Experiment of Rotating Detonation Turbine Engine with a Centrifugal Compressor and Axial Turbine

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1 Introduction

A propulsion system using detonation combustion is referred to as a detonation engine[1][2]. The advantages of using detonation engine include the ability to achieve higher temperature and pressure gases compared to deflagration combustion, as well as the potential for higher theoretical thermal efficiency[3].

Typical examples of a detonation engine are the pulse detonation engine (PDE) and the rotating detonation engine (RDE). PDE has a long tube, so called detonation tube, and RDE features an annular or hollow combustion chamber. By utilizing PDE or RDE, the combustor can be made smaller and simpler than conventional propulsion systems. Moreover, it may be able to achieve higher theoretical thermal efficiencies.

Recently it has been considered to apply detonation engines to gas turbine engines. Detonation turbine engines are gas turbine engines equipped with compressors and turbines placed before and after the PDE or RDE. The former is known as the Pulse Detonation Turbine Engine (PDTE), and the latter is the Rotating Detonation Turbine Engine (RDTE). These engines replace the conventional gas turbine combustor with a PDE or RDE, not only simplifying the combustor geometry but also potentially reducing the combustor's size and improving its efficiency.

Previous studies on PDTE and RDTE have mainly focused on the numerical analysis[4], [5] or turbine operation experiments using PDE and RDE[6-9]. The goal of this study is to operate RDTE independently.

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2 Design of RDTE

The structure of the RDTE is shown in Figure 1. As shown in Figure 1, air flows through the compressor, mixes with fuel gas supplied from the hole injector at the slit located in front of the combustion chamber and is then supplied to the combustion chamber. A pre-detonator is used for ignition. The combusted gas passes through the stator, where it gains circumferential momentum to drive the turbine.

Pressure and temperature are measured in the combustion chamber, pre-detonator, and stator. To design the RDTE system, a combustion pressure of 0.2 MPa was assumed for the RDE, and the performance requirements of the compressor and turbine were matched accordingly.

