HIGH-altitude Propeller Evaluation Research (HIGHPER) Report

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A Mars airplane is a type of spacecraft capable of exploring wide areas near the Martian surface by utilizing the planet's thin atmosphere. In Japan, a research team led by the Japan Aerospace Exploration Agency (JAXA) has been developing a fixed-wing Mars airplane and conducting high-altitude balloon experiments to demonstrate flight and acquire aerodynamic data in the stratosphere, which simulates Martian atmospheric conditions. In this study, we planned and carried out the High-Altitude Propeller Evaluation Research (HIGHPER) using a small rubber balloon to support the development of a future propeller-driven Mars airplane. The objective of HIGHPER was to demonstrate the operation of the propeller and its drive system in a simulated Martian environment. This paper presents an overview of the experimental system, preliminary ground tests, and the results of the balloon flight experiment.

Key Words: Mars Airplane, Propeller Balloon Experiment

Nomenclature

h	:	Heat transfer coefficient, W/(m²·K)
Nu	:	Nusselt number
P	:	Atmospheric pressure, hPa
Pr	:	Prandtl number
Re	:	Reynolds number

1. Introduction

A Mars airplane is an exploration vehicle capable of surveying wide areas near the surface of Mars by utilizing its thin atmosphere. In Japan, a research group led by the Japan Aerospace Exploration Agency (JAXA) has been developing a fixed-wing type Mars airplane,[1)]. To demonstrate flight feasibility and obtain aerodynamic data under conditions similar to those on Mars, a series of high-altitude balloon experiments (Mars Airplane Balloon Experiment, MABE) has been planned and conducted in the stratosphere,[2–5)] where environmental conditions can partially simulate the Martian atmosphere. To date, all MABE test aircraft have been unpowered gliders. However, for future Mars exploration missions that demand longer duration and wider-range flight capabilities, the use of electrically driven propellers is being considered. The development of a propeller-powered Mars airplane introduces two major technical challenges: (1) achieving high aerodynamic performance under low Reynolds number conditions, and (2) ensuring the reliable operation of the propulsion system in low-pressure, low-temperature environments. Addressing these challenges is essential for the realization of practical, long-range Mars aerial exploration.

To address these challenges and with a view toward future Mars airplanes equipped with propellers, we planned the High-Altitude Propeller Evaluation Research (HIGHPER) using a small rubber balloon. The objective of this experiment is to demonstrate the operation of a propeller and its driving system under a simulated Martian environment. The main success criteria are summarized in Table 1. In addition to serving as a preliminary test and component-level validation for the development of a propeller-driven Mars airplane, this experiment also contributes to the accumulation and transfer of technical knowledge related to balloon-based flight experiments. By utilizing small rubber balloons, which allow for frequent launch opportunities, the experiment aims to enhance operational experience and improve methodologies for high-altitude testing. This paper presents an overview of the HIGHPER experimental system and preliminary ground tests, as well as detailed results from the balloon flight experiment.

Table 1. Success criteria.

Minimum	The gondola operates at a high altitude, and telemetry data is transmitted until the experiment ends.
Full	The propeller operates under one condition at a high altitude, and the results are logged for analysis.
Extra	The propeller operates under multiple conditions at high altitudes, and the results are logged for analysis.

2. Overview of the Experimental System

2.1. Flight System

An overview diagram of the HIGHPER flight system is provided in a previous publication,[6)]. The flight system consists of a Principal Investigator (PI) gondola, which carries the experimental equipment, a House-Keeping (HK) gondola responsible for flight operations, and a rubber balloon. The PI (Principal Investigator, PI) gondola is equipped with a single propeller. After the entire flight system lifts off from the ground, the PI gondola activates the propeller, rotating it at a predetermined rotational speed. The propeller operation is automatically triggered at a specified atmospheric pressure. The conditions for activation are listed in Table 2.

If the propeller maintained rotation within ±30% of the target speed for 30 seconds, or if 120 seconds had elapsed since the start of the rotation, the system advanced to the next rotational speed setting. Flight data were downlinked to the ground station via a radio transmitter provided by the JAXA Balloon Group. After reaching an altitude of approximately 25 km, both the PI gondola and HK gondola were separated from the balloon and descended slowly to the sea surface, marking the end of the experiment.

