cooling Heat Exchanger

Two-dimensional pre-cooling heat exchanger is obliquely installed in a subsonic diffuser. The flow velocity of the air is set as 25~30m/s. The heat exchanger is made with the shell and tube system with fins.

Turbo-machinery

Cross section of the turbo-machinery of the pre-cooled turbojet engine is shown in Fig. 2. Six-stage axial compressor with pressure ratio of 10 and two-stage turbine with pressure ratio of 3 are selected. Normal materials, such as titanium for compressor and nickel-based materials for hot

section are assumed.

Nominal combustion temperatures of the main-burner and after-burner are set about 1700K and 2000K, respectively.

After-Burner

Duct part in the turbojet downstream is equipped with fuel injectors for after-burning. Variable geometry nozzle is attached to the after-burner. Exit area of the nozzle is assumed smaller than the intake capture area.

PERFORMANCE ANALYSIS OF PRE-COOLED TURBOJET

Analysis Conditions

Performance of the pre-cooled turbojet in the real flight environment is analyzed. Hydrogen is assumed as fuel. The analysis is carried out with the system diagram of Fig. 3. Thermo physical properties of hydrogen and air are calculated using approximate function obtained by Ref. 8.

Heat balance calculation is executed by design calculation method of Ref. 9. Operating map of the compressor is assumed based on existing compressor. The equivalence ratio is controlled to maintain fixed combustion temperature. Rotational speed, passage area of each component and fuel (coolant) flow rate are varied in order to satisfy the equation of shaft power balance, flow rate balance and heat balance in each flight condition. The convergent calculation is carried out.

Analytical Results
a. Flow Rate and Equivalence Ratio

Figure 4a) shows flow rate and equivalence ratio. The equivalence ratio is controlled to keep temperature of main-burner (T4) constant. Equivalence ratio (ϕ) increases when the Mach number rises. Air mass flow rate decreases under

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high Mach number condition because compressor inlet temperature is increased.

b. Temperature

Figure 4b) shows temperature of each component. Intake exit temperature (T1) increases with the increase of the Mach number. Therefore, heat-resistance material is required at intake and pre-cooling heat exchanger section. However, compressor outlet temperature (T3) is below 600K in the whole flight region. The temperature is equivalent to that of turbojet engines for Mach 3 class supersonic airplane. Turbine inlet temperature (T4) is kept nearly 1700K by controlling equivalence ratio

c. Pressure

Figure 4c) shows pressure of each component. Compressor exit pressure (P3) takes the maximum value (about 1.4MPa) at Mach 6. Compressor power decreases with temperature drop by pre-cooling. This brings high turbine exit pressure (P5) such as about 1.0MPa.

d. Passage Area

Figure 4d) shows passage area of each component. For taking the flow rate matching of intake and engine, intake throat area (Ait) varies. Effective capture area (Acef) with Mach 0.3~4 is smaller than maximum capture area (Acmax). The area is decided by front face area of the pre-cooler. The whole momentum of the spillage flow is considered as the resistance in this region. Acef at maximum rotation speed is larger than Acmax beyond Mach 4. Then, rotation speed is limited in this region.

The flow rate mismatching of compressor and turbine occurs when the compressor inlet temperature rose and the combustion temperature is kept constant. Since this mismatching is larger than normal turbojet, turbine stator vane is assumed to move and adjust turbine throat area (Att). Operating line on the compressor map can be set to

pass through the maximum efficiency line. Nozzle throat area (Ant) of after-burner should be slightly varied for taking the flow rate matching of engine and nozzle.

Nozzle exit area (Ane) is set to be smaller than Acmax. Ac beyond Mach 1.5 limits Ane. The exhaust gas is under expansion in this region.

e. Rotation Speed and Shaft Power

Figure 4e) shows analytical result of engine rotation speed and shaft power. Mechanical rotation speed (N) is decided by the upper limit of corrected rotation speed (Nc) in the Mach range between 0 and 2. This is because sound velocity drops by the pre-cooling. Compressor inlet temperature rises over the design point in the Mach range between 2 and 3.5. N is limited by a mechanical limit in this region. Acmax beyond Mach 3.5 limits air flow rate of intake. N is limited to match the air flow rate of intake and engine.

