Conceptual Study on Hypersonic Turbojet Experimental Vehicle (HYTEX)

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Pre-cooled turbojet engines have been investigated aiming at realization of reusable space transportation systems and hypersonic airplanes. Evaluation methods of these engine performances have been established based on ground tests. There are some plans on the demonstration of hypersonic propulsion systems. JAXA focused on hypersonic propulsion systems as a key technology of hypersonic transport airplane. Demonstrations of Mach 5 class hypersonic technologies are stated as a development target at 2025 in the long term vision. In this study, systems analyses of hypersonic turbojet experiment (HYTEX) with Mach 5 flight capability is performed. Aerodynamic coefficients are obtained by CFD analyses and wind tunnel tests. Small Pre-cooled turbojet is fabricated and tested using liquid hydrogen as fuel. As a result, characteristics of the baseline vehicle shape is clarified, and effects of pre-cooling are confirmed at the firing test.

Key Words: Hypersonic, Propulsion, Hydrogen

Nomenclature

\[ \begin{align*}
   Cp & \quad \text{pressure coefficient} \\
   CN & \quad \text{normal force coefficient} \\
   CA & \quad \text{axial force coefficient} \\
   CMB & \quad \text{pitching moment coefficient}
\end{align*} \]

1. Introduction

Pre-cooled turbojet engines and scramjet engines have been investigated aiming at realization of reusable space transportation systems. Evaluation methods of these engine performances have been established based on ground tests. X-43A\textsuperscript{1} flight experiment was successfully conducted to demonstrate scramjet engine technologies. There are some following plans on the demonstration of hypersonic propulsion systems.

JAXA focused on hypersonic propulsion systems as a key technology of hypersonic transport airplane (Fig. 1). Demonstrations of Mach 5 class hypersonic technologies are stated as a development target at 2025 in the long term vision. These hypersonic technologies can be applied to reusable space transportation systems by adding upper stage rockets.

In this study, systems analyses of hypersonic airplanes with Mach 5 cruising capability are performed in order to improve the speed of intercontinental transportations. Requirements for engine performance, thrust to mass ratio and heat resistant structure are discussed.

As a result, reference concept of a hypersonic airplane with liquid hydrogen fuel is shown. Then, a small hypersonic flight experiment is planned for demonstration of Mach 5 cruising technologies. And, aerodynamic coefficient was acquired on the basic shape of small hypersonic experimental vehicle by CFD and wind tunnel test.

2. System Evaluation of Small Hypersonic Turbojet Experiment Vehicle

There are several technical problems that should be solved though the performance of a hypersonic airplane with pre-cooled turbojet is shown in the foregoing paragraph. Therefore, plans of the engine wind tunnel experiment and the flight experiment that uses a small pre-cooled turbojet engine\textsuperscript{2,3} (Fig. 2) are planned. Production of this small engine is completed now.

The engine is composed of an air intake, a pre-cooler, a turbojet, a ram combustor and an exhaust nozzle. The air intake has a variable mechanism\textsuperscript{4} to adapt to wide flight speed range. The pre-cooler is installed in front of the turbojet engine to reduce the air temperature by the heat exchange with liquid hydrogen. The turbojet engine with a metal structure can be operated even at Mach 6, because the air temperature at the compressor is reduced by the pre-cooler. The ram
combustor is used to inject hydrogen fuel, which absorbed the heat of incoming air at the pre-cooler. The exhaust nozzle has a variable mechanism to adapt to wide variations of the ambient pressure and the air flow rate.

Figure 2 shows a drawing of hypersonic turbojet experimental vehicle with external solid booster. A small pre-cooled turbojet engine will be installed on this vehicle. The shape is defined based on an integrated optimization analysis result. The vehicle is supposed to install 2 sets of engines and to fly for several seconds at Mach 5 cruising speed. The vehicle size is 4.5m in length. In a small engine, because the engine parts should be installed even in the airframe, a necessary fuel for acceleration cannot be installed. Then, external acceleration devices such as stratospheric balloon and solid rocket booster are considered for this vehicle.

Figure 3 shows the outline of the flight experiment that assumes acceleration by a solid rocket booster. The vehicle will be launched by a solid rocket booster and reach 90 km height. After that, it will be accelerated by free drop flight and reach the speed of Mach 5 with dynamic pressure of 50kPa. Performance of the pre-cooled turbojet will be obtained with the experiment.

