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Mach 5 Propulsion Wind Tunnel Test of High-Mach Integrated Control Experiment Aircraft (HIMICO)

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Abstract

Research and development of the hypersonic integrated control experimental aircraft (HIMICO) was carried out with the aim of establishing elemental technologies for a hypersonic aircraft that flies at Mach 5. Hypersonic intake wind tunnel tests, hydrogen ramjet combustion tests, hypersonic aircraft aerodynamic tests, etc. were conducted to obtain elemental performance. A propulsion wind tunnel experiment simulating Mach 5 flight conditions is planned to confirm the heat-resistant aircraft structure and the function of the onboard equipment, and to evaluate the propulsive performance of the hypersonic engine mounted on the aircraft.

Keywords: *Propulsion, Air-Breathing, Hypersonic*

Nomenclature

TPR - Total pressure recovery rate
MCR - Mass capture ratio
FCV - Fuel flow control valve opening rate
ΔFCV - Fuel flow control valve control amount
Tc - Combustion temperature

1. Introduction

The Basic Plan for Space Policy[1)] in Japan indicates that development of elemental technologies will be promoted in areas expected to have large markets in the long term, such as high-speed point-to-point transportation and space travel. JAXA has been conducting system studies for hypersonic passenger aircraft[2)], as well as combustion tests of hypersonic engines[3)]. Furthermore, research and development of the High-Mach Integrated Control Experimental Aircraft (HIMICO) [4)](Fig. 1) has been progressed to demonstrate integrated airframe/propulsion control technology. The objective of the aircraft is to demonstrate the propulsive performance of a hypersonic engine with various flight speed and attitude during hypersonic flight.

Figure 1 shows the Hypersonic Integrated Control Experimental Vehicle (HIMICO) . The aircraft is 2000 mm long and 440 mm wide. It has a delta wing attached to its cylindrical fuselage. A vertical tail wing is attached to the top of the fuselage, and a hypersonic engine is attached to the bottom.

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This paper summarizes the plan for the Mach 5 propulsion wind tunnel test of the HIMICO experimental aircraft, the configuration of the test equipment, and the results of the control tests of hypersonic engine elements.

Figure 1: Hypersonic Integrated Control Experimental Vehicle (HIMICO)

2. Hypersonic Flight Experiment Concept

A flight experiment concept for the Hypersonic Integrated Control Experimental Vehicle (HIMICO)[5)] (Figure 2) has been proposed to demonstrate control methods for a hypersonic vehicle and hypersonic engine in a real-flight environment. This concept envisions using a sounding rocket operated by JAXA to launch the experimental vehicle into space at an altitude of over 100 km, accelerating it through free fall, and flying it at a speed of approximately Mach 5. The experimental vehicle was designed with consideration for the balance of lift and weight required to transition from free fall to level flight to achieve this flight trajectory. Aerodynamic performance data maps were created through wind tunnel test and CFD analysis. Flight control simulations[6)] were performed using a program developed at the University of Tokyo.

