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Verification of Variable Inlet Design through Wind Tunnel Test

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Abstract

Scramjet engines used for efficient flight in supersonic and hypersonic areas have the disadvantage of not generating thrust at subsonic and stationary conditions. Therefore, ramjet or scramjet engines are not used alone but in complex cycles such as TBCC(Turbine Based Combined Cycle) and RBCC (Rocket Based Combined Cycle) combined with turbine or rocket engines. In such an integrated propulsion system, a configuration design for a variable inlet is required since operation is essential in a wide range of Mach numbers. In this study, the required mass flow conditions of the TBCC aircraft were derived, and the shape design and detailed design procedures of the variable inlet satisfying them were presented. The maximum operating Mach number of the variable inlet was set to 7, and the shape of the variable suction port was designed using variable lamps and cowls to satisfy the required flow rate conditions for each Mach number. Boundary layer correction and computational analysis were performed on the designed shape. As a result of two-dimensional numerical simulation, it was confirmed that the mass flow rate flowing into the inlet satisfies the requirements. After that, a wind tunnel test was performed by creating a reduction model for the variable inlet for Mach 2 and 7. The supersonic wind tunnel was used in Mach 2, and the hypersonic shock wave tunnel was used in Mach 7. In each test, the inlet performance analysis was performed through back pressure control and verification of the designed inlet shape. As a result of the wind tunnel test, it was verified that the shape of the inlet in each Mach number was carried out properly, and the starting characteristics according to the back pressure were confirmed.

Keywords : *Variable Inlet, Turbine Based Combined Cycle, Boundary Layer Correction, Wind Tiunnel Test.*

Nomenclature

A – Cross-sectional area
$\dot{m}$ – Mass flow rate

Subscripts
out – Outlet of variable inlet
th – Throat of variable inlet

1. Introduction

Research on turbine-based combined cycle is being conducted in various countries[1-2]. Compared to the existing single propulsion system, the turbine-based combined cycle has an extensive operating range from subsonic to hypersonic areas and a broad flight altitude of more than 0 to 30 km, making applying fixed inlets designed to operate only in a specific Mach number range challenging. For this reason, research on variable inlets is essential for developing a turbine-based combined cycle. In the case of these variable inlets, various forms have been presented. Depending on the number of internal flow paths, it was divided into a single flow path inlet and a multi-flow path inlet with two or more flow paths. In the case of a single flow path inlet, a method of controlling the internal flow path by applying a variable system to the ramp or cowl of the two-dimensional inlet was mainly used [3-4]. Other variable intake performance analysis was performed according to the spike position of the axisymmetric inlet as

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in the operation method of SR-71. The multi-flow path intake was mainly equipped with a turbine engine in one flow path and a ramjet or scramjet engine in the other, with two flow paths arranged in parallel up and down. Since the multi-flow path intake is equipped with at least two engines, it can be operated in the broader flight area, and its performance is stable due to Mach number. Therefore, in the case of a turbine-based combined cycle that works to the hypersonic region, a multi-flow path inlet that easily expands the operating range by being equipped with many engines is essential.

In this study, the required flow conditions for TBCC aircraft that can be operated in the flight range from subsonic to Mach 7 were derived. Subsequently, a detailed shape design procedure for a two-dimensional dual-flow path variable inlet that satisfies the requirements was presented. After performing the shape design of the variable inlet according to the design requirements set for each freestream Mach number, the inlet performance for each flight Mach number was analyzed and verified through numerical simulation. Subsequently, in Mach 2 and 7, the starting characteristics according to the back pressure and verification of the design were observed through supersonic wind tunnel and hypersonic shock wave tunnel tests.

2. Variable Inlet Design

The variable inlet is designed to satisfy the shock-on-lip condition based on Mach 7, the maximum operating Mach number. The turbo-ramjet mode was designed in consideration of a position where the shock wave generated by a splitter falls on a ramp, and it was designed so that detached shock waves would not occur by the ramp or splitter at a low Mach number. The variable part of the inlet is shown in Fig. 1. The splitter acts as a second ramp in the scramjet mode, while the turbo-ramjet mode acts as a low-speed cowl. Table 1 shows the required mass flow rate according to Mach number, which is the inlet design condition. The required mass flow rate was divided into the required mass flow rate at Mach 7 and expressed as dimensionless. In the case of the scramjet mode, the required mass flow rate for each Mach number was satisfied using only the high-speed cowl, and in the case of the turbo-ramjet mode, the required mass flow rate was met using a splitter and variable ramps.