2.2. PI Gondola

The PI gondola was constructed using aluminum alloy panels and angle sections. It housed a battery and a heater for thermal management, with a propeller mounted on one face and avionics and a radio transmitter installed on the opposite face (Fig. 1). The motor used to drive the propeller and a thrust/torque sensor, were enclosed in a pyramidal-shaped windshield for protection. To retain heat, the five faces, except the propeller-mounted one, were covered with approximately 10 mm thick Styrofoam. Additionally, a wire-frame propeller guard was installed around the periphery of the propeller to prevent contact with suspension cords to the balloon. The PI gondola measured 180 × 120 × 120 mm (excluding the propeller, propeller guard, and antenna), and the total assembled mass was 1.96 kg.

The avionics and control software were developed in-house. A Raspberry Pi Pico microcontroller was employed as the main processing unit. The propeller was mounted on a brushless motor (FMA-2929-KV1150, Futaba Corporation) and driven by a motor controller (MC965A, Futaba Corporation). During the ring flight, the avionics system measured atmospheric pressure, atmospheric temperature, thrust sensor temperature, thrust, torque, rotational speed, three-axis geomagnetic field, three-axis angular velocity, three-axis acceleration, and avionics board temperature. The atmospheric pressure sensor and the geomagnetic, angular velocity, and acceleration sensors were mounted directly on the avionics board. Atmospheric temperature was measured using a thermocouple attached along an arm of the propeller guard. The aerodynamic forces on the propeller were measured using an in-house thrust/torque sensor. The motor rotational speed was calculated by monitoring the period of the alternating current driving the motor. All measurement data were downlinked at 5 Hz and recorded by a ground station PC. GPS signals were acquired by the HK gondola and downlinked and recorded through the HK communication system.

2.3. Propeller

The propeller mounted on the PI gondola was designed with a diameter of 300 mm and two blades, considering constraints on size and weight. The DAE-51 airfoil was selected based on aerodynamic performance and structural strength. The chord length and pitch angle distribution were optimized to maximize thrust at an altitude of 20 km and a rotational speed of 7,000 rpm, under the constraint that aerodynamic torque must remain below 0.020 N·m,[7,8]. The chord length and pitch angle distribution of the propeller are provided in previous publications,[9]. The propeller was fabricated using resin (AR-M2, Keyence) with a 3D printer. After fabrication, the mass balance between the two blades was adjusted to align the center of gravity with the axis of rotation, and the blade surfaces were finished with sandpaper (up to #2000 grit).

Table 2. Pressure and rotational speed conditions.

Pressure condition (altitude)	Target RPM (revolutions per minute)
P < 240 hPa (11.0 km)	1800, 2400, 3000, 3600 rpm
P < 128 hPa (15.0 km)	2000, 4000, 5000, 6000, rpm
P < 58 hPa (20.0 km)	2000, 4000, 5000, 7000 rpm

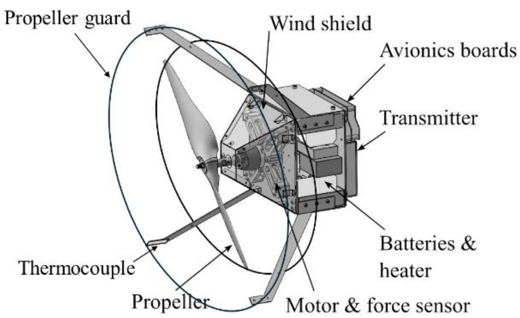

Fig. 1. Components on the PI gondola and its external view.

2.4. Thermal Vacuum Test and Thermal Design

Thermal mathematical modeling and thermal analysis were conducted using Thermal Desktop® and SINDA/FLUINT®, respectively. The thermal mathematical model of the HIGHPER system and the allowable temperature ranges of the main components are provided in the previous publication,[9]. Because the low-temperature conditions were expected to be more severe during the HIGHPER flight sequence, a cold-biased thermal design was adopted in which a heater was installed on the battery, the component with the highest minimum allowable temperature.

For the thermal environment, convective heat transfer was considered by setting the ambient air node as the boundary condition. The forced convection heat transfer coefficient h was determined based on the average Nusselt number Nu for a horizontal flat plate in laminar flow, as shown in Equation (1),[10]. Here, Re is the Reynolds number and Pr is the Prandtl number. Additionally, forced convection heat exchange was assumed to occur only between the ambient air node and the exterior surface of the gondola. For the interior of the gondola, the heat transfer coefficient was set by considering natural convection and thermal conduction of air, referring to the literature,[11,12].

$$Nu = 0.664 Re^{1/2} Pr^{1/3}. \tag{1}$$

To validate the thermal mathematical model and verify operation under worst-high and low-temperature environments, thermal tests were conducted in a vacuum chamber at JAXA

Sagamihara Campus. The steady-state temperatures measured at multiple points during the thermal tests were compared with the analysis results from the correlated thermal mathematical model. As reported in the previous publication,[9], the temperature discrepancies at all measurement points were within ±5°C.