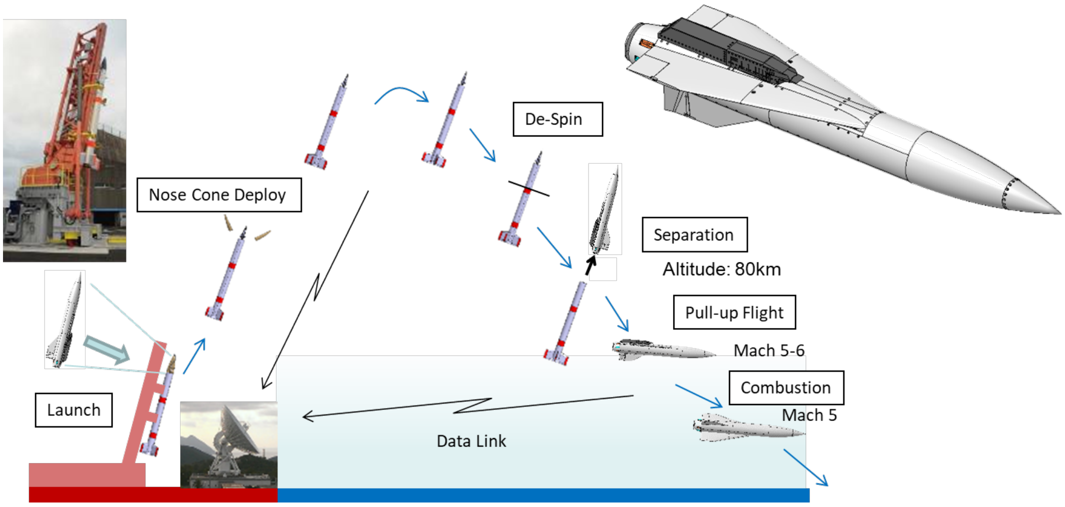


Figure 2 Hypersonic flight experiment concept[5)]

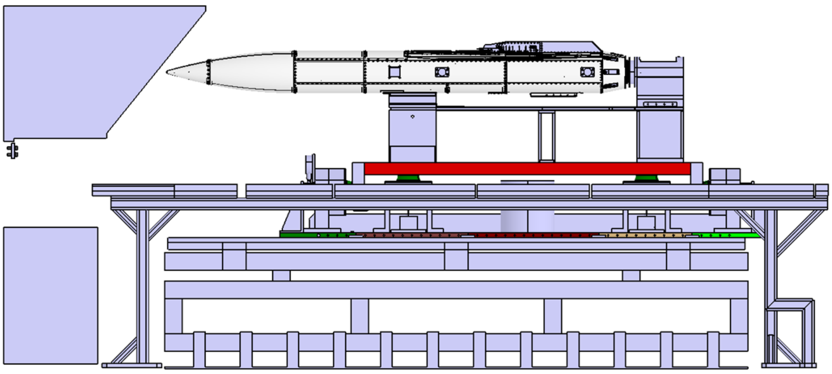
3. Airframe/Propulsion Integrated Control Experiment

A propulsion wind tunnel test is planned with the aim of establishing airframe/propulsion integrated control technology for a hypersonic aircraft in a Mach 5 flight environment. The HIMICO experimental aircraft will be installed in the ramjet engine test facility at JAXA's Kakuda Space Center. The plan is to operate the hypersonic engine and control surfaces in a Mach 5 airflow to obtain engine control and attitude control characteristics.

