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Tip Clearance Effect on the Performance of a Shrouded Supersonic Impulse Turbine

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An experimental investigation of the effect of tip clearance on the performance of a shrouded supersonic impulse turbine was performed in this study. A single-staged axial flow impulse turbine designed to have a rotor inlet relative Mach number of 1.7 was used for the experiment. Turbine efficiency was measured at various settings of tip clearances, rotational speeds, and turbine pressure ratios to observe the characteristics of the efficiency gradient. The overall efficiency of the supersonic impulse turbine was largely affected by rotational speed. For a fixed rotational speed, local maximum efficiency was found near a turbine pressure ratio at which the turbine nozzle was fully expanded. At a reference test point, the linearly estimated efficiency gradient was 0.09. However, efficiency variation with respect to tip clearance was nonlinear, and relatively larger efficiency gradients were found at small tip clearances and high rotational speeds. It has been found that the efficiency gradient varies linearly with the cube of rotational speed and shows its minimum value near the reference turbine pressure ratio.

Nomenclature

c	=	tip clearance
c_i	=	ideal turbine nozzle exit jet velocity
h	=	turbine rotor blade span
M_{w1}	=	turbine rotor inlet relative Mach number
N	=	rotational speed
N^*	=	corrected rotational speed, $N/\sqrt{T_{00}}$
N_r^*	=	corrected rotational speed at the reference test point
p_{00}	=	turbine inlet total pressure
p_1	=	turbine rotor inlet static pressure
p_2	=	turbine exit static pressure
T_{00}	=	turbine inlet total temperature
u	=	rotor tangential velocity at mean diameter
η	=	total-to-static efficiency
η_0	=	total-to-static efficiency at zero tip clearance
$\eta_{r,d}$	=	total-to-static efficiency at the reference test point
π	=	turbine total-to-static pressure ratio
π_r	=	turbine total-to-static pressure ratio at the reference test point

I. Introduction

QUANTIFYING the tip-clearance-loss characteristics of a turbine is one of the major concerns of turbine designers. In axial flow turbines, the amount of tip-clearance loss depends on parameters such as stage loading, degree of reaction, size of tip clearance, etc. The effect of tip clearance on axial flow turbine efficiency can be quantified by the efficiency gradient [1] [a rate of change of efficiency with respect to change of tip clearance $(-d(\eta/\eta_o)/d(c/h))$] and much research on the efficiency gradient and its behavior has been done for various axial flow turbines by many researchers.

The majority of experiments on the efficiency gradient of axial flow turbines were conducted for unshrouded subsonic turbines that rotor inlet relative Mach numbers are below unity. Following the reported results of unshrouded subsonic reaction turbines [2–10], the absolute value of the efficiency gradient and its behavior with change in tip clearance was different from turbine to turbine, depending on design pressure ratio π_t, velocity ratio u/c_i, rotor hub-to-tip-radius ratio, rotor inlet relative Mach number M_{w1}, and flow choking characteristics at the nozzle and rotor. Measured efficiency gradients ranged from 1.7 to 3.7 and a higher rotor reaction resulted in a higher efficiency gradient. In subsonic reaction turbines, increased tip clearance usually entails increased corrected mass flow rates [10]. This phenomenon may change the turbine rotor inlet flow condition and can cause additional turbine losses to boost the magnitude of efficiency gradient.

It is well known that the efficiency gradient of an impulse turbine is lower than that of a reaction turbine [11]. If the impulse turbine is shrouded, the efficiency gradient is further reduced [12]. In the experiments of shrouded subsonic impulse turbines [12,13], linearly estimated efficiency gradients were 0.25–0.3, an order of magnitude smaller than those of unshrouded reaction turbines.