MISSION ANALYSIS

Mission performance of air-breathing propulsion systems are analyzed by simplified method in order to make a fair comparison. Discussion of absolute values of payload and components make little sense, because the values change sensitively with assumptions of material, aerodynamic performance, etc. Objective of this section is the qualitative comparison of propulsion systems with a same assumption.

Engine Systems for Comparison

Table 1 shows analysis condition of engine systems. Calculation is conducted from take off to Mach 6 with dynamic pressure of 34kPa.

Figure 5a) is the engine system diagram of pre-cooled air turbo ramjet (PCATR). Institute of Space and Astronomical Science carry out firing test of pre-cooled air turbo ramjet (ATREX)[4]. The

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engine cycle under sea level static condition has been verified. The fan of the engine is driven by hot hydrogen gas, which is generated by heat exchanger installed in the main combustor.

Figure 5b) is the engine system diagram of turbo ramjet (TJ+RAM). Turbo ramjet with design operating range of Mach 0 to 5 was developed in research and development project of super/hyper-sonic transport propulsion systems (HYPR)[3] by Ministry of International Trade and Industry. The engine operation under condition between Mach 0 and 3 has been verified by high altitude test.

Engine Performances

Figure 6 shows analytical results of engine performance analysis of the engines.

Specific impulse (Isp) of TJ+RAM is higher than that of PCATR and PCTJ. This is because the compressor exit temperature is high and the equivalence ratio is relatively low with same combustion temperature limit. Thrust / capture area of PCATR and PCTJ is higher than that of TJ+RAM. This is because pre-cooling increases the mass flow rate of air.

Differences between PCATR and PCTJ are primary brought by pressure ratio. The temperature of hot hydrogen at the turbine inlet limits the pressure ratio of PCATR.

Flight Analysis Condition

Figure 7 shows the force diagram of the flight analysis. Calculation procedure and aerodynamic data is the same as Ref. 10. The vehicle is treated as a mass point. The motion is fixed at the equatorial plane, and the vehicle moved in the direction of east. Thrust, gravity force at the altitude, centrifugal force, lift and drag is involved in the equations. Angle of attack and thrust are controlled to attain the designated flight pass.

Table 2 shows the flight analysis conditions. The flight analysis is carried out using engine performance mentioned above. Liquid hydrogen is used as fuel. Initial mass of 350Mg and dynamic pressure of 34 kPa are assumed. Front area of the engine is decided by the results of the performance analysis at sea level. Maximum thrust at each flight speed is calculated using approximate function of the performance analysis results.

Mass Estimation

Table 3 shows the mass estimation conditions. Mass of airframe parts is estimated using Ref. 11. Wing size is determined by total take off mass. Wing loading is assumed as $500kg/m^2$. Mass of tanks is estimated by design calculation. Composite material with safety coefficient of 4.5 is assumed as the materials for Liquid hydrogen tank. Aluminum alloy with safety coefficient of 1.5 is assumed as the material of liquid oxygen tank. Mass of pre-cooler is estimated by a design analysis method, which is evaluated by experiments using scaled models. Mass of the turbojet engine is estimated by actual engine trends, using function of pressure ratio and volume flow rate. Mass of ramjet is estimated by a duct design analysis with Carbon/Carbon panels. Mass of rocket engine is estimated using data of LE-7A engine[12].

Mass Ratio

Figure 8 shows the comparison of calculated payload. First stage engine mass with turbo-based engines is very large. However, payload mass with turbo-based engines is larger than that of rocket-based engines. This is because the first stage propellant mass of those is very small.

First stage engine mass of PCATR and PCTJ are lower than that of TJ+RAM. Then, it is estimated that the pre-cooled engines brings comparatively large payload than other engines considering fly back operation. However, further study with precise mass estimation and mission analysis is necessary for selection within turbo-based engines. Figure 9 show the airframe configuration with PCTJ, obtained by above mentioned mission analysis.

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CONCLUDING REMARKS

Pre-cooled turbojet engine for TSTO spaceplane is designed and its features are clarified by analyses. Followings are confirmed as results.

1) Pre-cooled turbojet engine cycle give enough performance for TSTO spaceplane.
2) Exiting compressor structure can be used to the pre-cooled turbojet engine.
3) Payload mass of TSTO spaceplane with turbo-based engines is larger than that of rocket-based engines.
4) Further study with precise mass estimation and mission analysis is necessary for selection within turbo-based engines.