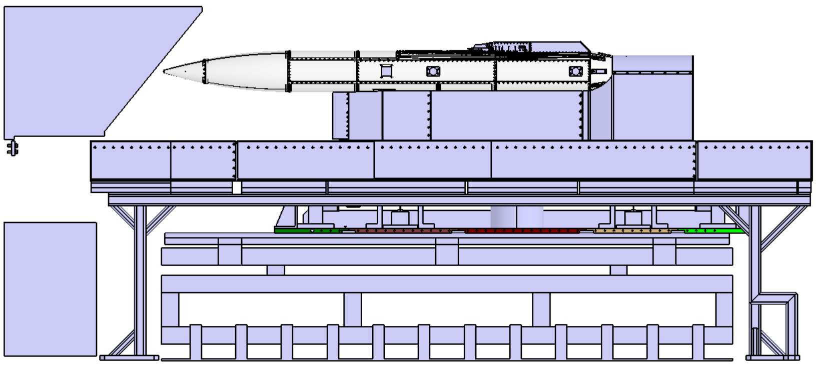
3.1 Test Setup

Figure 3 shows the experimental setup for the HIMICO airframe/propulsion integrated control experiment. (a) shows the aircraft model with strut installation. The experimental aircraft is supported by struts at the rear and bottom to withstand the wind tunnel startup load. The vertical tail wing is not attached with this support system, and the engine is located above the fuselage. The struts are connected to a three-component balance, allowing for measurement of the three vertical force components of the airflow. One side of the test specimen may be supersonic and have low pressure, while the other side is subsonic and has high pressure at the start of testing in supersonic/hypersonic wind tunnels. It can cause a starting load to be generated that pushes the test specimen with great force. The support column mounting points are reinforced to prevent the test specimen from being damaged by the starting load for this reason. In addition, a mechanism is provided to fix the balance when the wind tunnel is started and stopped to prevent the three-component balance from being damaged by the starting load. This mechanism is operated by pneumatic cylinders.

b) is a setup image at fairing installation status. A Mach 5 airflow flows from the equipment nozzle on the left. The cross section of the airflow is a 500mm x 500mm rectangle. The HIMICO experimental aircraft is placed in the center of the airflow. A fairing plate is placed around the support strut to prevent the airflow from hitting the strut, and the fairing plate is fixed onto a fairing mount connected to the floor of the wind tunnel. This ensures that only the aerodynamic force acting on the HIMICO experimental aircraft is transfered to the three-component balance.



a) Strut installation status



b) Fairing installation status

Figure 3: HIMICO vehicle/propulsion integrated control experimental setup

3.2 Wind Tunnel Startability Verification Test

Figure 4 shows a photograph of the wind tunnel startability verification test. The ratio of the frontal area of the HIMICO experimental aircraft to the airflow cross-sectional area of the ramjet engine test facility is 15.3%. The verification test was conducted using a 20%-scale pilot wind tunnel and a 25%-scale HIMICO experimental aircraft model to confirm that the wind tunnel could start even with this ratio. As a result, both the Mach number calculated from the total pressure and static pressure of the facility nozzle and the Mach number measured from the Pitot tube installed behind the model were approximately Mach 5. This data represent the establishment of hypersonic airflow around the model.

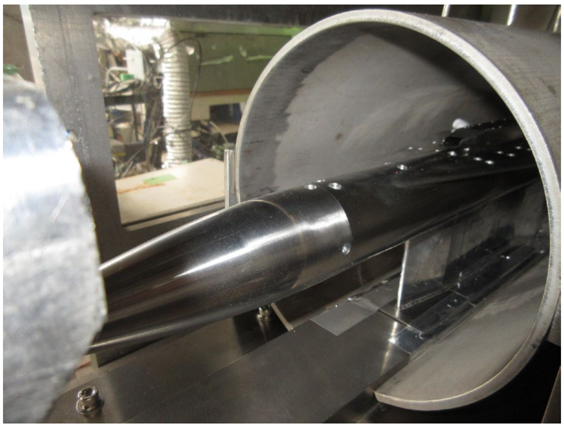


Figure 4 Wind tunnel startability confirmation test

3.3 Structural Analysis

Figure 5 shows the HIMICO structural analysis model. The HIMICO experimental aircraft is supported at two points, the forward strut and the rear strut, with the engine on the top. Structural analysis was performed using this analysis model, assuming the wind tunnel startup load was applied upward and laterally. The analysis was performed by applying downstream pressure (85 kPa) from a vertical shock wave to one side assuming that the airflow on one side of the fuselage becomes subsonic and recovers pressure.