Only limited literature data on the efficiency gradients of supersonic impulse turbines exist. Supersonic impulse turbines are of extreme turbine design, adopted in high-specific-power-generating devices (e.g., turbopump turbines of gas-generator-cycle liquid rocket engine, torpedo-driving-power turbines, etc.). The major portions of energy losses in a supersonic impulse turbine come from profile losses at the nozzle (or stator vane)/rotor passage and shock loss at the rotor inlet. Secondary losses by disk windage, partial admission, and tip clearance are relatively small. In the case of the supersonic turbine addressed in this paper, the predicted profile and shock losses were 87% of the total loss, and just 6% of the total loss was due to tip-clearance loss. This prediction is somewhat different from the fact that more than 30% of the total loss is due to tip-clearance loss in subsonic reaction turbines [9]. Referring to the preceding prediction, efficiency variation with tip-clearance change in supersonic impulse turbines could be small compared with a subsonic reaction and impulse turbines. In this research, overall performance characteristics and the effects of tip clearance on the performance of the supersonic impulse turbine are investigated experimentally.

II. Supersonic Impulse Turbine, Test Facility, and Test Conditions

The supersonic impulse turbine used in this experiment was originally designed as a subcomponent of a turbopump that was developed for gas-generator-cycle liquid rocket engine application [14–17]. Its design power is 1.6 MW at a rotational speed of

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Table 1 Summary of turbine design and reference test point data

Parameters	Design point	Reference test point (working medium is air)
Corrected rotational speed N^*	667	587
Turbine total-to-static pressure ratio π	14.5	20.2
Velocity ratio u/c_i	0.25	0.25
Rotor inlet relative Mach number M_{w1}	1.69	1.79
Stage loading $\Delta H/u^2$	4.3	~4.7
Power, kW	1620	——
Hub-to-tip-radius ratio	0.875	0.875
Pitch-to-chord ratio	0.67	0.67

20,000 rpm. The turbine adopted 11 straight-centerlined axisymmetric convergent–divergent nozzles that result in a rotor inlet relative Mach number of 1.7 at design operating condition. The partial admission ratio, based on nozzle exit area and rotor inlet area, is 0.58. The turbine rotor is equipped with bucket-shaped straight blades and a shroud. The basic design parameters of the turbine are summarized in Table 1. The turbine–nozzle block and rotor used for the experiments are shown in Fig. 1, together with a cross-sectional view of the nozzle–rotor assembly.

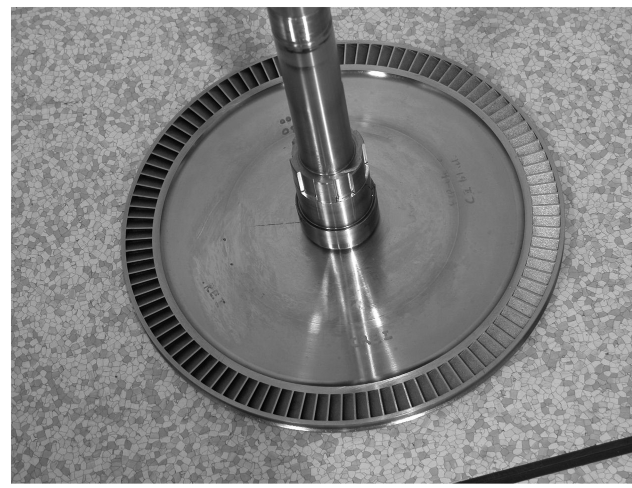
For the investigation of the efficiency gradient of a shrouded supersonic impulse turbine, the size of the tip clearance was controlled using replaceable outer casing rings of different inner diameters. Considering the various applications, a large tip-clearance ratio range ($c/h > 21\%$) was covered. Four different tip-clearance settings used in this experiment are shown in Fig. 2.

The turbine test was conducted using high-pressure air. Highly compressed air (above 250 bar) was charged in vessels of total volume of 40 m^3. The dew point of the compressed air was maintained below −40°C. Pressure at the turbine inlet was controlled by an automatic air-pressure regulator. For mass flow rate measurement, a sonic flow meter with a 15 mm throat diameter was installed just downstream of the regulator. The flow meter was calibrated within the range of Reynolds numbers of the current tests at a certified institute. For dissipating the power generated by the turbine, controlling rotational speed, and measuring the torque of the turbine, a hydraulic dynamometer (Froude Hoffmann, model F249) was used. The dynamometer load cell was calibrated using a balancing weight before every turbine test to guarantee reliable and consistent turbine efficiency measurements. During load cell calibration, the weighing sequence was set from high-to-low mass to simulate high-to-low torque variation in the experiments, thus reducing reading errors due to hysteresis. For pressure measurements, strain-gauge-based diaphragm-type pressure transducers (Sensortec, TJE model) were used. All pressure sensors were calibrated using known pressure sources. Offset readings of pressure transducers to the ambient pressure were all carefully corrected in the efficiency calculation. A resistance temperature device (PT-100) was used for temperature measurements. Every temperature channel was 2-point-calibrated physically using ice water and liquid nitrogen. To enhance the reliability of the measured values, every series of tests was repeated. The schematics of the test facility and a cutaway diagram of the test rig are shown in Fig. 3.

