An experimental study on the flow characteristics of a supersonic turbine cascade

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Abstract

In this paper, a small supersonic wind tunnel was designed and built to study the flow characteristics of a supersonic impulse turbine cascade by experiment. The flow was visualized by means of a single pass Schlieren system.
The supersonic cascade with 3-dimensional supersonic nozzle was tested over a wide range of pressure ratio. Highly complicated flow patterns including shocks, nozzle-cascade interaction and shock boundary layer interactions were observed.

Introduction

Conventional turbines operate with subsonic or transonic rotor inlet relative velocities.
A recent need for high power turbines for airborne application has renewed the need for a supersonic turbine. The main feature of supersonic turbine is high specific power output with low efficiency. So it is need for the power generation with low eight and low inertia for fast start. Propellant feed system often employs supersonic turbine in spite of its low efficiency. Other turbo-pump system which supplies high pressure oil also adopts supersonic turbine.
Conventional turbines are fully analyzed with many previous experimental and computational studies resulting in various reliable performance data.
But the flow characteristics of supersonic turbine are quite different from those of conventional turbines.
The studies about the flow characteristics of supersonic turbine were hardly worked except studies performed by C. D. Colclough[1,2], B. S. Stratford[3, 4], etc.
At the present time, there is little reliable performance data available. In order to design a supersonic turbine with better efficiency, the flow characteristics must be fully investigated to supply sufficient performance data.
In this paper, a small supersonic wind tunnel was designed and built to study the flow characteristics of a supersonic impulse turbine cascade by experiment. The flow was visualized by means of a single pass Schlieren system.
The supersonic cascade with 3-dimensional supersonic nozzle was tested over a wide range of pressure ratio.

Test apparatus and Method

Test apparatus

A supersonic wind tunnel was designed and built to study the performance and flow through the cascade blades. The schematic of experimental setup is shown in Fig. 1.

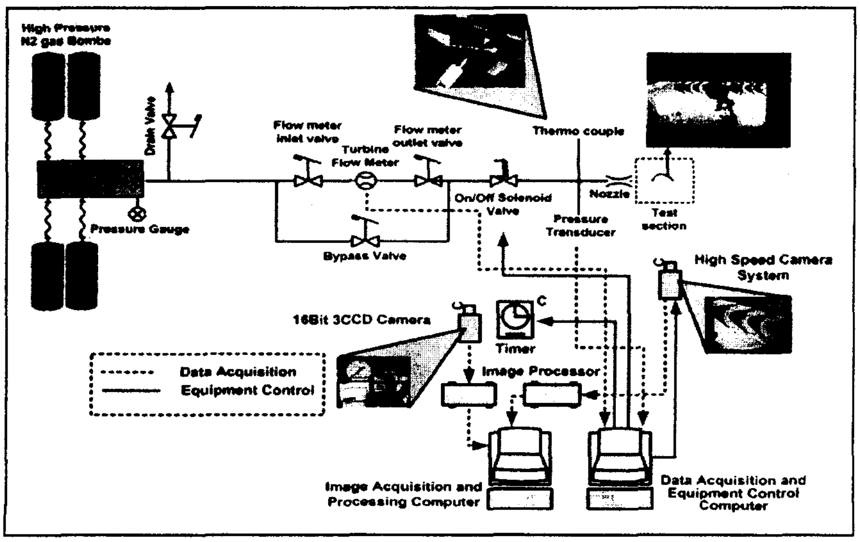

Fig. 1 Experiment control and measurement equipment scheme

The test apparatus consists of four parts - four high pressure nitrogen tanks (pressure and volume of each tank is 1500psi and 42liter), intermediate pressure chamber, on/off solenoid valve and test section.
And the test section also consists of four parts - nozzle, nozzle adapter, blades and a pair of test section window. The picture of converging-diverging nozzle used in experiment and the dimensions of nozzle core are shown in Fig. 2 and Fig. 3, respectively. The nozzle throat diameter is 5.85mm and the nozzle exit diameter is 7.6mm. The nozzle area ratio is 1.687. The nozzle core was manufactured from Stainless Steel.
Fig. 4 shows the nozzle and nozzle adapter assembly which was designed for an easy replacement of nozzles. The installation angle of the assembled nozzle adapter is 26.14°.