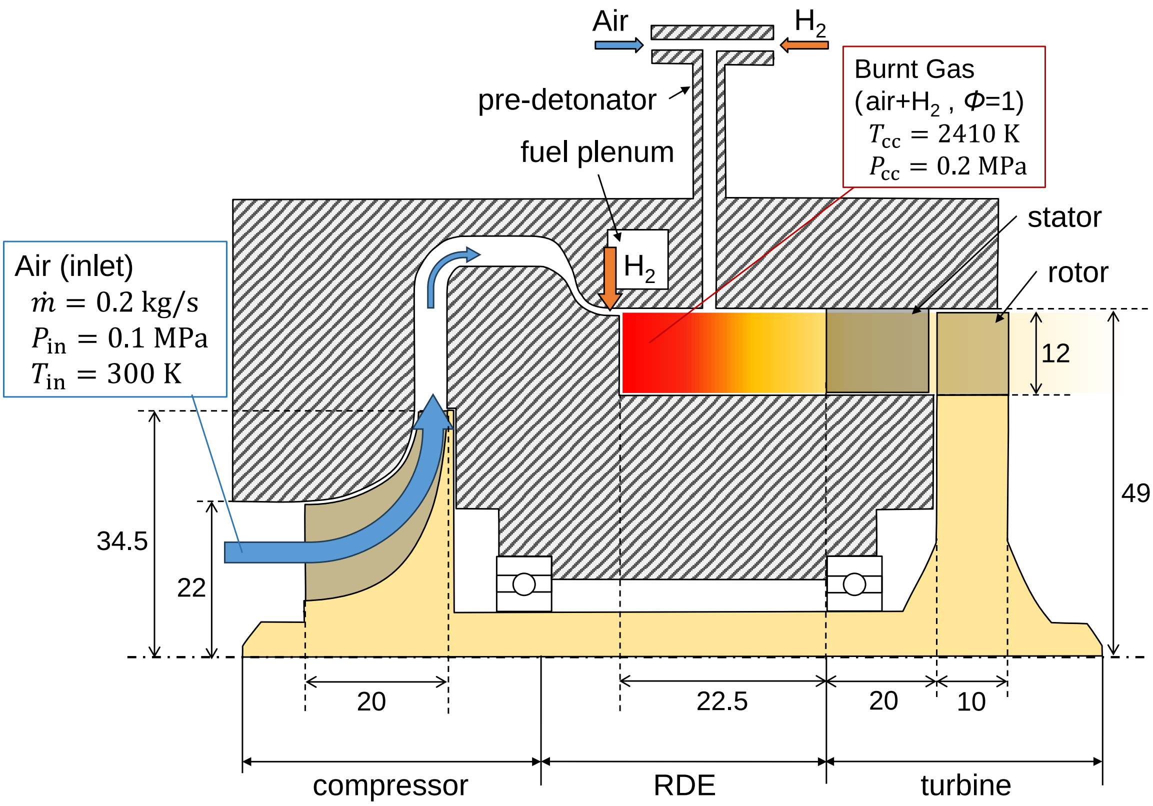

Figure 1 : structure of the RDTE

3 Analysis

To confirm whether RDTE can run independently or not, theoretical analysis is conducted. The combustion field is assumed to operate under detonation conditions, with the previously combusted gas expanding to atmospheric pressure at the turbine outlet. The combustion field is also modeled as a constant-pressure H_2-Air combustion field. According to a previous research[10], combustion pressure is decided as:

$$P_3 = 0.2 \text{ [MPa]}$$

Then using NASA-CEA, the H_2/air($\phi = 1$) combustion temperature of the exhaust gas is calculated as:

$$T_3 = 2410 \text{ [K]}$$

First of all, the radius of centrifugal compressor impeller is decided as 34.5 mm. Then velocity triangles were used to calculate the amount of work done by RDE on the turbine. Figure 2 shows the illustration of it. The arrows indicates each velocities. The red one is gas velocity in the laboratory system, and the blue one is gas velocity in rotating system, and the yellow one is the velocity of rotating turbine vanes. Combustion gas flows through the stator and accelerates to 833.3 m/s with $\alpha_1 = 29$ deg circumferential velocity. To reach sufficient rotational speed in order to get 0.2 MPa gas supply from centrifugal compressor, the angles of turbine vane are decided as $\beta_1 = 49$ deg , $\beta_2 = 106$ deg.

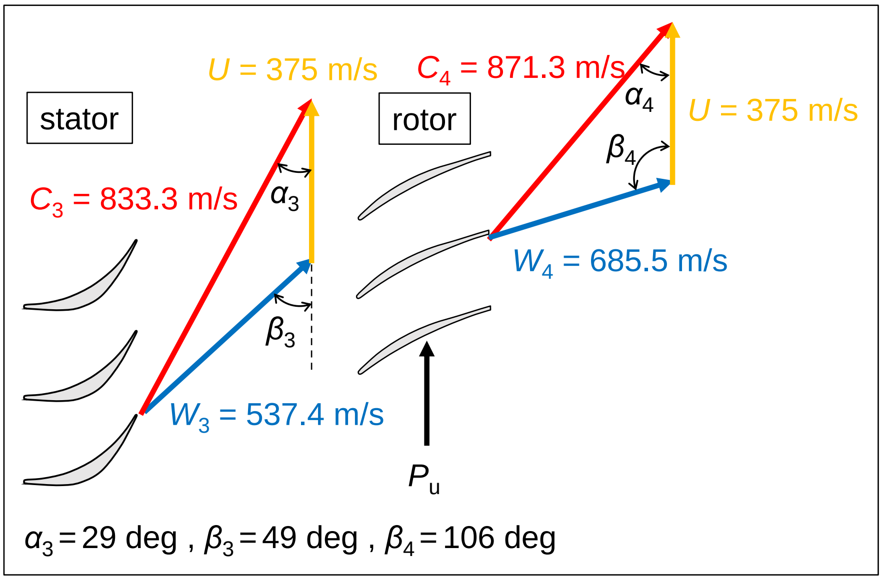

Figure 2 : illustration of velocity triangle of the axial turbine

After the shape of turbine vane is decided, the shape of compressor impeller have to be decided. Figure 3 shows the illustration of velocity triangle of the centrifugal compressor. The color of the arrows indicates the same velocity as turbine one. In this RDTE design, compressor has to supply at least 0.2 kg/s and 0.2 MPa air. The radius of 34.5 mm is decided to satisfy these conditions.