3. Experimental Results

3.1. Flight History

The HIGHPER flight system was launched at 5:00 AM on August 21, 2024, from the JAXA Taiki Aerospace Research Field in Taiki, Hokkaido. Figure 5 shows the altitude, atmospheric pressure, and temperature histories during the flight. The pressure and temperature histories also include the standard atmospheric model shown as dashed lines for comparison. After launch, the HIGHPER flight system ascended to an altitude of approximately 23 km over about one hour, then gradually descended over 30 minutes before landing at sea. Both pressure and temperature decreased with the gondola's ascent, reaching approximately 39 hPa and -25°C, respectively, at the maximum altitude of 23 km.

3.2. Temperature History

Figure 6 shows the temperature history obtained during the flight alongside the pre-flight analysis results from the thermal mathematical model. The temperature of the avionics board measured during the flight is plotted in red, while the temperature of the thrust measurement block is plotted in blue. As shown in Fig. 6, the thermal mathematical model accurately predicts the trend of temperature decreases with increasing altitude. However, in the latter part of the flight at higher altitudes, the model underestimates the temperature compared to the actual measurements. This discrepancy is believed to be caused by the actual atmospheric temperature being approximately 20°C higher than the standard atmospheric temperature assumed in the thermal model.

3.3. Propeller Operation and Vehicle Dynamics

Figure 7 shows the propeller rotational speed history during flight. As planned, the propeller was automatically rotated at multiple predetermined altitudes. The rotational speed generally followed the target values; however, communication was interrupted during the transitions between sequences. The highest altitude at which the propeller rotated was approximately 20 to 22 km, where the atmospheric temperature was about -25°C, as shown in Fig. 5.

The roll, pitch, and yaw axes of the PI gondola are shown in Fig. 8, and the history of the vehicle acceleration is shown in Fig. 9. Significant accelerations occurred during propeller rotation, indicating that the vehicle experienced oscillations.

3.4. History of Thrust and Torque

The histories of thrust and torque are shown in Fig. 10. The periods during which the propeller was operating are indicated in gray. It is evident that temperature drift and vehicle motion have significant effects, indicating that corrections are essential. To correct for temperature drift, the value just before the propeller rotation is subtracted, assuming that the temperature changes in the thrust and torque sensors during propeller operation are negligible. For correcting the effects of gondola motion and attitude, it is considered necessary to subtract the influences of vehicle acceleration and angular acceleration on thrust and torque.

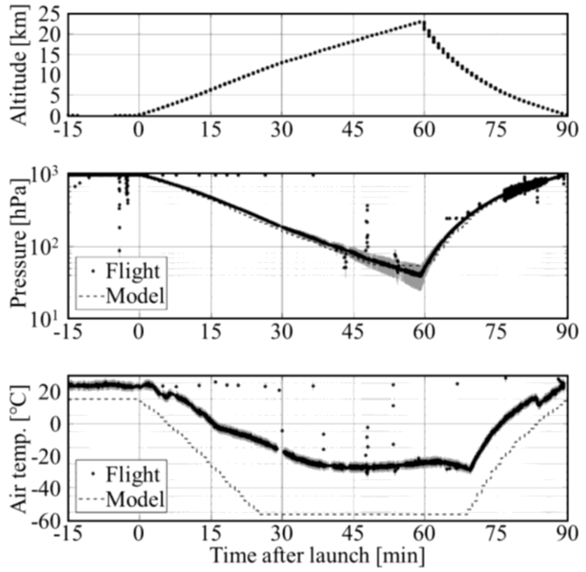

Fig. 5. Altitude, pressure, and temperature histories during flight.

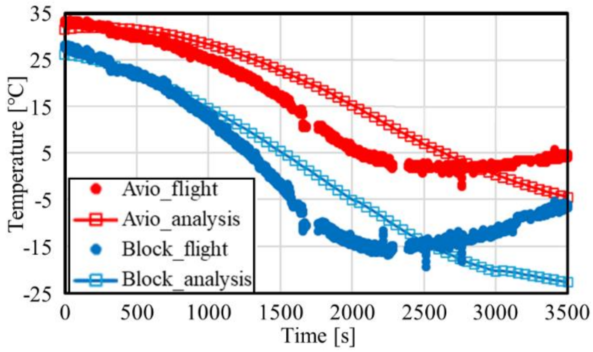

Fig. 6. Comparison of temperature history during flight and thermal analysis results.