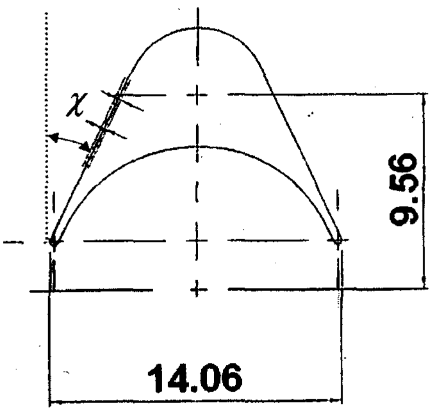

Fig. 5 Supersonic blade profile

Fig. 2 Supersonic nozzle core

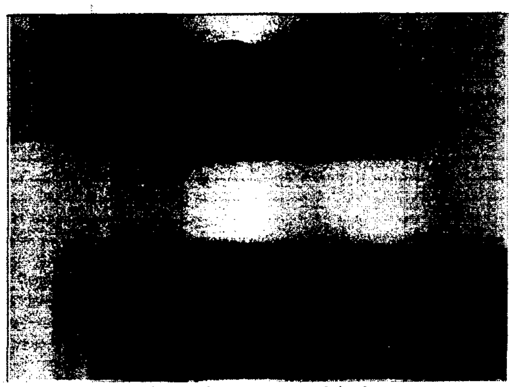

Fig. 6 Supersonic blade

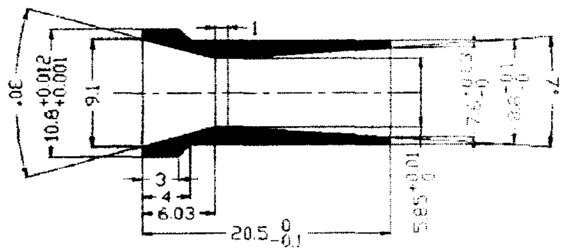

Fig. 3 Supersonic nozzle profile

Fig. 7 Test section part

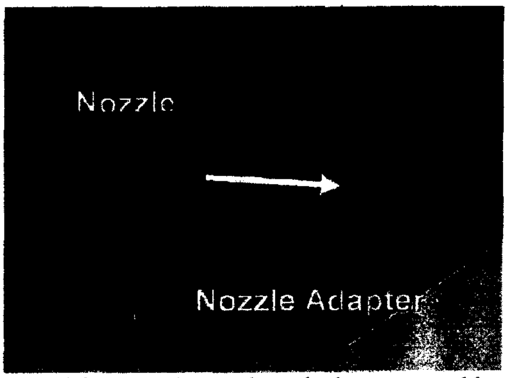

Fig. 4 Supersonic nozzle and adapter assembly

The blade profile used in the experiment is shown in Fig. 5 and Fig. 6. The blade chord length is 14.06mm and the pitch is 9.56mm. The angle between Nozzle adapter and blade suction surface (χ) is 25.34°. The blade was made of Aluminum Powder Alloy.
There were two holes on each blade to fix it to the test section windows by pins as shown in Fig. 7. The test section windows were made of Silica Glass to acquire clear Schlieren images.

Test procedure and data measurement

All procedure of the experiment is operated and controlled by a program. After the valve of nitrogen tanks was open to fill the intermediate pressure chamber, the atmosphere pressure was measured for 3 seconds by pressure transducer (Furness Control Ltd., FC034). And then, the experiment would begin with opening the on/off solenoid valve.

At that time, the data such as the mass flow rate, the nozzle inlet static pressure and the total temperature were simultaneously measured by the turbine flow-meter (Flow Technology Inc., LN-5-C-V1-9), the pressure transducer (Kulite, BME-1100-2500SG-A-4) and thermo- couple, respectively. The measured data were transferred directly to the computer through DAQ board. The schematic of equipment for control and measurement are shown in Fig. 1.

Flow visualization and images capture

Shadowgraph and Schlieren system were used for the flow visualization of supersonic turbine cascade in this study.

