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Turbine Performance Experiments for the Turbopump of a Liquid Rocket Engine

Hanggi Lee†, Juhyun Shin, Eunhwan Jeong, Changho Choi
Korea Aerospace Research Institute
KOREA
†E-mail:hglee@kari.re.kr

Abstract : This paper highlights the performance of an impulse turbine which is a part of turbopump in a liquid rocket first stage engine. The turbopump, currently under development at Korea Aerospace Research Institute, has an impulse type turbine with 12 nozzles and a single rotor. The impulse turbine can archive high specific power with the low gas flow rates. The supersonic impulse turbine with a single rotor can make a simple structure. High-pressure gases are converted into the dynamic energy with flows through the 12 nozzles and drive the rotor to make the power for the pumps. The turbine test was performed in the high-pressured turbine test facility with air gas instead of burned gas. A hydraulic dynamometer was used to absorb the power from the turbine and control the rotational speed and torque. The test points were at several pressure ratios with 7 different rotational speeds. Results showed the efficiency was highest at the design pressure ratio. The efficiency was insensitive to the pressure ratio variation than the rotational speed. It was a typical characteristic in an impulse turbine.

Key Words : Turbopump, Impulse, Rocket, Efficiency, Supersonic

1. Introduction

The turbopump in a liquid rocket engine is a powerful device used to supply high-pressured propellants with the required mass flow rate to the combustion chamber. The Korea Aerospace Research Institute (KARI) is developing a turbopump for the liquid rocket engine with the 75 tons of thrust [1].

The turbine for the turbopump is capable of producing enough power for the connected propellant pumps. The turbine is required to have a simple configuration because rocket elements need a high degree of reliability and it requires high specific power to generate the enough power with a low mass flow of the driven gas so that a smaller amount of rocket propellants storage is required. Therefore the turbopump under development at KARI adopted an impulse supersonic turbine at the partial admission which had the simple configuration and could generate the enough power with the small gas flow. Partial admission is for the driven gas to go through nozzles arrayed in partial sections. Partial admission could design the larger sized blade by making the larger mass flow passed through each nozzle. And the turbine developed at KARI has the starting and operating sections. The nozzles are arrayed circumferentially. Some nozzles in partial areas are used for the starting gas, main driving gas after the starting sequence has passed through the remaining areas, called the partial admission.

Another advantage of the impulse turbine is not creating the axial thrust due to the low pressure

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†Corresponding Author
Tel:+ 82-42-860-2887,
E-mail: hglee@kari.re.kr

difference across the turbine rotor. All static

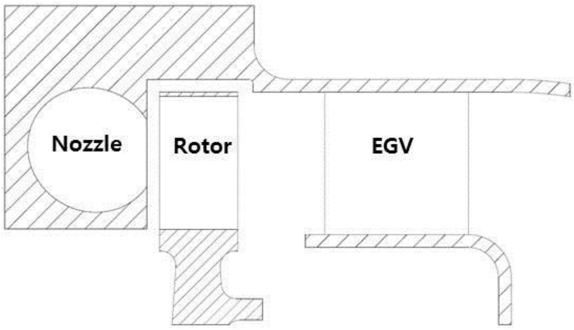

Fig. 1 Turbine Configurations

pressure changes occur in the nozzles. Less axial thrust can relieve the bearing load.

The supersonic impulse turbine with partial admission has not been thoroughly investigated experimentally. Stratford et al.[2] studied supersonic turbine blades using the cascade test. This study was not for the rotating turbine. Some experimental studies have also been conducted by Huzel and Huang [3]. The performance characteristic of the impulse turbine was researched. Dorney et al. [4] studied partial admission turbine performance using the simulation method. They assumed full admission instead of partial admission to save calculation time.

Jeong et al.[5],[6] studied the performance of the shrouded supersonic turbine for the turbopump experimentally. The test models by Jeong et al. were turbines capable of 30-ton thrust and a preliminary version with 75-ton thrust.

This paper studied the latest designed turbine model of 75 ton thrust and investigated the characteristics of the turbine experimentally. The exact performance by test is evaluated.

2. Experimental Setup

2.1. Test Facilities

The turbine model was assembled with turbine nozzle block, a single rotor and the exit guide vane as shown in Figure 1. Figure 2 shows the nozzle block and the turbine rotor. Nozzles were arrayed circumferentially and using converging-divergent shapes to accelerate the hot pressured gas to the supersonic speed gas. The nozzle block had 12 nozzles of which 2 nozzles were for starting by pyro and 10 nozzles were for the steady operation by the burned gas. During normal operation, the turbine was operated by gases from the partially distributed nozzles. The single rotor was impulse shrouded with symmetric blades. A shrouded rotor could reduce leakage loss through blade tip clearance to protect the tip leakage flow. Exit guide vanes were located in the downstream of the rotor to remove the swirled components and recover the static pressure of the gas.