The turbine–nozzle full-expansion pressure ratio, based on the nozzle area ratio and nozzle efficiency, was selected as the reference turbine pressure ratio π_r. The reference corrected rotational speed N_r^* was selected such that, for a given reference turbine pressure ratio, the design velocity triangle at turbine rotor inlet could be accomplished. The reference test point is summarized in Table 1, together with the design parameters.

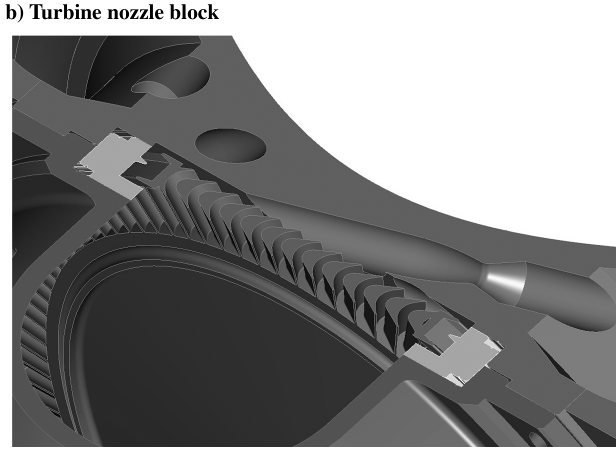
To measure the behavior of the efficiency gradient in a wide range of operating conditions, the subject turbine was tested in the range of 50–125% of the reference test pressure ratio and 42–130% of the reference corrected rotational speed.

In tests, the turbine inlet pressure was preset and then the rotational speed was changed from a low to a high value. The turbine pressure ratio was controlled by changing the turbine inlet pressure. Turbine exit static pressure was set close to ambient pressure. Respective rotational-speed levels were kept at a constant value for over 20 s for stable measuring of static performance parameters.



a) Turbine rotor

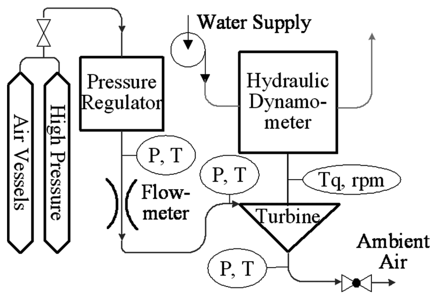
b) Turbine nozzle block



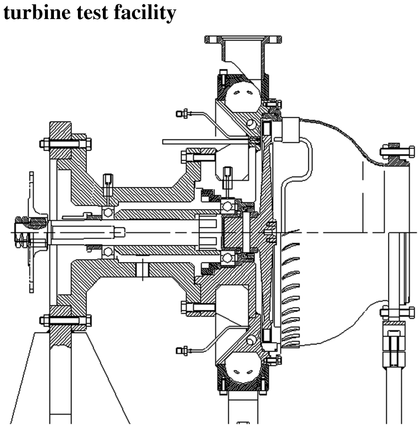
c) Nozzle centerline cross sectional view of turbine

Fig. 1 A supersonic impulse turbine.

Fig. 2 Comparison of tip-clearance setting.



a) Schematics of the supersonic impulse turbine test facility



b) Cutaway view of the turbine test rig

Fig. 3 Supersonic impulse turbine test facility and test rig.