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11. Harloff, G. J. and Berkowitz, B. M., "HASA-Hypersonic Aerospace Sizing Analysis for the Preliminary Design of Aerospace Vehicles," NASA CR-182226, 1988.

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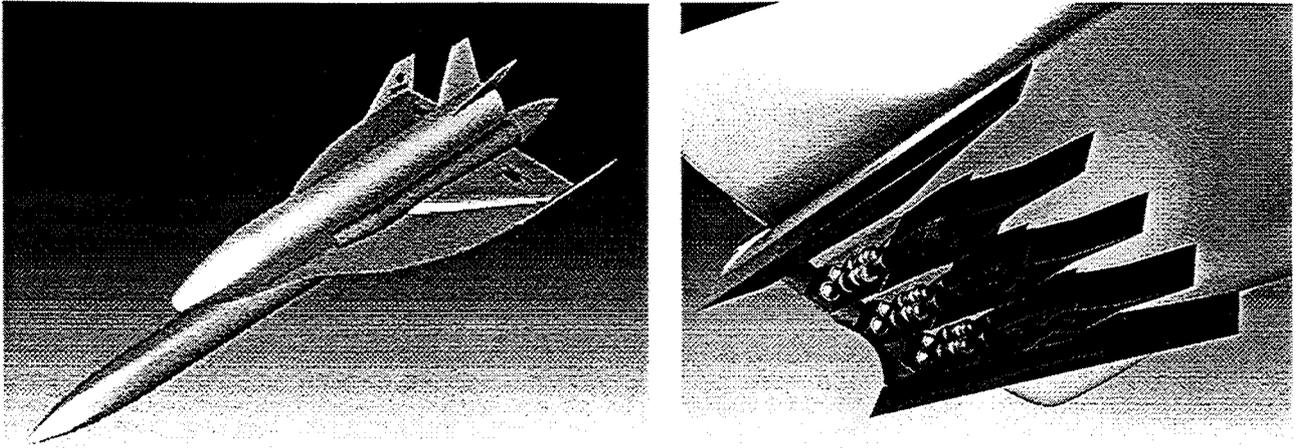
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Fig. 1 TSTO Spaceplane Concept