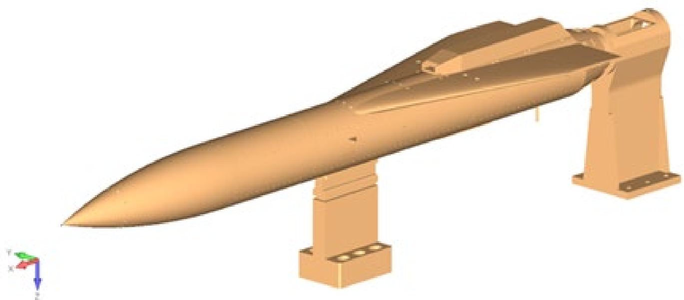


Figure 5: HIMICO Structural Analysis Model

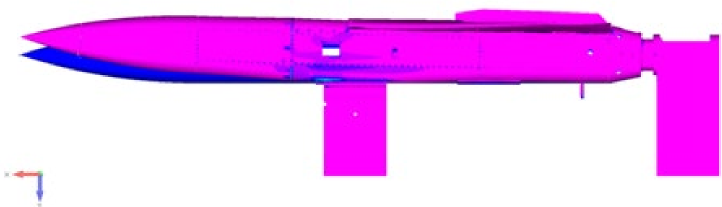


Figure 6: Displacement at wind tunnel starting load

Figure 6 shows the displacement of the model during wind tunnel startup loading. The displacement is enlarged for clarity. The HIMICO experimental aircraft has a high-stress area where the forward strut is attached. The strut had to be positioned forward to reduce this stress. The fuselage between the struts shows almost no deformation, but the fuselage in front of the forward strut is deformed upward.

Figure 7 shows the surface temperature distribution of the HIMICO aircraft. A CFD analysis was performed with a total pressure of 1.34 MPa and total temperature of1320 K assuming that the HIMICO experimental aircraft would fly at Mach 5 with a dynamic pressure of 50 kPa. The analysis was performed using an analysis code from Keio University[7)]. As a result, high-temperature areas were observed at the tip of the fuselage, the tips of the main wing, and the tip of the vertical tail wing. Fuselage parts parallel to the airflow had lower temperatures. A thermal stress analysis of the aircraft structure was performed using this temperature distribution. It was confirmed that a safety factor of 2 or more could be ensured with the designed structure.

Figure 7: Surface temperature distribution of the HIMICO aircraft (Mach 5)

3.4 Construction of a measurement system for the flow around the hydrogen ramjet

Figure 8 shows the hydrogen ramjet mounted on the HIMICO experimental aircraft. The hydrogen ramjet consists of a variable geometry air intake, ram combustor, and variable exhaust nozzle. Fuel shutoff valve, flow control valve, intake/nozzle actuator, igniter, and other components are installed inside the fuselage near the engine. An observation window is located on the fuselage behind the exhaust nozzle, and two CCD cameras for two-color measurement are installed to measure the temperature field. Another two-color measurement system will be placed at the side of the engine to measure the temperature field from outside of the aircraft model.

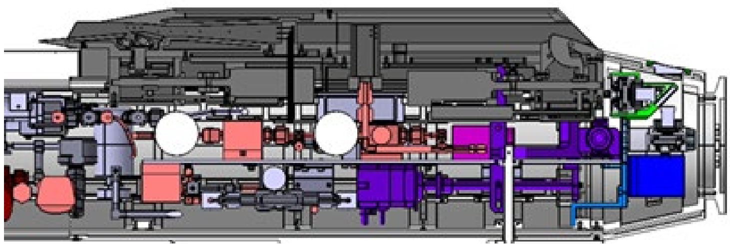


Figure 8: Hydrogen Ramjet Mounting Configuration

Figure 9 shows the visualization window layout for the ramjet engine test facility. An observation window will be installed on the side of the wind tunnel's diffuser to visualize the internal flow of the air intake of the hydrogen ramjet engine. An observation window will also be installed on the side wall of the variable intake. A CCD camera and a light source emitting a dot pattern will be placed outside the observation window, and the internal flow will be visualized using background-oriented schlieren (BOS) method.