The uncertainty of the measured efficiency was estimated in the range of 80–120% of the reference turbine pressure ratio and 80–110% of the reference corrected rotational speed. The uncertainty was ranged from 0.5 to 0.8% of the measured efficiency. In the high-pressure-ratio region, uncertainty was relatively low. At the reference test point, measurement uncertainty was found to be lower than 0.7%.

III. Results and Discussions

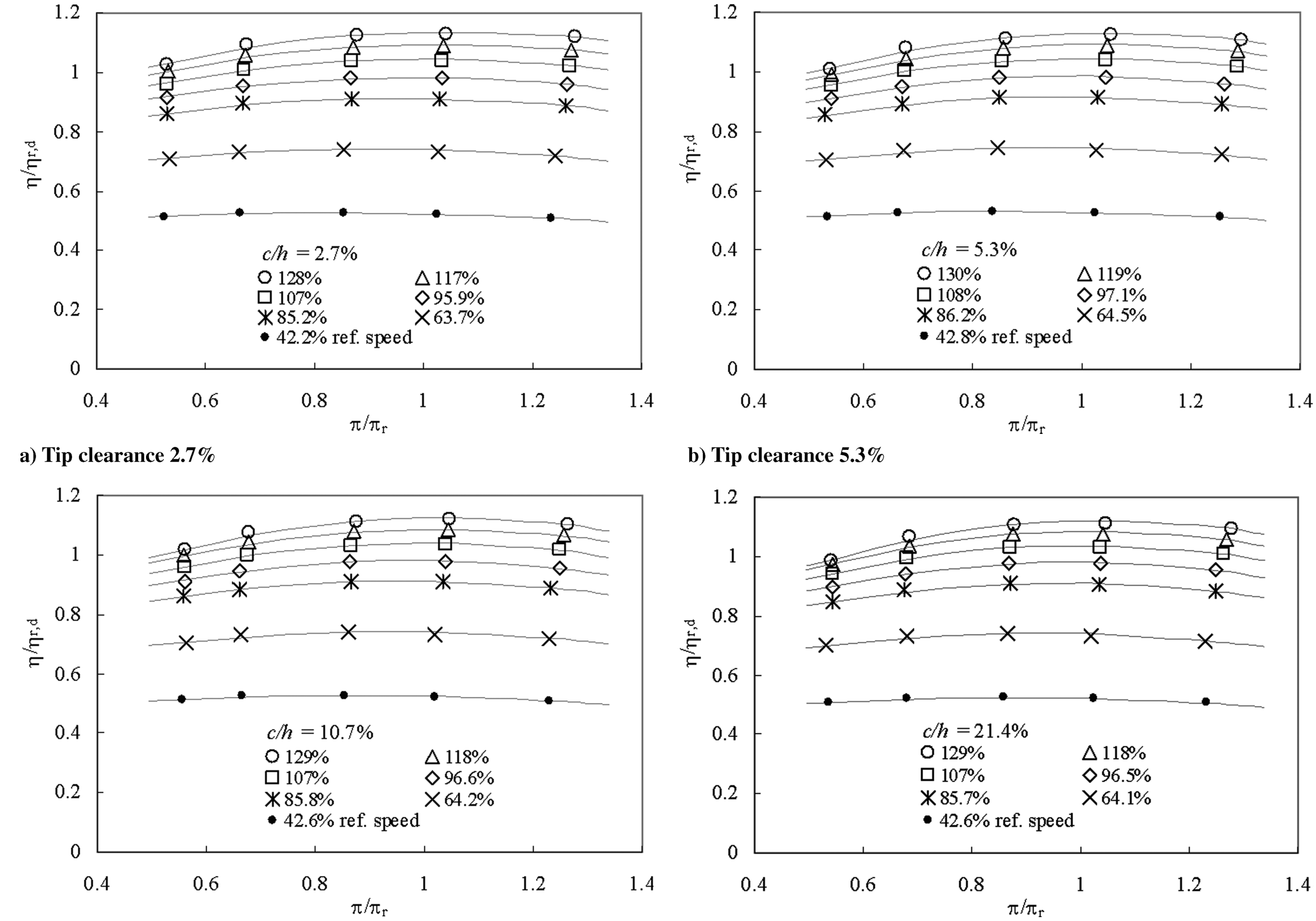
Figure 4 shows measured turbine total-to-static efficiency variation as a function of turbine pressure ratio and corrected rotational speed for different settings of tip-clearance ratios ($c/h = 2.7$, 5.3, 10.7, and 21.4%). Plotted efficiencies are normalized using the efficiency of the tip-clearance ratio of 10.7% (the tip clearance of the original design) at the reference test point (denoted as $\eta_{r,d}$). Solid curves of each plot are curve fits of measured efficiency.