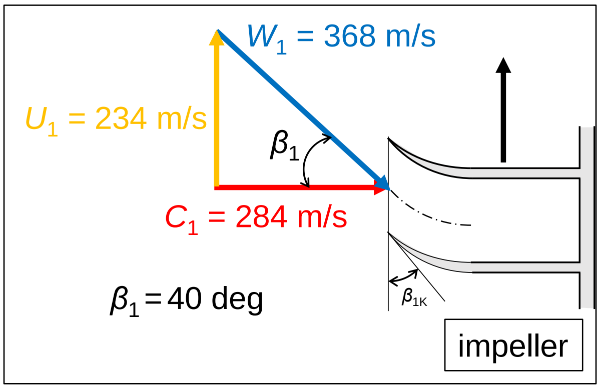

Figure 3 : illustration of velocity triangle of the centrifugal compressor

Transient state is evaluated theoretically in an RDE combustion test. The rotor used in this study is assumed to be made entirely of SUS304, including the moving blade portion. The inertial moment is:

$$I = 7.02 \times 10^{-5} [\mathrm{kg\ m^2}]$$

As an initial condition, the angular velocity can be expected to be approximately $\omega = 8{,}000$ [rad/s] for the total pressure ratio in the compressor is 2.

Figure 4 shows the result of the calculation about change of rotational speed and total pressure ratio. In the combustion test, the maximum rotational speed reaches approximately 112,000 rpm and it takes less than 0.5 seconds. From this analysis, actual testing can be assessed within a second combustion test. For actual testing, an external power source or similar method should be used to provide the initial drive required to reach the rotational speed necessary for detonation operation.

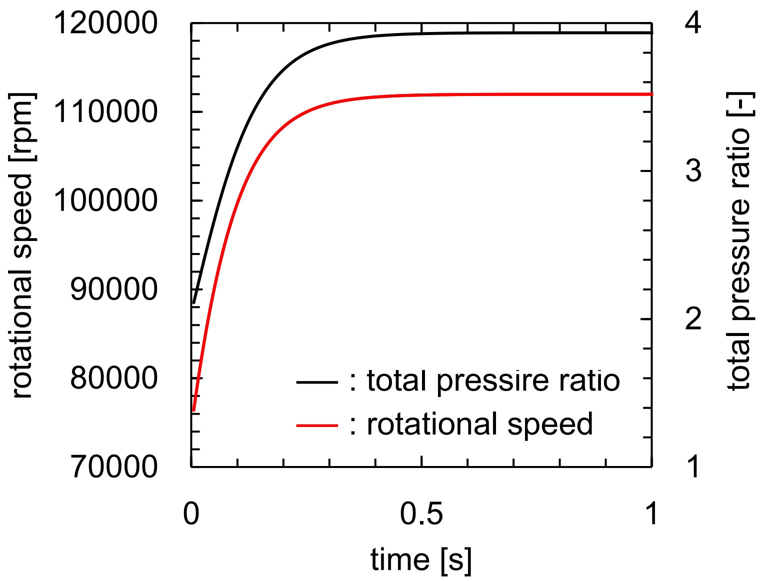

Figure 4 : transient state of the rotational speed and total pressure ratio

4 Experiments

In this study, a closed impeller with side plates was fabricated using a 3D printer and tested as a stand-alone compressor driven by a motor. Figure 5 shows the photograph of the experiment. The 3D printer used was Formlabs Form 2, with Clear resin as the material. The radius of the rotor blades was 30 mm, the inlet angle of the inducer was 60 degrees, and a MABUCHI MOTOR RS-380PH motor was employed.

Measurements were conducted using a pressure transducer (Keller: PAA-23) with a measurement frequency of 1 kHz, connected to a total pressure tube angled at 60 and 80 degrees. The compressor was operated at atmospheric pressure, and the rotational speeds tested were 5660 rpm, 6349 rpm, and 7894 rpm, within the motor's operational capacity.