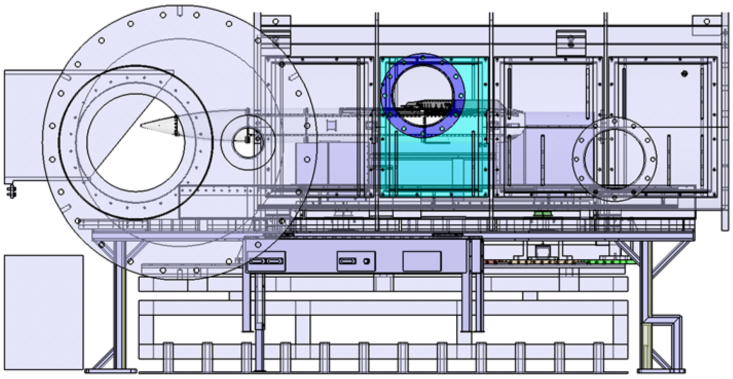


Figure 9: Visualization Window Arrangement

3.5 Fuel Supply System Construction

Figure 10 shows the fuel supply system diagram. The HIMICO experimental vehicle is equipped with hydrogen and nitrogen gas cylinders.

Hydrogen and nitrogen are filled from external gas cylinders before each test. The onboard cylinders are filled to a pressure of 19.6 MPa. The external gas cylinders are removed and the supply tube is closed before testing. The pressure reducing valve is then operated to set the secondary pressure to 1 MPa or less.

Hydrogen fuel is supplied to the fuel injector via a differential pressure flow meter, shutoff valves, and a flow control valve. The differential pressure flow meter consists of an orifice and a differential pressure gauge. The differential pressure was measured by directly connecting it to a calibrated hydrogen flow meter during combustor testing with direct connect setup. A correlation equation between differential pressure and flow rate was created in the test.

Purge nitrogen is used to exhaust hydrogen from the hydrogen fuel supply system and to create a pressure balance to prevent high-temperature airflow from entering the variable geometry air intake and variable exhaust nozzle actuators. Nitrogen gas is also supplied to the inside of the aircraft body to prevent combustion even in the event of a hydrogen leak.