In Fig. 4, overall turbine efficiency variation is greatly affected by rotational speed. For a fixed turbine pressure ratio, the efficiency change with respect to rotational speed is greater at low rotational speeds than at high rotational speeds. This phenomenon is a typical characteristic of supersonic turbines originating from the unique-incidence condition [18,19]: the direction of a supersonic cascade flow with a subsonic axial component is solely determined by the blade angle and blockage. At a fixed turbine pressure ratio, turbine efficiency is proportional to the rotational speed u and the difference between rotor inlet and outlet tangential flow speed Δc_θ. Basically, supersonic impulse turbine has a low design velocity ratio (u/c_i, 0.25 for the subject turbine) and a large axial flow angle of nozzle flow. If the supersonic impulse turbine operates at a rotational speed much lower than the design value, the magnitude and direction of the nozzle exit flow velocity and rotor inlet relative velocity are very close. However, the rotor inlet relative flow angle is fixed by the unique-incidence condition. Consequently, the nozzle exit flow is forced to deflect toward the turbine rotor to satisfy the given velocity triangle at the rotor inlet. The deflected nozzle flow results in additional stagnation pressure loss and reduction in Δc_θ. These facts explain the greater efficiency change of the supersonic impulse turbine at low rotational speeds. As rotational speed increases, the difference of magnitude between the nozzle exit flow velocity and the rotor inlet relative velocity becomes larger and the nozzle flow deflection by the unique-incidence-condition is relieved, thereby reducing Δc_θ decrement and stagnation pressure loss. Considering mass continuity in supersonic flow, flow deflection by low rotational speed must accompany relatively lower static pressure. Figure 5 is a plot of rotor inlet pressure p_1 measured near the hub of the turbine rotor with respect to rotational speed at the reference turbine pressure ratio. As can be seen in the figure, the rotor inlet pressure decreases when rotational speed is lowered and this experimentally supports the preceding argument.

In Fig. 4, a local maximum turbine efficiency is found near the reference turbine pressure ratio for any fixed rotational speed. This is also a typical feature of supersonic impulse turbines that can be found in other experiments [11,20]. Because the turbine nozzle expands fully at the reference turbine pressure ratio, there are no additional losses due to nozzle underexpansion ($\pi/\pi_r > 1.0$) or overexpansion ($\pi/\pi_r < 1.0$) in front of the turbine rotor and, as a result, a local maximum efficiency is attained.

Figure 4 shows that overall turbine performance characteristics are not much affected by tip-clearance change. For the direct comparison of turbine efficiencies at different tip-clearance settings, curve fits of Fig. 4 are used in regenerating turbine characteristics of Fig. 6. In Fig. 6, turbine efficiency is represented as a function of velocity ratio for the same values of pressure ratios and rotational speeds. Solid and dotted curves correspond to the conditions of constant rotational speeds and pressure ratios, respectively. Although the absolute efficiency differences are small, decrement of turbine efficiency with increasing tip clearance is well observed in the figure. The effect of pressure ratio on the turbine efficiency at a fixed rotational speed is more clearly seen in this figure.

In Table 2, interpolated turbine efficiencies at the reference test point are compared. In a tip-clearance-ratio range of 2.7–21.4%, turbine efficiency variation is less than 1% with respect to $\eta_{r,d}$. If the efficiency gradient is linearly estimated in the clearance ratio range between 2.7 and 10.7%, it is around 0.09. This value is about 3 times smaller than that of subsonic shrouded impulse turbines [12,13]. If the efficiency gradient is calculated in the clearance ratio range of 2.7–21.4%, an even lower value of 0.03 is found. The exact value of the efficiency gradient at design tip clearance ($c/h = 10.7\%$) and reference test point is 0.053 (see Table 3). This result well supports the argument of the relatively small effect of tip clearance on the efficiency loss in the supersonic impulse turbine given in the Introduction.



a) Tip clearance 2.7%

b) Tip clearance 5.3%

c) Tip clearance 10.7%

d) Tip clearance 21.4%

Fig. 4 Efficiency of supersonic impulse turbine.