Figure 4 shows the distribution of pressure coefficient (Cp) obtained as an analytical result. It is understood from this figure to cause a high pressure coefficient in the leading edge part of the airframe, and tail wings. The aerodynamic coefficient for comparison with the wind tunnel test is calculated by using this analytical result.

The CFD analysis of the basic shape of HYTEX is executed. Two types of analysis model is used. One is without engines and the other is with engines. UPACS\textsuperscript{6} code of JAXA is used as an solver. In this analysis, the Matrix-Free Gauss-Seidel method is used by a cell center finite volume method with compressible Navier-Stokes equations. Spalart-Allmaras model is used for the turbulent flow model. The analytical grid is assumed to be 34 blocks and about 4.9 million points. It is assumed that the experimental vehicle flies with dynamic pressure of 50kPa and Mach 5, and the Reynolds number is set to 3.1×10\textsuperscript{7}.

Table 1 shows the specification of a small Pre-cooled turbojet engine. The engine is designed to be installed on the test stand of Ramjet engine test facility (RJTF) in JAXA. The total length is about 2.7m. The wind tunnel test on a variable geometry intake, the heat exchange experiment of pre-cooler, the high-speed rotation test of the core engine, and the burning test of combustion nozzle had been executed up to now. Elemental technical data for each components has been acquired. Then, the engine system combustion test has been done on a ground test facility.

<table>
<thead>
<tr>
<th>Element</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>2.7 m</td>
</tr>
<tr>
<td>Mass</td>
<td>150 kg</td>
</tr>
<tr>
<td>Thrust (Mach 0)</td>
<td>1500 N</td>
</tr>
<tr>
<td>Thrust (Mach 6)</td>
<td>800 N</td>
</tr>
<tr>
<td>Fuel</td>
<td>LH2</td>
</tr>
<tr>
<td>Mach number (Metal Engine)</td>
<td>0 - 2</td>
</tr>
<tr>
<td>Mach number (Composite Engine)</td>
<td>0 - 6</td>
</tr>
</tbody>
</table>

The aerodynamic coefficient of basic shape of HYTEX is measured in JAXA hypersonic wind tunnel facility.

Table 2 shows the test case with the wind tunnel test. The blow condition was Mach 5.1, total pressure 1.0 MPa, and total temperature 673 K. Two types of models are prepared for the experiment. One is “with engine” and the other is “without engine.” The model with engine aims to evaluate the influence of engine to the aerodynamic coefficient of the airframe. The model without engine aims to obtain the verification data of the CFD analysis result.

On the wind tunnel experiment, 5% scale model made of stainless steel with the size of 225 mm in length is used. Aerodynamic coefficients are measured with a load cell that is installed in the model downstream part.

Figure 6 shows the Schlieren photograph of the wind tunnel experiment (with engine, Mach 5, α = 5 deg). A strong shock wave is generated from the airframe leading edge, and a shock wave is generated from the vicinity of a vertical tail. The expansion wave has been generated from an external nozzle under the rear side of the airframe.

Next, the aerodynamic coefficient measured in the Mach 5 wind tunnel test is arranged. Coefficients for normal force (CN), axial force (CA), pitching moment (CMB), are defined. The standard area for aerodynamic coefficients is calculated with the product of total length and width of the body. The reference point of the moment is set at the 35% position of the total length from the nose.

Figure 7 shows the change in the aerodynamic coefficient when attack angle (α) is changed. Experimental values by the wind tunnel test are indicated with solid marks. Analytical values by CFD are indicated with open marks. CFD result of axial force (CA) and pitching moment (CMB) correspond to those of experiments. As for normal force (CN), the inclination of CFD result is slightly low though the tendency is similar. It is possible that the difference of the airframe surface flow described later influence to this coefficient.

<table>
<thead>
<tr>
<th>Table 2 Wind tunnel test case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mach number</td>
</tr>
<tr>
<td>Total Pressure</td>
</tr>
<tr>
<td>Total Temperature</td>
</tr>
<tr>
<td>Engine</td>
</tr>
<tr>
<td>Attack Angle</td>
</tr>
<tr>
<td>Side Slip Angle</td>
</tr>
</tbody>
</table>

Fig. 5  Pressure coefficient (Cp) distribution 
(with engines, Mach 5, α = 5 deg)

Fig. 6  Schlieren photograph 
(with engines, Mach 5, α = 5 deg)

Fig. 7  Aerodynamic coefficients 
(without engines, Mach 5, α sweep)
Lift to drag ratio in Mach 5 at $\alpha = 5$ deg is predicted as about three. This is enough for the flight demonstration of a small Pre-cooled turbojet engine.