A single Schlieren mirror for Shadowgraph images and a Z-type Schlieren arrangement for Schlieren images were employed. And a continuous 150 watt Tungsten light was also used as light source.

Flow Images were captured using a 3CCD digital camera (Panasonic, DC330) and a high speed camera system (Kodak, SR Ultra-C). The high speed camera system could capture the images at the maximum speed of 10000 frame/sec. The captured images transformed into digital images and were processed by the image processing computer.

All cameras were connected with the computer for data acquisition and equipment control, and they were operated simultaneously when the experiment begun. The captured images were compensated by the optical filter of each camera.

Result and Consideration

Nozzle inlet total pressure

The static pressure at the nozzle inlet was measured by a pressure transducer. It can be assumed as total pressure because the Mach number is very small at the measurement position.

Nozzle Flow

The experiment for nozzle flow was executed to find the nozzle flow characteristics with the change of nozzle pressure ratio by blowing out the flow to the atmosphere, as shown in Fig. 8. And the experimental results are shown in Fig. 9 ~ Fig. 14.

Fig. 9 is the shadowgraph image for pressure ratio of 4.2. The dark part as shown in Fig. 9 is nozzle adapter. The white dot lines represent the position of nozzle core and the axis of nozzle center. Oblique shock is observed at the upper part of the nozzle exit while the flow is expanded around the lower part of the nozzle exit. The diamond shape of shock system is also observed. The main flow is deflected to upper direction.

Fig. 10 is the result for pressure ratio of 6.3. The shock system is very close to the result for pressure ratio of 4.2 but the diamond shape becomes clearer. Nozzle exit flow angle (λ) is still smaller than nozzle installation angle (φ). Fig. 11 is the result for the pressure ratio of 7.34. in this case Nozzle exit flow angle (λ) is almost same as nozzle installation angle (φ). Fig. 12 is the result for the pressure ratio of 8.39. The shock system becomes very complex with the shock originated from the nozzle inside. Fig. 13 is the result for the pressure ratio of 10.49. And Fig. 14 is the result for the pressure ratio of 12.59. As the nozzle pressure ratio increase, the main flow is more directed toward lower side, and the flow around part A (Fig. 8) is more bent to inside the flow with oblique shock while the flow around part B (Fig. 8) is more spread to outside the flow with expansion waves.

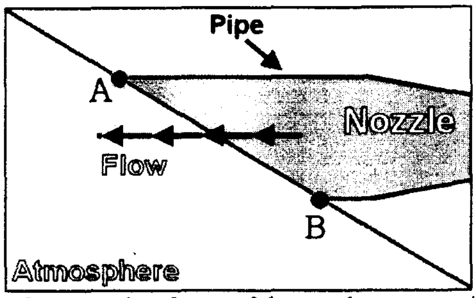

Fig. 8 geometric scheme of the nozzle cross section

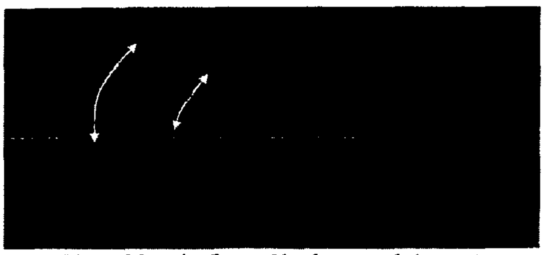

Fig. 9 Nozzle flow (Shadowgraph image)

P_{01}:61.68psi, P_2:14.697psi, P_{01}/P_2:4.2

Fig. 10 Nozzle flow (Shadowgraph image)

P_{01}:92.52psi, P_2:14.697psi, P_{01}/P_2:6.3

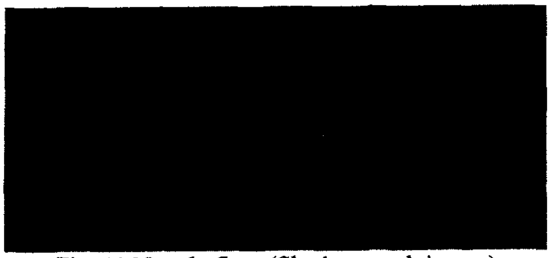

Fig. 11 Nozzle flow (Shadowgraph image)
p_{01}:107.94psi, p_2:14.697psi, p_{01}/p_2:7.34