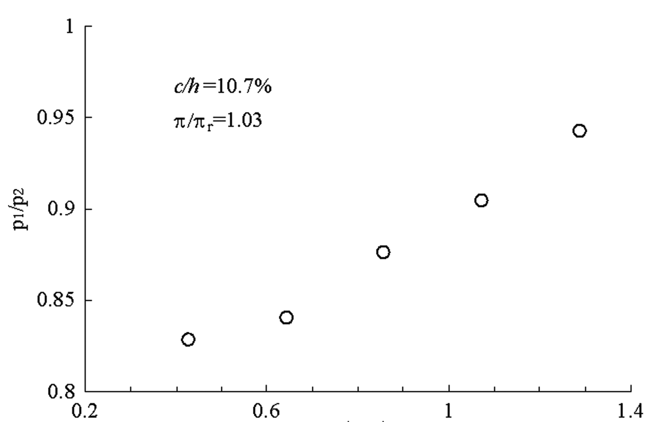


Fig. 5 Variation of turbine rotor inlet pressure with respect to rotational speed.

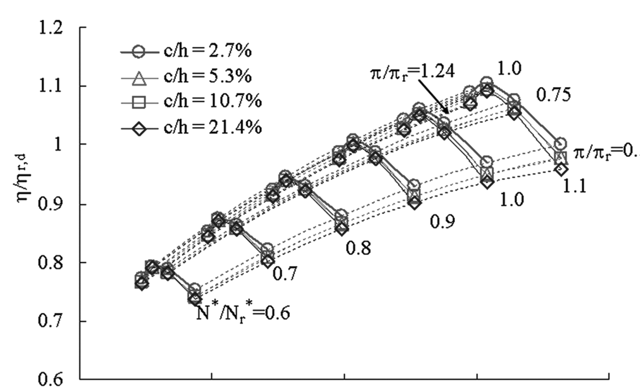


Fig. 6 Comparison of turbine performance for various tip-clearance settings.

The following discussions on the efficiency gradient are based on regenerated data using efficiency curve fits of Fig. 4. Efficiency variation with respect to tip clearance at reference turbine pressure ratio is shown in Fig. 7. Four different rotational speeds are compared. All efficiency values are normalized using extrapolated zero-clearance efficiency at corresponding constant rotational speeds (denoted as η_0). It can be seen in Fig. 7 that turbine efficiency decreases nonlinearly with tip clearance. The efficiency gradient (slope of each curve) is relatively high at small tip clearances and decreases with increasing tip clearance. In the tip-clearance-ratio range of 10.7–21.4% turbine efficiency change is almost negligible. It can also be seen in Fig. 7 that the higher the rotational speed, the larger the efficiency gradient. Detailed effects of rotational speed on the efficiency gradient can be found in Fig. 8. Estimated efficiency gradients of Fig. 8 are plotted using $(N^*/N_r^*)^3$ on the x axis. It is observed that the efficiency gradient changes linearly with the cube of rotational speed. Quantitative values of the efficiency gradients in Fig. 7 are tabulated in Table 3.

In Fig. 9, efficiency-gradient variations with respect to the turbine pressure ratio are compared at the reference corrected