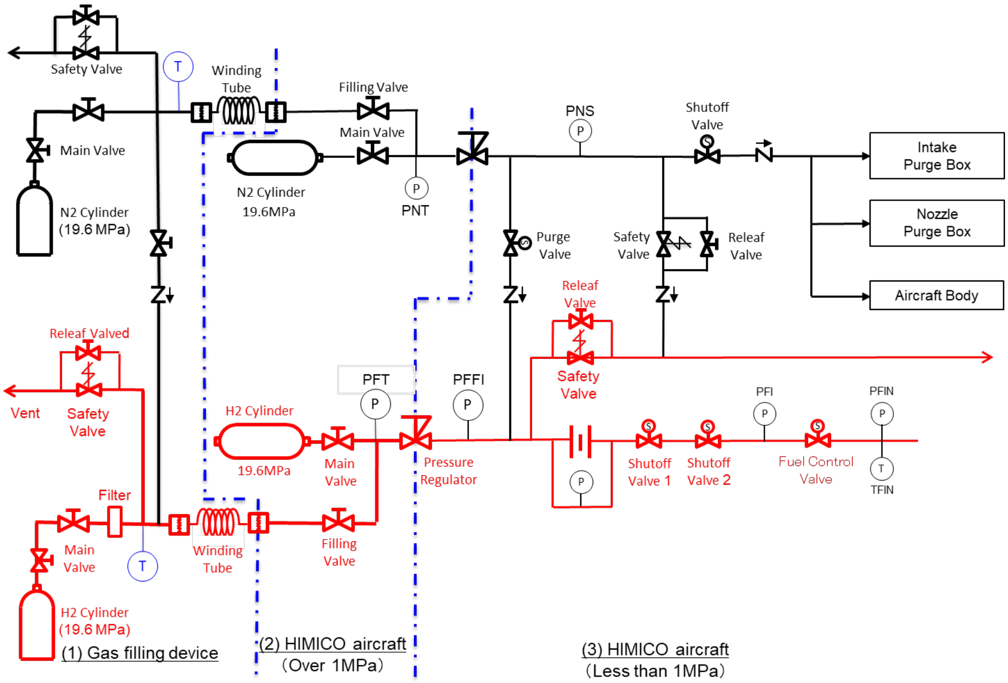


Figure 10: Fuel Supply System Diagram

4. Hypersonic Engine Component Testing

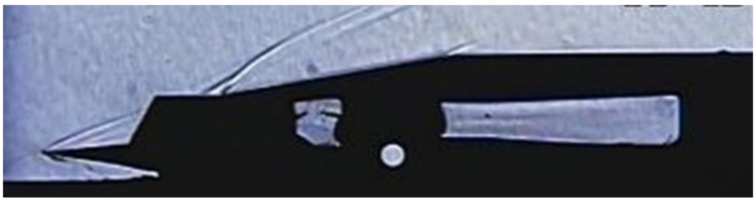
Component testing of the hypersonic engine was conducted in preparation for integrated airframe/propulsion control tests of the HIMICO experimental vehicle. The hydrogen ramjet installed on the HIMICO experimental vehicle consists of a variable geometry air intake, ram combustor, and variable geometry exhaust nozzle. The control elements for each are the intake throat height, fuel flow rate, and nozzle throat height. Control tests were conducted on the air intake, ram combustor, and exhaust nozzle to establish control methods.

4.1 Variable Geometry Air Intake Control Test

It is necessary to maintain high total pressure recovery rate (TPR) and high mass capture ratio (MCR) for the air intake to maximize the propulsive performance of a hypersonic engine. The air intake for the hydrogen ramjet installed on the HIMICO experimental aircraft is a mixed-compression type air intake that combines an external compression section and an internal compression section. A variable intake test was conducted in the hypersonic wind tunnel at JAXA's Chofu Aerospace Center to conduct performance and control tests of the air intake. Test conditions were a total pressure of 1 MPa and a total temperature of 650 K. The hydrogen ramjet engine was mounted on a flat plate simulating the upside of the fuselage in the wind tunnel test. Additionally, an integrated control system for engine measurement and control, a pressure scanner, and other equipment were installed within the support struts supporting the engine.

Figure 11 shows a Schlieren photograph of the inside of the air intake taken during the wind tunnel test. The flow around the intake throat and the internal flow of the subsonic diffuser were observed. a) shows the flow field in the starting state, where supersonic flow accompanied by oblique shock waves exists both at the intake inlet and inside the intake. If the throat height of the exhaust nozzle at the outlet is reduced after this state, the normal shock wave formed inside the intake moves upstream and reaches the vicinity of the intake throat. At this point, the total pressure recovery rate (TPR) reaches its maximum value. b) show the flow field in the unstart state. The flow field appears if the throat height of the exhaust nozzle is further reduced and the total pressure recovery rate drops significantly. A strong detached shock wave is formed at the intake inlet before compression and deceleration by the oblique shock wave occurs in the unstart state. It causes the total pressure recovery rate to drop.

a) Starting state



b) Unstarting state

Figure 11. Variable intake ambient and internal flows

Figure 12 shows the time history of the total pressure recovery rate. The air passes through the intake at supersonic speed from the start of the wind tunnel until 10 seconds later. Then the intake throat height is reduced to strengthen compression due to the oblique shock wave. The nozzle throat height is gradually reduced from 7 to 25 seconds. The total pressure recovery rate at the nozzle inlet increases during this phase. The total pressure recovery rate drops significantly from 20 to 25 seconds by unstarting of the flow field. The nozzle throat height is increased from 20 to 25 seconds. The total pressure recovery rate increases at around 34 seconds, indicating that the intake has restarted.

The total pressure recovery rate will decrease and engine thrust will also decrease if the intake fails to start. Therefore, it is necessary to keep the intake in the starting state to maintain high engine thrust. It is necessary to monitor the static pressure distribution inside the intake for this reason. The nozzle throat height is opened to prevent unstart when signs of unstart appear. A control law was established for this purpose, and control tests were conducted. Specifically, the nozzle throat height was controlled to keep the normal shock wave at the intended position, taking advantage of the fact that the gradient of the static pressure distribution changes depending on the position of the normal shock wave.