Fig. 12 Nozzle flow (Shadowgraph image)
p_{01}:123.36psi, p_2:14.697psi, p_{01}/p_2:8.39

Fig. 13 Nozzle flow (Shadowgraph image)
p_{01}:154.2psi, p_2:14.697psi, p_{01}/p_2:10.49

Fig. 14 Nozzle flow (Shadowgraph image)
p_{01}:185.04psi, p_2:14.697psi, p_{01}/p_2:12.59

Cascade Experiment

Experiments of the cascade flow were executed to study the flow characteristic within cascade by changing the nozzle pressure ratio with experimental device as shown in Fig. 15. Fig. 17 ~ Fig. 23 show flow-visualizations of the flow visualized by the Schlieren system and Shadow-graph system.

In case of impulse turbine, p_2 and p_3 are same. So, Experiment was executed under the assumption of p_2 and p_3 of atmospheric pressure.

0° incidence angle was assumed when the angle (χ) between nozzle adapter and blade suction surface are same as the nozzle installation angle (φ). The experiments were performed with χ of 25.34° and φ of 26.14°.

Fig. 17 and Fig. 18 show the results with positive incidence angle when λ is smaller then φ. λ is almost same φ in Fig. 19 and Fig. 20. So, Fig. 19 and Fig. 20 becomes almost 0° incidence angle. λ is large than φ in Fig. 21~23. So, Fig. 21~23 becomes negative incidence angle.

Fig. 16 shows the Shadowgraph of the supersonic cascade flow with negative incidence angle. Detached shock is formed at the leading edge of the 2nd blade by the bluntness of the leading edge. And second shock is observed behind the detached shock.

The angle of the detached shock formed at the leading edge of the 1st blade is smaller than that formed at the leading edge of the 2nd blade. This seemed to be caused by the reason that the angle of the flow at the exit of nozzle became decreased by the shocks propagated from the leading edge of the 2nd blade. And weak shock was observed at the front of the suction surface of the 2nd blade. This seems to be caused by gap between the test section windows and blades. A separation bubble is formed at 35 percent chord of the 2nd blade on the suction surface. The separation is bent by the detached shock propagated from the leading edge of the first blade. Fish tail shocks are observed at the tailing edge of the 1st and 2nd blade. Oblique shocks propagated from the nozzle are shown on the suction side of cascades. And the shocks formed at the leading edge of the 2nd blade are refracted. This is seemed to be caused by the 3D nozzle flow which is not uniform. Semicircle shapes observed at the 3rd blade is a mark of pinhole crack on window.

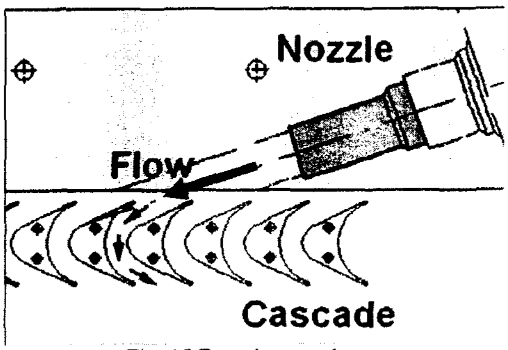

Fig. 15 Experiment scheme

Fig. 17 ~ Fig. 23 show the visualized image of supersonic turbine for wide range of the pressure ratio of the nozzle.

Fig. 17 shows the visualized image at $p_{01}/p_2 = 4.2$. Detached shock is observed at leading edge of the 2nd blade. Fig. 18 shows the results at $p_{01}/p_2 = 5.25$. Weak normal shock is propagated from the leading edge of the 1st blade to 35% of the chord on the suction surface of the 2nd blade.

Detached shock formed at the leading edge of the 2nd blade pass into a blade passage as nozzle pressure ratio increase. This is caused by the reason that the flow angle of nozzle (λ) increases, the turbine incidence angle decreases as the nozzle pressure ratio increase. Moreover, due to the decrease of the turbine incidence angle, the separation bubble is formed at a half of the chord on the suction surface of the 3rd blade as shown in Fig. 21 ~ Fig. 23.