Axial force (CA) moves in a positive direction with the model with engine. The reason for the deflection may caused by friction drag and surface flow around the engine comparing to that without engine. The other aerodynamic coefficients are similar to that without engines. Moreover, un-start phenomenon of flow through engine duct has happened at high attack angle. Therefore, it is necessary to examine the influence of the surface flow around the engine to the aerodynamic coefficients considering the presence of un-start.

4. Evaluation of Airframe Surface Flow

The surface flow of the model is visualized to evaluate the influence of the surface flow to aerodynamic coefficients.

In the wind tunnel test, the airframe surface flow is made visible by an oil flow method. In the oil flow test, the surface of the model was painted with black paint, silicon oil that had mixed the fluorescent coating is spread on the surface of the model before blowing. Several pictures and a movie of the flow pattern are taken during the blowing of wind tunnel.

Figure 8 shows the surface flow pattern obtained by CFD (Mach 5, without engine, $\alpha = 2$ deg). Because pressure of the lower surface rises more than that of the upper surface, the roll flow is formed from the lower side to the upper side. On the other hand, pressure of the lower surface of the back part of the airframe is lower than that of the upper surface because of expansion. Then, the falling flow is formed in this area. A large-scale separation is formed in the center part of upper surface. It is thought that this separation region influences the difference of normal force in CFD and the wind tunnel test.

5. Firing Test of a Small Pre-cooled Turbojet

Those engine components are assembled to a core engine and tested. The setup of the firing test is shown in fig. 9. Firing tests were carried out in both Combustion Test Facility and Noshiro Multi-Purpose Test Center in JAXA. Gas hydrogen is used for the core engine. Liquid hydrogen is used for the pre-cooler and after burner.

Air intake with pitot tubes is connected in the upstream of the core engine. Variable geometry exhaust nozzle is connected downstream of the core engine. The air flow rate is modulated with changing the throat area of exhaust nozzle. The initial rotation was made by a brushless motor with high-speed rotation type. In the experiment, the followings were measured: Rotational speed, outer shell vibration, total pressure distribution, static pressure distribution, temperature distribution, air mass flow rate and fuel flow rate.

![Fig. 8 Surface flow pattern obtained by CFD (without engine, Mach 5, $\alpha = 2$ deg)](image)

![Fig. 9 Set-up for firing test](image)

5.1 Test Sequence and Conditions

Table 3 shows nominal test sequence. Rotation of core engine is initiated by an electric motor. Rotation speed of 5% (4000rpm) is sustained until -5 sec. Then, rotation speed is increased to 20% (16000rpm) until 0 sec. Injection of main fuel to the core engine is started at 0 sec. Fuel flow rate is gradually increased to keep the main burner temperature below the design limit of 1223K. At 90sec, liquid hydrogen is supplied to the pre-cooler and after burner. Pre-cooler fuel is stopped at 110sec, and main burner fuel is stopped at 120sec.

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>-20 sec</td>
<td>Starter Motor Start (5% Rotation)</td>
</tr>
<tr>
<td>-5 sec</td>
<td>20% Rotation</td>
</tr>
<tr>
<td>0 sec</td>
<td>Main Fuel Supply (Gas Hydrogen)</td>
</tr>
<tr>
<td>20 sec</td>
<td>Starter Cut-off</td>
</tr>
<tr>
<td>90 sec</td>
<td>Pre-Cooler Fuel Supply (Liquid Hydrogen)</td>
</tr>
<tr>
<td>110 sec</td>
<td>Pre-Cooler Fuel Cut off</td>
</tr>
<tr>
<td>120 sec</td>
<td>Main Fuel Cut-off</td>
</tr>
</tbody>
</table>

Pa_30
Table 4 shows test cases described in this paper. Mechanical rotation speed of the core engine is about 50% of design speed for all cases. In Case 1, only core engine is operated. In Case 2, core engine and pre-cooler are operated. Combustion in the after burner is not happened. In Case 3, all the engine parts are operated. However, the test is stopped at 95sec because of a temperature limit at downstream of the engine. In all cases, exhaust nozzle is fully opened.