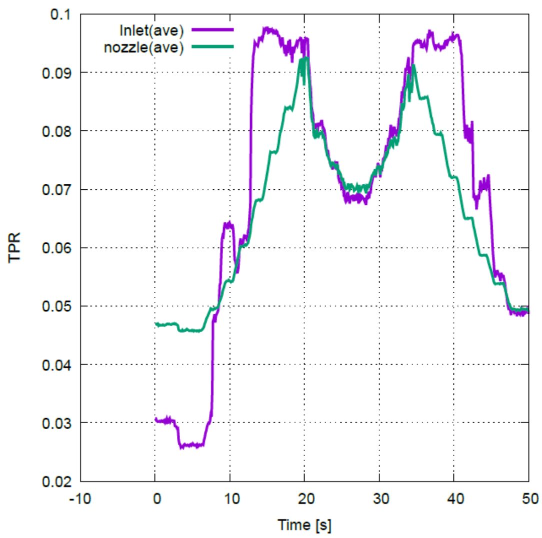


Figure 12: Total Pressure Recovery Rate (TPR) of Air Intake

4.2 Ramjet Combustion Control Test

A combustion temperature control test was conducted on a hydrogen ramjet combustor for the purpose of thrust control of a hypersonic ramjet engine. The HIMICO experimental engine was directly connected to the hypersonic high-enthalpy wind tunnel at the Kashiwa Campus of the University of Tokyo, and combustion tests were conducted. The opening rate of the fuel flow control valve was controlled to approach the target combustion temperature.

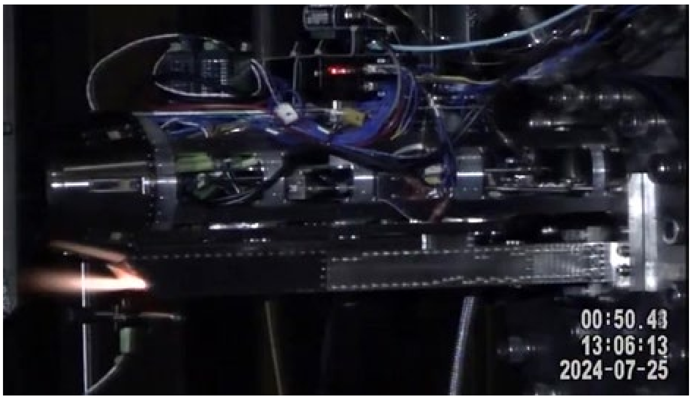
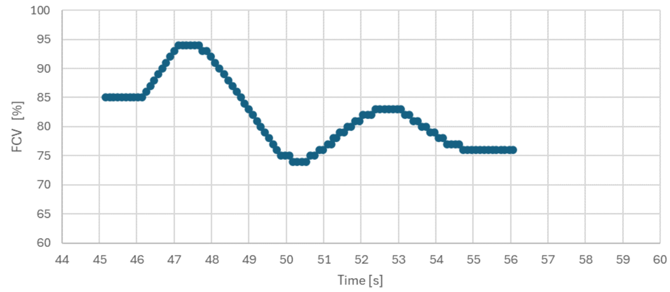


Figure 13: Ramjet Combustion Temperature Control Test

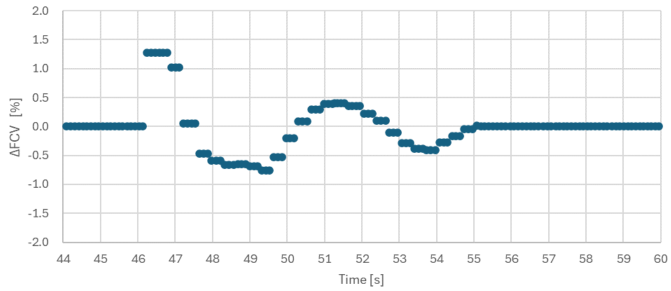
Figure 13 shows a photograph of the ramjet combustion temperature control test. The target temperature was set to 1500 K in this test. The response characteristics were obtained while changing the control gain. High-temperature air was supplied to the engine from a storage air heater on the right.