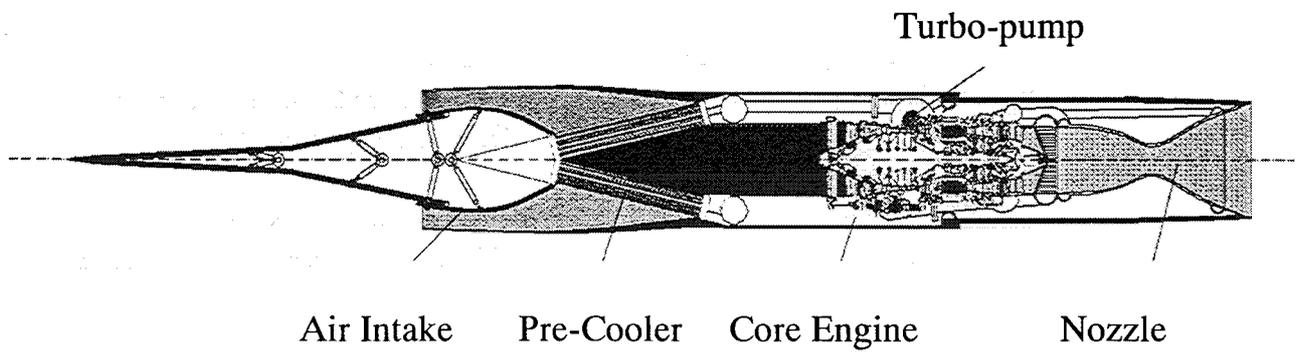Turbo-pump

Air Intake   Pre-Cooler   Core Engine   Nozzle
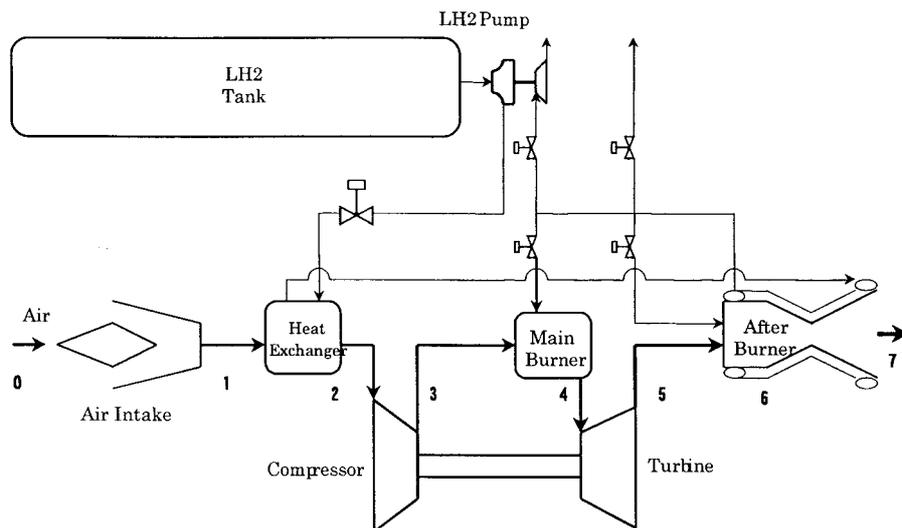
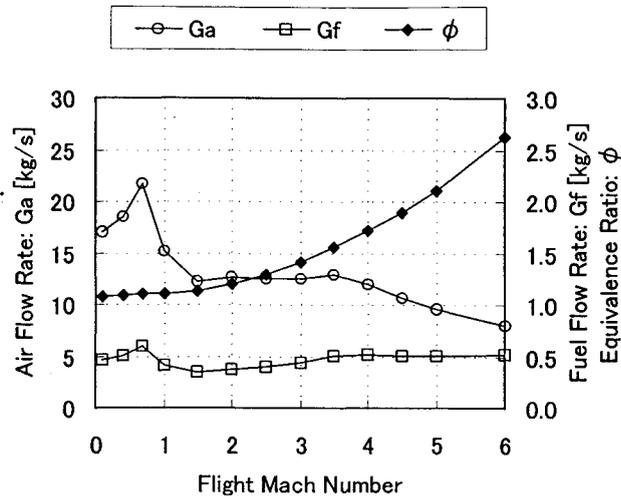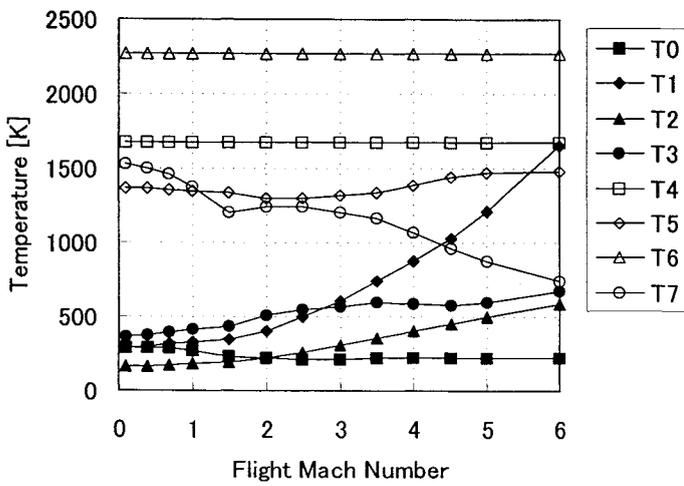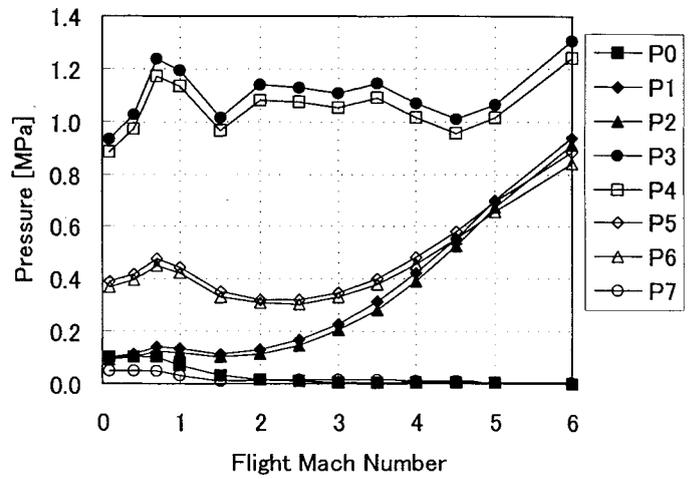Fig. 2 Cross Section of Pre-Cooled Turbojet Engine (PCTJ)