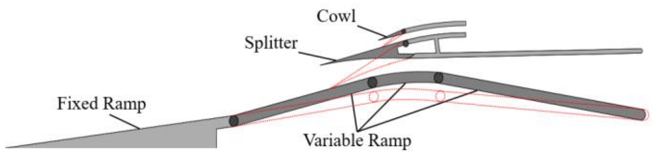


Fig 1. Variable inlet configuration

Table 1. Required mass flow rate according Mach number

Mach number	2	4	7
$\dot{m}$	1.00	0.81	1.00

3. Numerical Simulation

Numerical simulation was performed as a steady-state RANS simulation using a density-based compressible solver. Convection terms were calculated using the ASUM+ FVS scheme and maintained third-order accuracy based on MUSCL. For both two-dimensional and three-dimensional analysis, analyzed the viscosity conditions, the k-w SST model was applied as the turbulence model, and the working fluid was set as an ideal gas. To reduce numerical simulation costs, grids were applied sparsely to areas where shock waves and Mach waves did not occur, and most grids were configured to be used inside compression surfaces and inner surfaces. The wall grid was constructed so that y+ is less than 1. The grid is four times the size of the existing grid size for visibility, which is shown in Fig. 2.

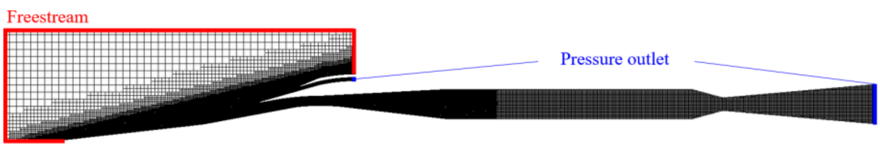


Fig 2. 2-Dimensional computational domain

The 2D numerical simulation results satisfied the shock-on-lip condition in the freestream Mach number 7. Mach 5-7 in scramjet mode and Mach 2-4 in turbo-ramjet mode confirmed that separation did not occur inside, and the suction port operated normally. The required mass flow rate, which is the inlet requirement, was satisfied in all Mach numbers. The results of two-dimensional numerical simulation in each Mach number are shown in Fig. 3. A shock-on-lip condition was formed at Mach 7, confirming that the inlet was started normally in each Mach number. The error rate between the required flow rate and the incoming mass flow rate calculated by computer analysis was within 1%.

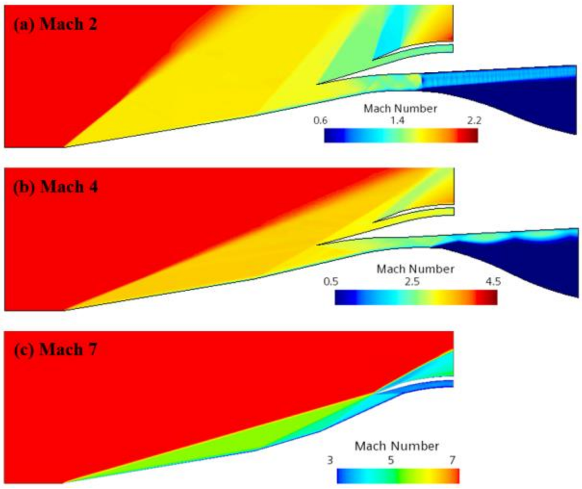


Fig 3. Mach number contours of variable

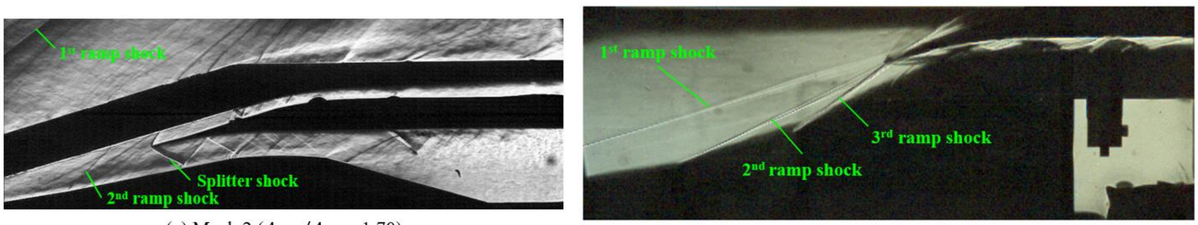
4. Wind Tunnel Test

Table 2 shows the conditions of the wind tunnel tests performed at Mach 2 and 7. Tests were performed at an altitude of 1.2 km for Mach 2 and 33.8 km for Mach 7. In Mach 2, the test was conducted through a supersonic wind tunnel, and the test section size was 150*150 mm. In Mach 7, a hypersonic shock tunnel was used, and the diameter of the nozzle outlet of the test section was 189 mm. Each experiment changed the back pressure by adjusting the outlet area through a plug at the rear end of the test model.