The size of the separation bubble area is a little decreased as the nozzle pressure ratio increase as shown in Fig. 19 ~ Fig. 23.

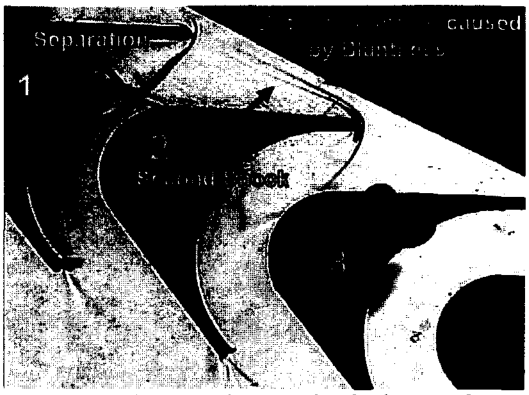

Fig. 16 Supersonic cascade Shadowgraph
p_{01}:205.6psi, p_2:14.696psi, p_{01}/p_2:13.99

Fig. 17 Supersonic cascade Shadowgraph
p_{01}:61.68psi, p_2:14.696psi, p_{01}/p_2:4.2

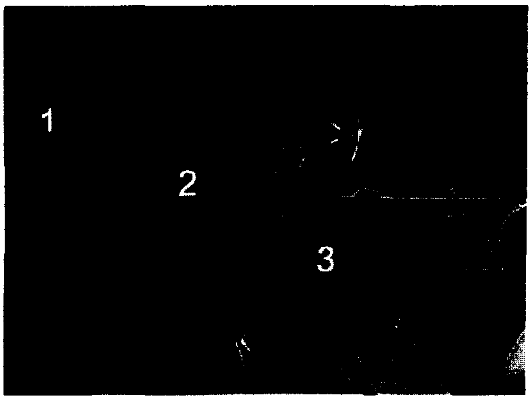

Fig. 18 Supersonic cascade Shadowgraph
p_{01}:77.1psi, p_2:14.696psi, p_{01}/p_2:5.25

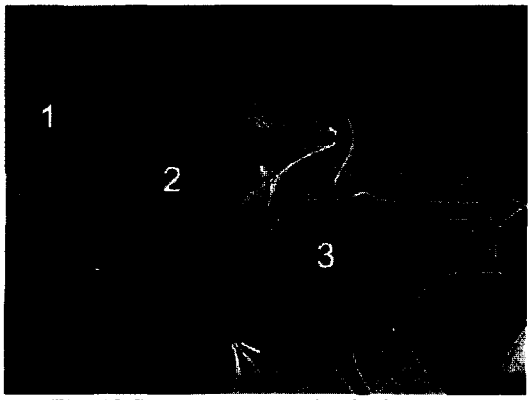

Fig. 19 Supersonic cascade Shadowgraph
p_{01}:92.52psi, p_2:14.696psi, p_{01}/p_2:6.3

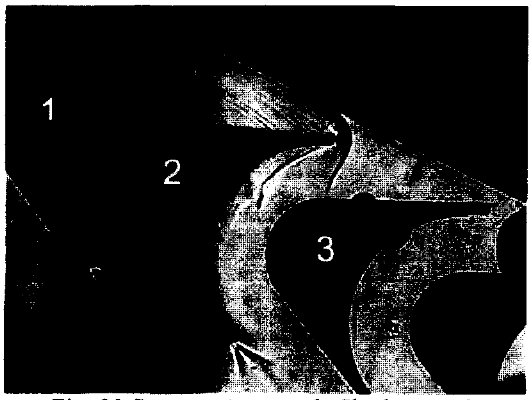

Fig. 20 Supersonic cascade Shadowgraph
p_{01}:107.94, p_2:14.696psi, p_{01}/p_2:7.34