The turbine was tested at the turbine similarity test facilities in KARI. Figure 3 shows the turbine

Fig. 2 Nozzle Block and Turbine Rotor

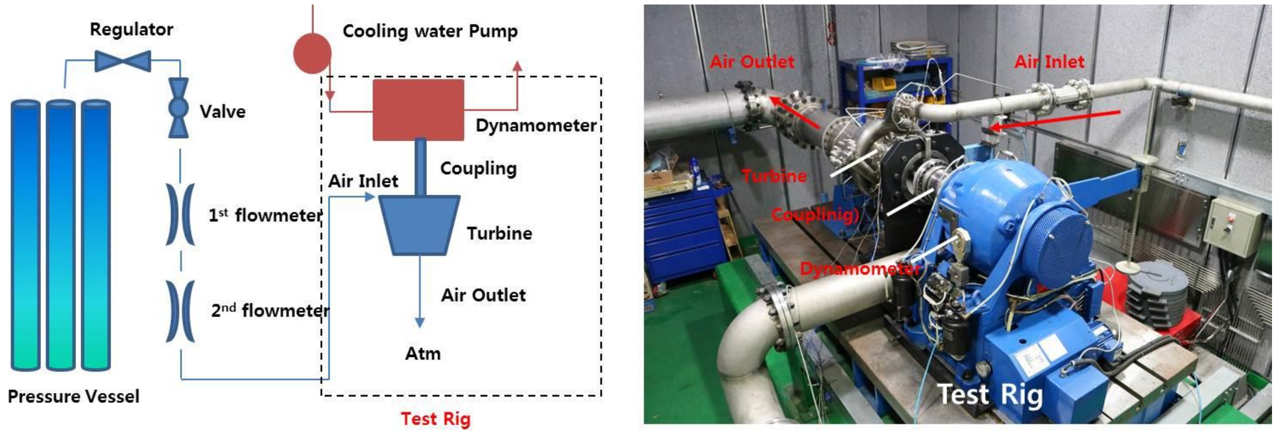

Fig. 3 Turbine Test Facilities

test facilities. The test was performed to use high-pressured air instead of real burned gas

The test with an air system could control the system easily and operate it more safely than with real hot gas.

The configuration of the facilities was composed of high-pressure air systems, a hydraulic dynamometer, the data acquisition system. The high pressure systems consisted of air compressors to supply air with a maximum of 320 bar, pressure vessels with 40 m3 volume to store the pressurized air and control systems such as valves and regulators.

The 320-bar compressed dry air from the compressor was stored in the pressure vessels.

Through regulators, the 320-bar compressed air was down to medium pressure conditions to meet the pressure ratio of the turbine test points. The turbines were connected to the dynamometer which was the hydraulic brake type. The dynamometer absorbs the power from the turbine and controls the torque and rotational speed. The dynamometer being used had a 1.6 MW absorbing power range and a 9000 rpm maximum capability. It was an F359 model made by Froude Hoffman. The dynamometer needed water circulation systems to convert the energy from the turbine into the heat of water.

2.2. Test Conditions

Test points were set using the similarity method as shown in Table 1, which had same dimensionless parameters such as Mach No. and velocity ratio (U/C_{ad}) at the rotor inlet.

The velocity ratio was calculated as the ratio of the rotor tip speed (U) to the adiabatic speed of the gas (C_{ad}) from the nozzles.

Tests were performed on several points with different pressure ratios and rotational speeds.

The uncertainty of this test was ±1.05% of the design efficiency. The result of the uncertainty analysis showed that the largest uncertainty originated from the torque sensor in the dynamometer. Before every test, torque calibration was performed.

Table 1 Test Specifications

Parameter	Design Point	
	Real Condition	Similarity Condition
Medium	Burned Gas	Cold Air
Pressure Ratio	18	18.3
U/Cad	0.21	0.21
Nozzles No.	10	10
Inlet Temperature [K]	900	270

3. Results and Discussion

Figure 4 shows the performance curves with the pressure ratio (PR) and at the constant corrected rotational speed (N*). Corrected rotational speed and pressure ratio are expressed as the equations below.

Pt_in is the total pressure at the turbine inlet and P_out is the static pressure at the turbine outlet.