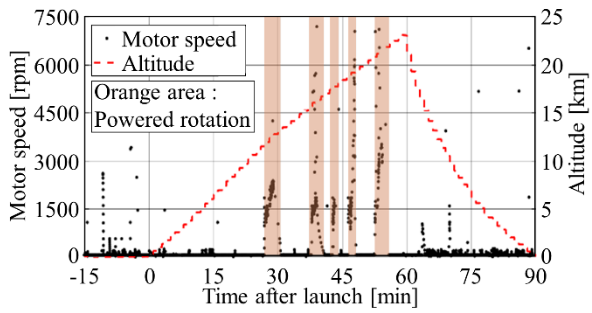

Fig. 7. Rotational speed history during flight

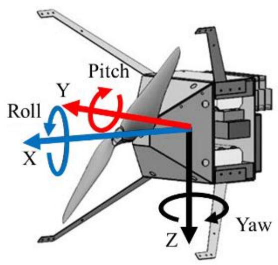

Fig. 8. Definition of the roll, pitch, and yaw axes.

Figure 11 shows a comparison between the experimental results and calculations based on Blade Element Momentum Theory (BEMT). The torque exhibits an increasing trend with respect to *Re*, which agrees with the BEMT predictions. On the other hand, the thrust occasionally takes negative values, indicating significant effects from the gondola's attitude and acceleration. Further analysis is required.

4. Conclusion

In this paper, we reported on the demonstration experiment of a propeller and its drive system under a Mars-like environment, including an overview of the experimental system and the results of a balloon flight test. Since the operation of the propeller drive system was successfully verified, it can be concluded that the original objective—demonstrating propeller rotation and acquiring data at multiple altitudes—was achieved. On the other hand, the performance data of the propeller still requires further analysis, including corrections for vehicle motion and attitude.

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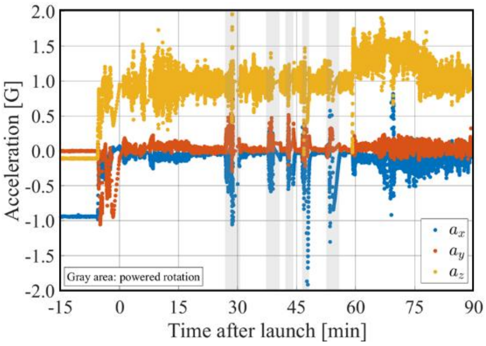

Fig. 9. History of gondola acceleration.

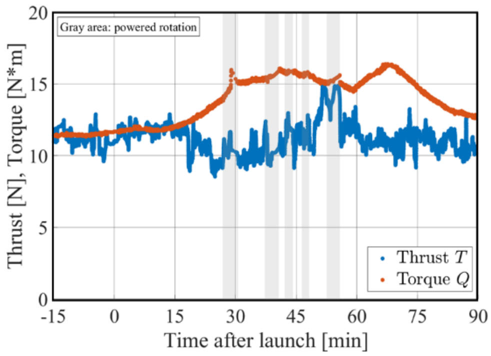

Fig. 10. Thrust and torque history (raw data).

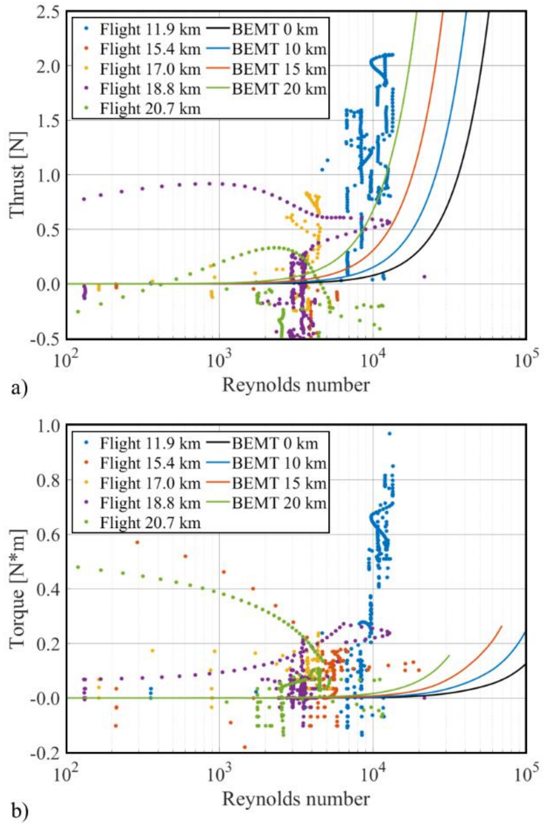

Fig. 11. a) Thrust and b) torque.

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