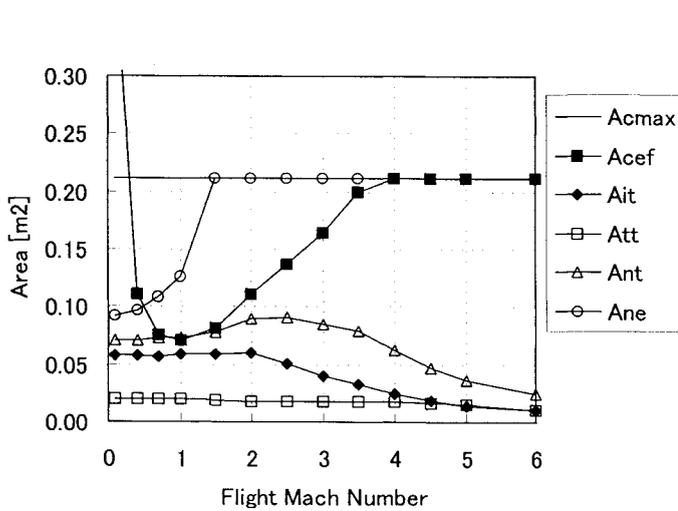Fig. 3   System Diagram of Pre-Cooled Turbojet Engine (PCTJ)

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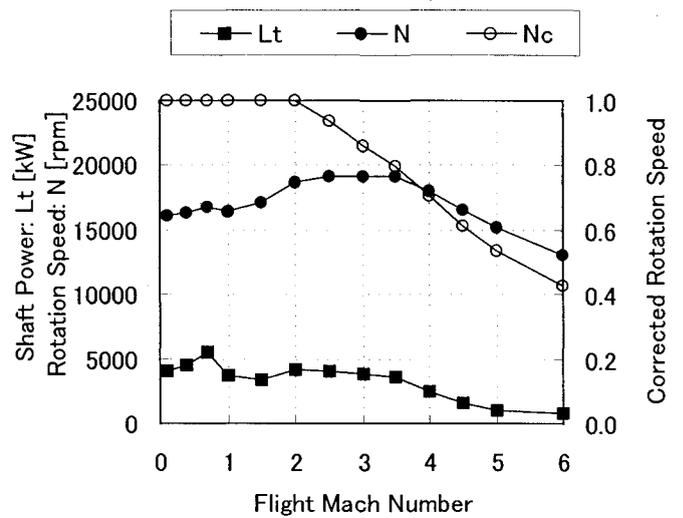a) Flow Rate, Equivalence Ratio

b) Temperature Distribution

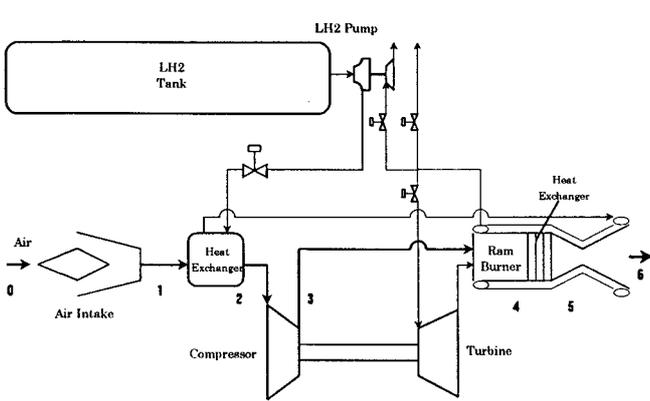c) Pressure Distribution

d) Passage Area

e) Shaft Power, Rotation Speed

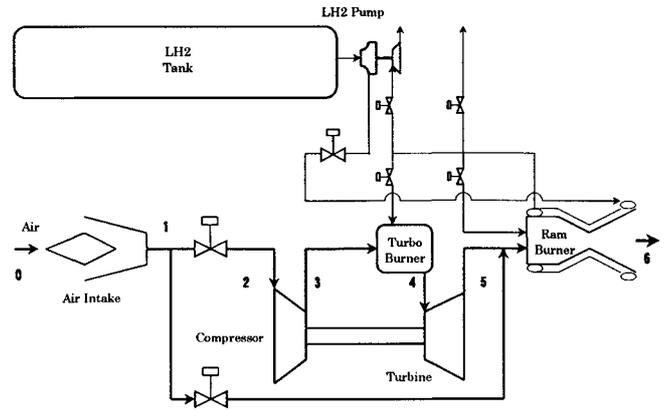Fig. 4   Performance of Pre-Cooled Turbojet Engine (PCTJ)