Table 2. Test section conditions of wind tunnel test

Mach number	2	7
Pressure [Pa]	87148	683
Temperature [K]	166.67	64.81
Total pressure [bar]	6.82	28.29
Re per unit length	6.95×10^6	2.58×10^6

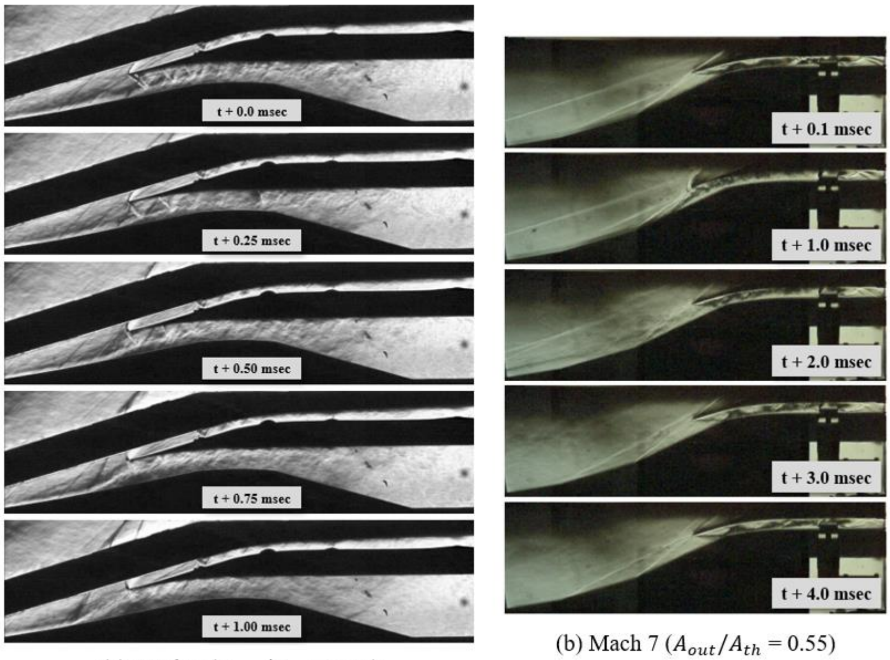
Fig. 4 shows the Mach 2 wind tunnel test results at the outlet area ratio of 1.70 and the Mach 7 shock wave tunnel test results at the outlet area ratio of 1.0. The design of the inlet shape was verified by comparing the shock wave angle calculated through theoretical and two-dimensional numerical simulation with the shock wave angle shown in the wind tunnel test. The theoretical shock wave angle in an inviscid condition compared to the shock wave angle in a wind tunnel test showed an error rate of up to 4.9%, and the shock wave angle in the two-dimensional numerical simulation showed up to -5.4%. Still, it was confirmed that similar shock wave angles were formed overall. In Mach 7, it was confirmed that the shock-on-cowl lip condition, the design condition of the variable inlet, was satisfied. The ratio of the outlet area to the throat where the buzz phenomenon occurred was 0.72 for Mach 2 and 0.32 for Mach 7. The results of each test are shown in Fig. 5.



(a) Mach 2 (A_{out}/A_{th} = 1.70)

(b) Mach 7 (A_{out}/A_{th} = 1.00)

Fig 4. Wind tunnel test visualization results



(a) Mach 2 ($A_{out}/A_{th} = 0.72$)

(b) Mach 7 ($A_{out}/A_{th} = 0.55$)

Fig 5. Wind tunnel test results at each Mach number

5. Conclusion

In this study, a design procedure for a variable inlet of a TBCC engine was presented, and an inlet shape design was performed. The shape of the inlet designed through two-dimensional numerical simulation was verified, a reduced inlet model was produced, and a wind tunnel test was performed. The wind tunnel test was conducted at Mach 2 and 7, and the inlet shape design was verified by comparing the test results with the theoretical and computational analysis results. After that, the starting characteristics and performance changes according to the back pressure were observed.

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