Mach 4 flight conditions were simulated in this test with a total air pressure of 300 kPa and a total air temperature of 900 K. Hydrogen fuel was injected into the ramjet combustor after the air temperature had risen and stabilized after the supply of high-temperature air was started.

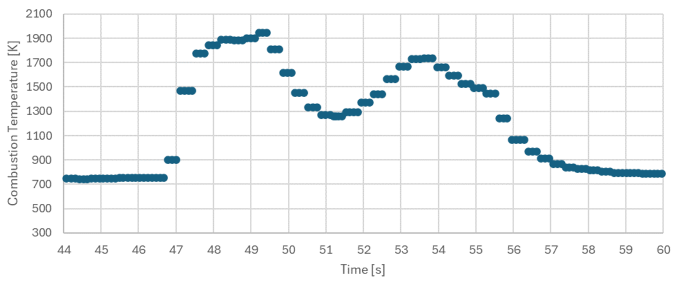
Figure 14 shows the results of a ramjet combustor temperature control test. (a) shows the time history of fuel flow control valve opening rate (FCV). (b) shows the time history of fuel flow control valve control amount (ΔFCV) . (c) shows the time history of combustion temperature (Tc).



a) Fuel flow control valve opening rate (FCV)



b) Fuel flow control valve control amount (ΔFCV)



c) Combustion temperature (Tc)

Figure 14. Ram combustor temperature control test results

The initial FCV opening rate was set to 85%, and proportional control was performed against the target temperature (1500K). The combustion temperature was lower than the target temperature from 46 to 47 s. ΔFCV was positive and the FCV opening rate increased in this phase. The combustion temperature was higher than the target temperature from 47.5 to 50.5 s. ΔFCV was negative and the FCV decreased in this phase. Similarly, the FCV increased from 50.5 to 52.5 s. Then, the FCV decreased from 53 to 55 s.

The rise and fall of combustion temperature occurs with a delay of about 1 second compared to the change in FCV. This may be due to the influence of both the response speed of the fuel supply system and the response speed of the thermocouple. The temperature history also changes approximately every 0.3 seconds. This is due to the processing speed of the temperature measurement device.

5. Conclusions

The hypersonic integrated control experimental aircraft (HIMICO) for Mach 5 propulsion wind tunnel experiments was designed, manufactured, and tested. The following findings are obtained in this research.

- A strut, fairing, and balance fixing mechanism to measure the three longitudinal components of the HIMICO experimental aircraft during propulsion wind tunnel experiments are designed and fabricated.
- A wind tunnel startability verification test using a 25%-scale model of the HIMICO experimental aircraft in a 20%-scale pilot wind tunnel at the ramjet engine test facility was conducted. It was confirmed that a Mach 5 airflow was established around the model.
- Structural and aerodynamic heating analyses of the HIMICO experimental aircraft were conducted and it was confirmed that the structure ensures a sufficient safety factor against stresses due to starting loads and aerodynamic heating during propulsion wind tunnel tests.
- An optical measurement system was designed to perform two-color measurements at the nozzle exit and background-oriented Schlieren (BOS) measurements around the intake to visualize the flow around the hydrogen ramjet.
- Control experiments on the hypersonic air intake were conducted to confirm intake control methods for maintaining a high total pressure recovery rate.
- Control experiments on the ramjet combustor were conducted to confirm fuel control Fuel control methods for maintaining a constant combustion temperature.

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