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Table 1 Engine Analysis Conditions

	PCTJ	PCATR	TJ+RAM
Dynamic Pressure [kPa]:	34	34	34
Compressor Pressure Ratio:	10	3.3	10
Main Burner Temperature [K]:	1673	-	2000
After/Ram Burner Temperature [K]:	2273	2400	2400

a) Pre-Cooled Air Turbo Ramjet (PCATR) b) Turbo Ramjet (TJ+RAM)
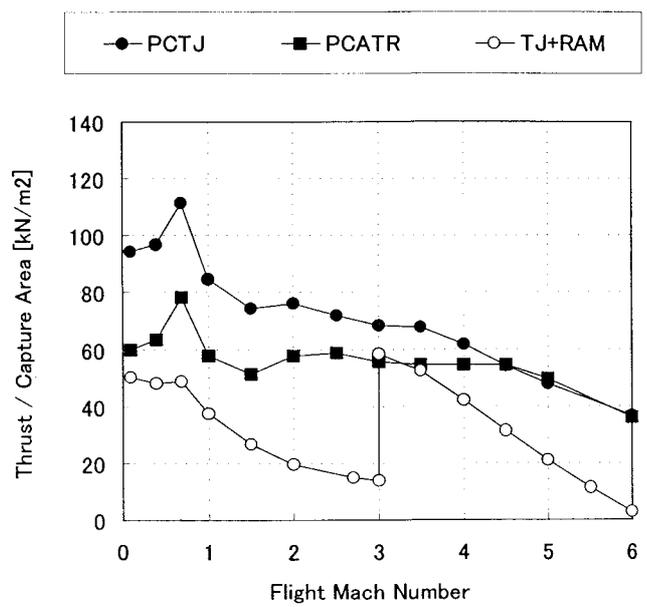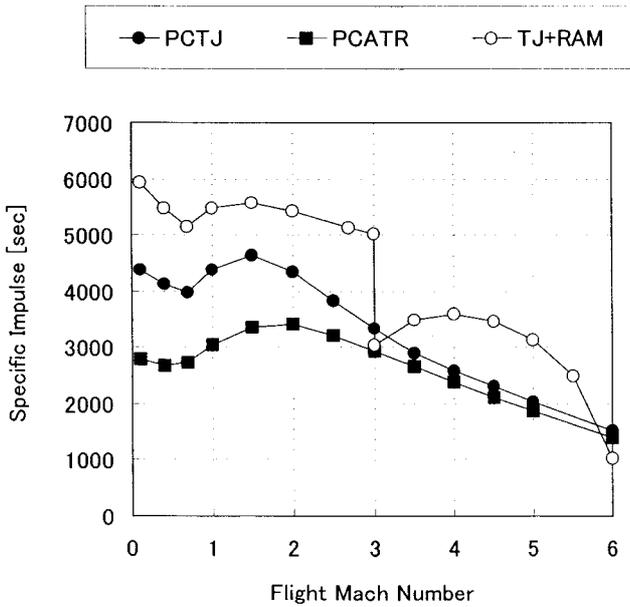
Fig. 5 Engine System Diagrams
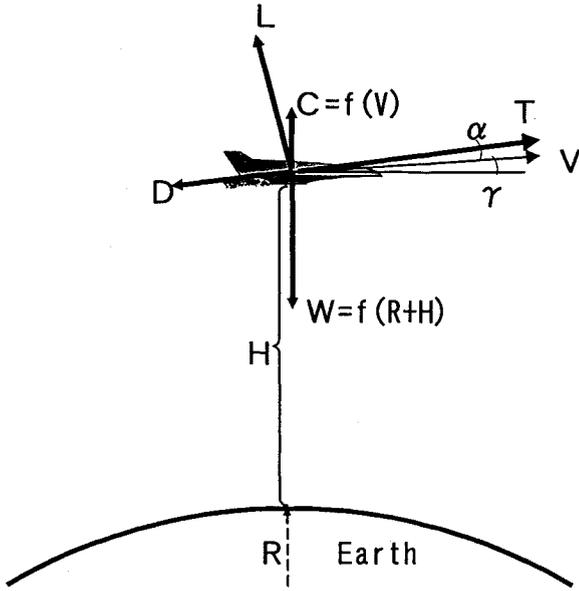