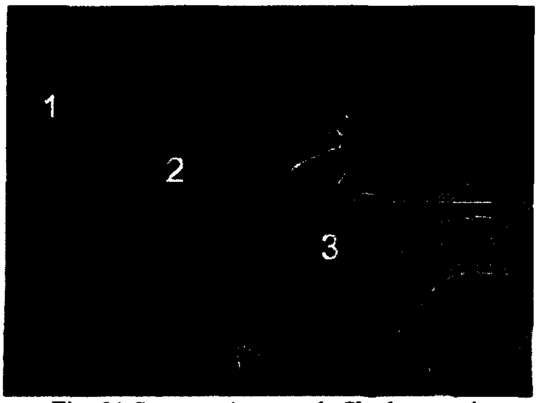

Fig. 21 Supersonic cascade Shadowgraph
p_{01}:123.36psi, p_2:14.696psi, p_{01}/p_2:8.39

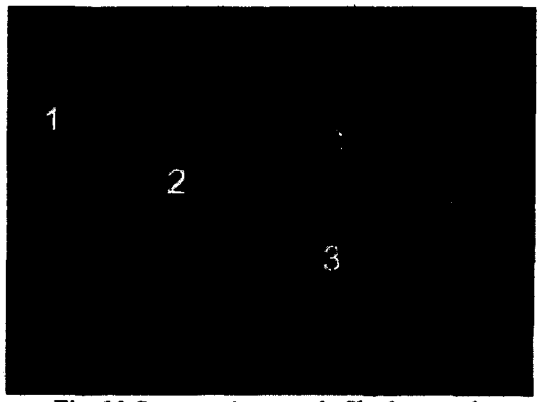

Fig. 22 Supersonic cascade Shadowgraph
p_{01}:154.02psi, p_2:14.696psi, p_{01}/p_2:10.48

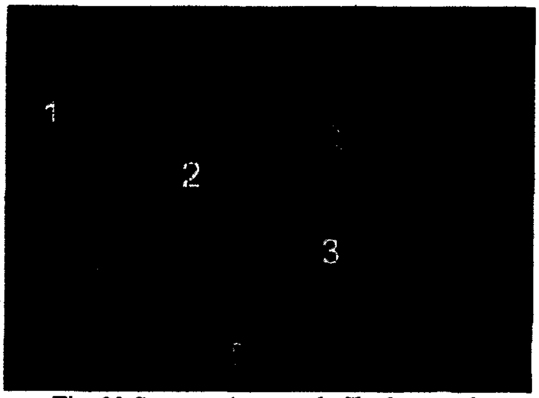

Fig. 23 Supersonic cascade Shadowgraph
p_{01}:185.04psi, p_2:14.696psi, p_{01}/p_2:12.59

Conclusion

In this study, experiments have been performed to analyze for the flow characteristic including the shock pattern of partial admission supersonic impulse turbine with a small wind tunnel. These experiments were divided into a visualization of nozzle flow and that of turbine cascade flow over a wide range of the pressure ratio of nozzle.

The followings are concluded by the experiments:

1. Nozzle exit flow angle (λ) is increased as the pressure ratio increase resulting in the decrease of turbine incidence angle.
2. Complex flow and shock patterns occurred by sloped exit nozzle.
3. Detached shock due to leading edge bluntness is clearly observed.
4. Separated flow area is decreased a little as the nozzle pressure ratio is increased.

References

1) C. D. Colclough.: Design of turbine blades suitable for supersonic relative inlet velocities and the investigation of their performance in cascades: part I – theory and design, journal of mechanical Engineering science, 8 (No. 1), 1966
2) C. D. Colclough.: Design of turbine blades suitable for supersonic relative inlet velocities and the investigation of their performance in cascades: part II – experiments, results and discussion, journal of mechanical Engineering science, 8 (No. 2), 1966
3) Stratford, B. S. and Sansome, G. E.: Tunnel tests on a double cascade to determine the interaction between the rotor and the nozzles of a supersonic turbine, N.G.T.E. M 359, 1962.
4) Stratford, B. S. and Sansome, G. E.: Theory and tunnel tests of rotor blades for supersonic turbines, R&M 3275, 1965.

Nomenclature

p_{01} : Nozzle Inlet Total Pressure
p_2 : Nozzle Exit Static Pressure
p_3 : Cascade Exit Static Pressure
φ : Nozzle incidence angle
λ : Nozzle exit flow incidence angle
χ : Angle between blade suction surface and nozzle adapter