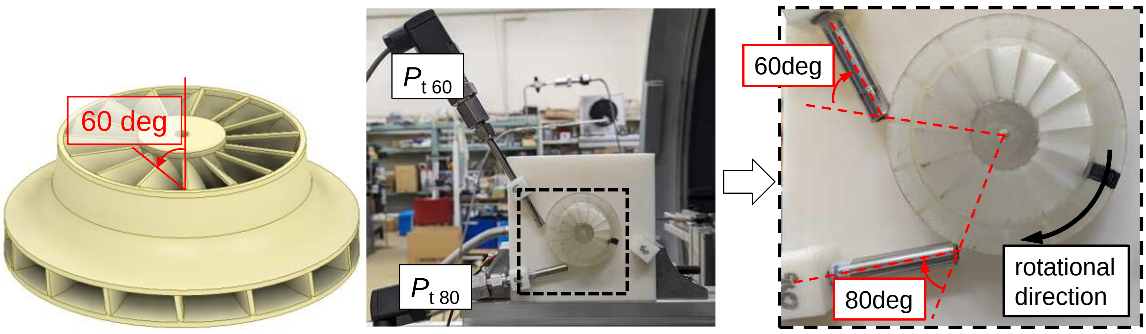

Figure 5 : Photograph of the experimental setupleft: 3DCAD model of impeller, center: from the front, right: enlarged view

Figure 6 shows the comparison of the rotational speed variation data of the total pressure ratio of the compressor. Now the ηp is the adiabatic efficiency. This indicates that the tested compressor impeller operates with a performance close to the theoretical predictions under the assumption of an adiabatic efficiency of ηp=0.6.

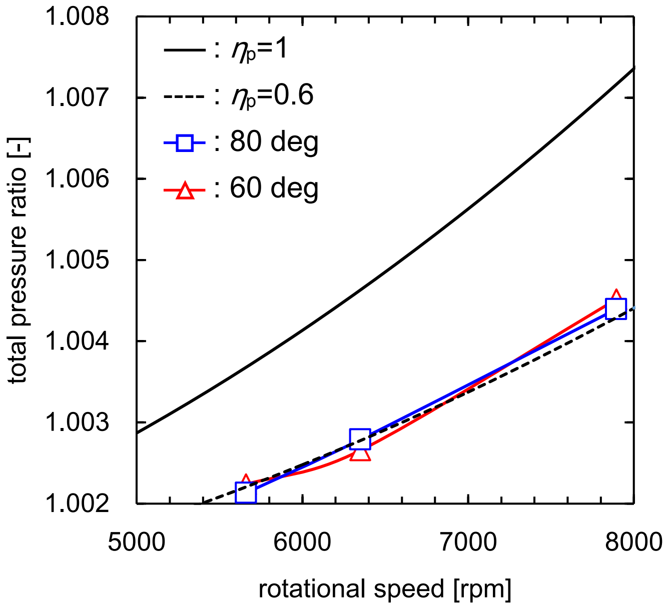

Figure 6 : Rotational speed variation data of the total pressire ratio

5 Conclusion

In this study, a compact RDTE was designed. In designing the RDTE, the performance of the compressor and turbine was determined by matching the performance of the compressor and turbine with the assumed performance of an H2-air RDE. Velocity triangles were used for deciding each blade shape, and theoretical analysis confirmed that the RDTE could operate independently. The maximum rotational speed was confirmed to be 112,000 rpm analytically. In addition, a simple experiment was conducted to confirm whether the pressure is boosted by the centrifugal compressor. In this experiment, a small increase of total pressure confirmed, and the total pressure ratio at this time matched the theoretical curve when the adiabatic efficiency was 0.6.

Acknowledgement

One of the authors (K. Higashino) is thankful to the Asian Office of Aerospace Research and Development for their partial support by the project number of FA2386-23-1-4061. The development of the rotating detonation engine received financial support through the “Study on Innovative Detonation Propulsion Mechanism,” Research-and-Development Grant Program (Engineer- ing) from the Institute of Space and Astronautical Science, the Japan Aerospace Exploration Agency. The fundamental device develop- ment was subsidized by a Grant-in-Aid for Specially Promoted Research No. JP19H05464 from the Japan Society for the Promotion of Science.

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