<table>
<thead>
<tr>
<th>Case</th>
<th>Rotation Speed</th>
<th>Core Engine</th>
<th>Pre-Cooler</th>
<th>After Burner</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>50%</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
</tr>
<tr>
<td>Case 2</td>
<td>50%</td>
<td>ON</td>
<td>ON</td>
<td>OFF</td>
</tr>
<tr>
<td>Case 3</td>
<td>50%</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
</tr>
</tbody>
</table>

5.2 Rotation Speed

Figure 10 shows time history of rotation speed and corrected rotation speed for compressor in Case 2. Rotation speed is measured using gap sensors installed at the compressor rotor blades and main shaft. At -20sec, rotation speed is about 4000rpm. From -5sec, rotation speed is rapidly increased by electric motor. From 0sec to 20sec, rotation speed is increased by the power of electric motor and main burner. From 20sec to 80sec, rotation speed is increased by the power of main burner. At around 20sec, rotation speed exceeds 30% and started acceleration without help of electric motor. From 90sec to 110sec, liquid hydrogen is supplied to pre-cooler and after burner. At 120sec, supply of main burner fuel is stopped.

Corrected rotation speed is almost the same as mechanical rotation speed before 90sec. After the supply of liquid hydrogen, corrected rotation speed is increased in spite of almost constant mechanical rotation speed. This phenomenon is happened by the effect of pre-cooling. When the liquid hydrogen is supplied to the pre-cooler, air temperature at the compressor inlet is decreased and the corrected rotation speed is increased. In this experiment, maximum corrected rotation speed is about 75% (60000rpm).

5.3 Air Flow Rate, Fuel Flow Rate

Figure 11 shows time history of air flow and fuel flow in Case 2. Air flow rate is calculated using measured pressure data of pitot tubes installed at the exit of air intake. The accuracy of pressure sensor is not enough for low flow rate region, because the measured pressure level is very low comparing to the maximum range of the sensor. Tendency of air flow variation is similar to that of corrected rotation speed.

Fuel flow rate is measured by an orifice flow meter installed upstream of main fuel valve. There is a spike at about -3sec. This is caused by an initial leakage of flow control valve. Then, main valve is opened after the initial leakage is settled. From -3sec to 0sec, the fuel is supplied to a vent line.

At 0sec, fuel flow rate for ignition is set. Then, from 0sec to 20sec, fuel flow rate is increased to attain self acceleration condition. From 20sec to 40sec, fuel flow rate is set constant in order to make stable condition. In this period, rotation speed is increased by excessive power of turbine. From 40sec to 90sec, the fuel flow rate is increased again, to reach 50% mechanical rotation speed.

5.4 Main Burner Temperature

Figure 12 shows time history of main burner temperature in Case 2. The temperature is largely increased from 0sec to 20sec. At 18sec, temperature increase is stopped in spite of increasing fuel flow. This may indicate the transition point to self accelerating condition. After 20sec, temperature is increased again in spite of constant fuel flow. At this time, power supply to the electric motor is stopped. Possible reason of the temperature increase is combustion efficiency is changing. After 40sec, temperature is increased as well as the increase of fuel flow and become stable condition.

From 90sec to 110sec, temperature is largely decreased because of pre-cooling. At this period, air flow rate is increased and fuel flow is constant. Then, equivalence ratio is reduced and combustion temperature is decreased. Air
temperature at the inlet of compressor is largely reduced by pre-cooling. This also affect the decrease of main burner temperature. From 110sec to 120sec, temperature is increased again. This is because the pre-cooling is stopped.

6. Concluding Remarks

Basic shape of a small hypersonic turbojet experimental vehicle (HYTEX) is defined and its aerodynamic coefficients are evaluated by CFD analyses and wind tunnel tests. A small pre-cooled turbojet engine is tested using liquid hydrogen fuel. As a result, followings are obtained.

- Lift to drag ratio of the basic shape of HYTEX at 5 deg attains about 3, and the flight experiment of a small pre-cooled turbojet engine is possible by this shape.
- The core engine can be accelerated by combustion gas when the rotation speed is over 30%.
- Effects of pre-cooling such as increase of air flow and decrease of compression power are confirmed in the firing test.

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