Fig. 6 Comparison of Engine Performances

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Fig. 7 Force Diagram of Flight Analysis

Table 2 Flight Analysis Condition

Dynamic Pressure:	34 kPa
Fuel:	LH2
Initial Mass:	350 ton
Initial Acceleration:	0.5G
Mach Number:	0 ~6

Table 3 Mass Estimation Condition

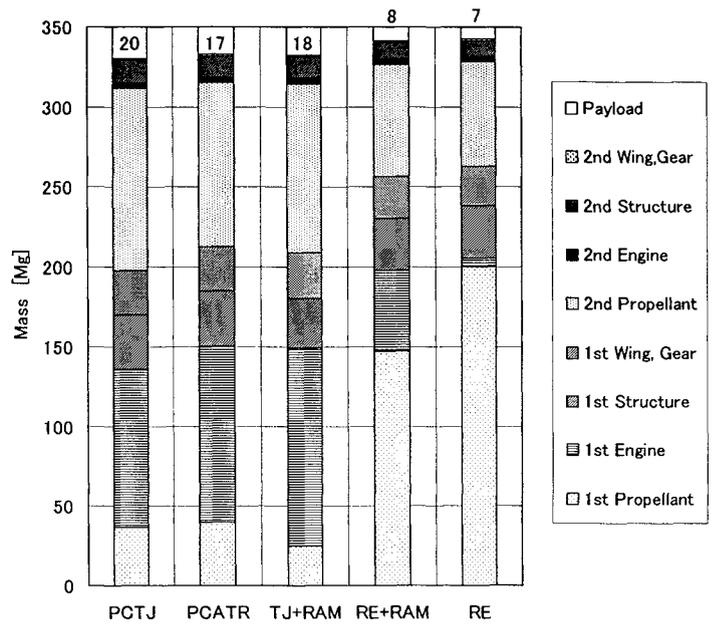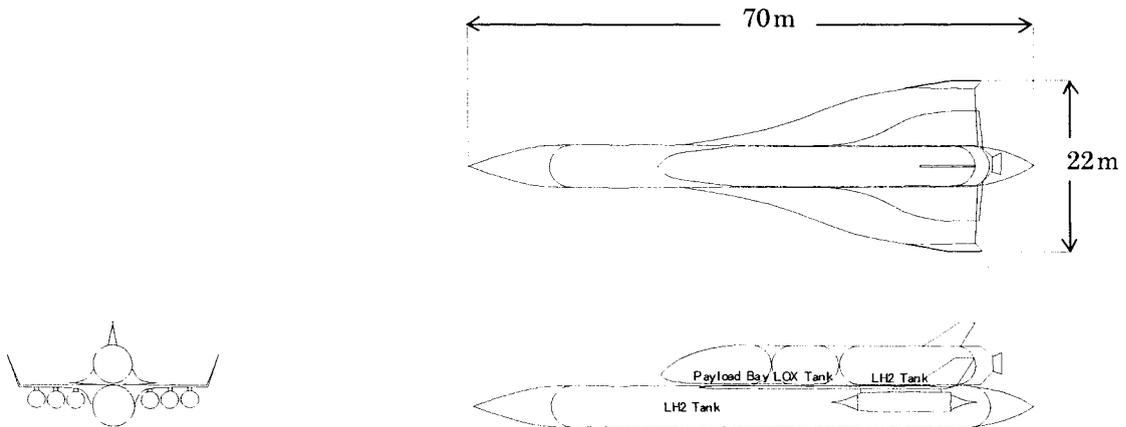|	
Base:	HASA
Wing Size:	Estimated by Take-off Mass
Wing Loading:	500 kgf/m^2
Airframe, LH2 Tank:	Composite (Safety coefficient = 4.5)
LOX Tank:	Alminum (Safety coefficient = 1.5)
Turbojet Engine:	Estimated by Trend Curve (π, Q)
Ramjet Engine:	C/C Panels and Beams
Rocket Engine:	Estimated by LE-7A

Fig.8 Comparison of Mass Ratio

Fig. 9 Airframe configuration

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