N is the rotational speed and T_in is the static temperature at the turbine inlet.

$$PR = Pt\_in/P\_out \quad (1)$$
$$N^* = N/\sqrt{T\_in} \quad (2)$$

All values were normalized with the values at the design point. Pressure ratio varied from 15 to 29 which covered the off design point including the design point. Test ranges covered from 0.7 to 1.2 in the normalized corrected rotational speed.

Figure 4 (left) shows the efficiency as changes in the rotational speed at the several pressure ratios. The performance of the impulse turbine is sensitive to the rotational speed rather than the pressure ratio. This is a typical characteristic of an impulse turbine [5]. The maximum efficiency point is located near the design pressure ratio.

The efficiency variations are large as rotational speeds changes. This gives the design guide lines of the turbine. To achieve higher efficiency, a larger rotor diameter or higher rotational speed is required. However, increasing the diameter means a disadvantage in the weight. A higher rotational speed can be limited to the structural strength of the rotor as well as pump suction performance. Under these limitations, higher rotational speed gives better performance.

Being insensitive to the pressure ratio can give advantages to the rocket's operation. In the downstream of the turbine the heat exchanger and the Roll Control System (RCS) devices are installed. If the pressure losses of these devices are changed during operation, the efficiency does not change dramatically.

The velocity ratio (U/C_{ad}) effect with the constant pressure ratio is also shown in Figure 4(right). The efficiency increases at higher velocity ratio. The impulse turbine with a single rotor had a peak efficiency point at the velocity ratio of 0.5. Because the velocity ratio of the design point is 0.21, the higher velocity ratio has better performance in the range of a velocity ratio of 0 – 0.5.

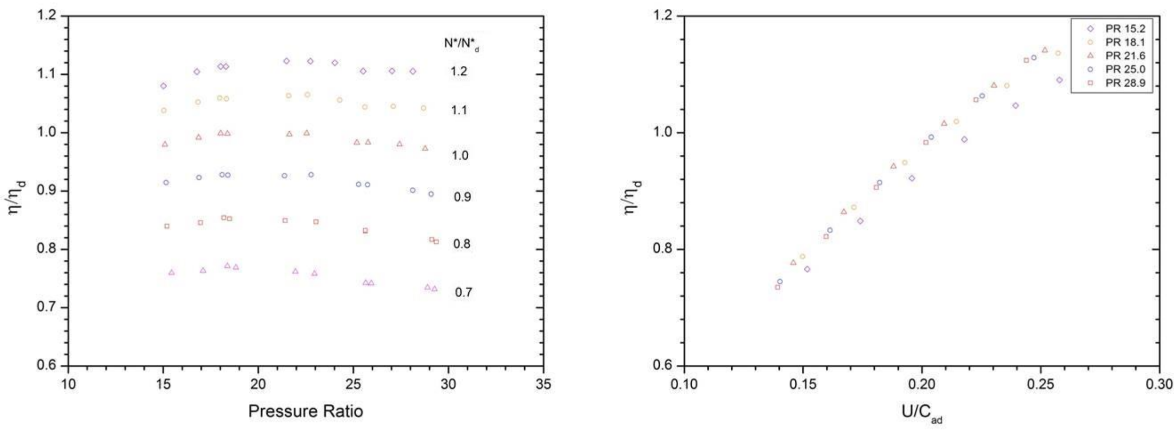

Fig. 4 Turbine Efficiency Variations as Pressure Ratio and Velocity Ratio

4. Conclusions

The turbine in a turbopump was tested. The characteristics of a supersonic impulse turbine with a single rotor were investigated experimentally. The experiment represented the following:

1) The efficiency changed large as the rotational speed changes and small as the pressure ratio. It is a typical characteristic of a supersonic impulse turbine.

2) The maximum efficiency was estimated at the pressure ratio of 18, which was the design pressure ratio.

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Authors

Hanggi Lee

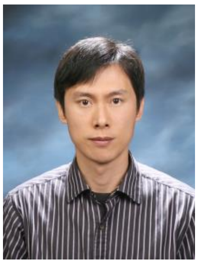
MS in Seoul National University
Senior researcher in Korea Aerospace Research Institute

Juhyun Shin

Ph.D. in Seoul National University
Senior researcher in Korea Aerospace Research Institute

Eunhwan Jeong

Ph.D. in Texas A&M
Principal researcher in Korea Aerospace Research Institute



Changho Choi

Ph.D. in Seoul National University
Principal researcher in Korea Aerospace Research Institute