Table 2 Efficiency at the reference test point ($N^*/N_r^* = 1.0$ and $\pi/\pi_r = 1.0$)

c/h	2.7%	5.3%	10.7%	21.4%
$\eta_r/\eta_{r,d}$	1.007	1.003	1.0	0.999

Table 3 Efficiency gradients at reference turbine pressure ratio [$-d(\eta/\eta_o)/d(c/h)$ at $\pi/\pi_r = 1.0$]

	c/h			
N^*/N_r^*	2.7%	5.3%	10.7%	21.4%
110%	0.155	0.126	0.066	0.014
100%	0.128	0.104	0.053	0.008
90%	0.106	0.085	0.043	0.004
80%	0.087	0.070	0.036	0.002

rotational speed. For any fixed turbine pressure ratio, efficiency-gradient values decrease with increasing tip clearance. In other words, the behavior of nonlinear turbine efficiency variation can also be found in offdesign operating conditions. For every setting of tip clearance, the minimum efficiency gradient takes place near the reference turbine pressure ratio. This means that the efficiency change of the supersonic impulse turbine due to the tip-clearance variation is the smallest when the supersonic impulse turbine operates at a turbine pressure ratio at which the turbine–nozzle flow is fully expanded.

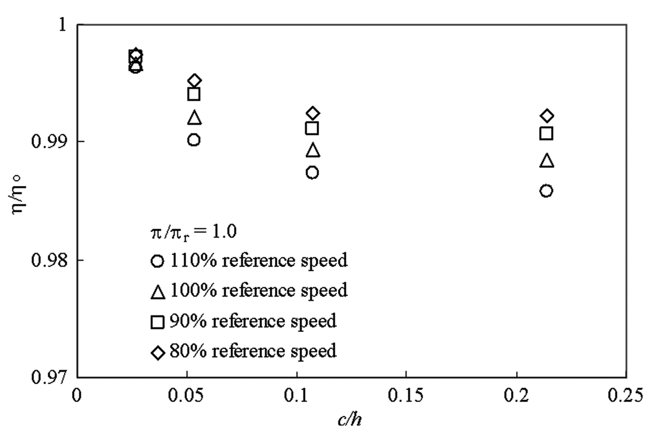


Fig. 7 Efficiency variation with respect to tip clearance.

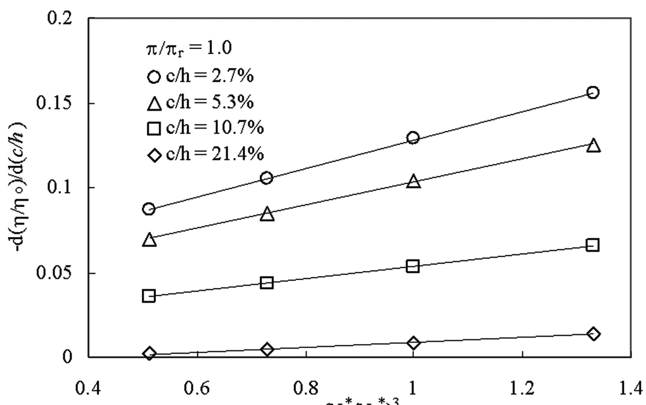


Fig. 8 Efficiency gradient variation with respect to rotational speed.

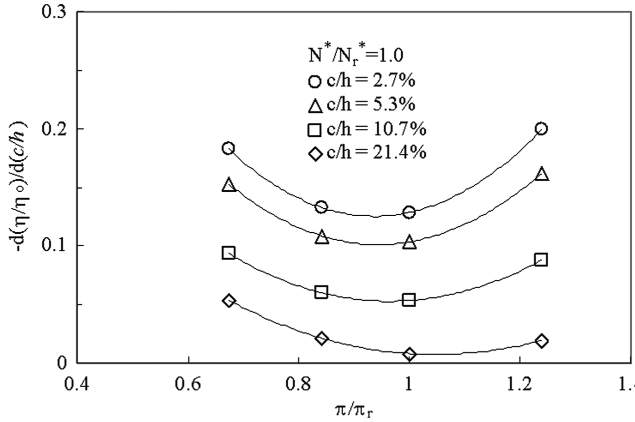


Fig. 9 Efficiency gradient variation with respect to turbine pressure ratio.

IV. Conclusions

The effect of tip clearance on the performance of a shrouded supersonic impulse turbine has been investigated experimentally. A supersonic impulse turbine designed to have a rotor inlet relative Mach number of 1.7 is used for the experiment. The ratio of turbine tip clearance to the turbine blade height (c/h) was varied between 2.7 and 21.4%. The experiment revealed the following:

1) The static efficiency of the supersonic impulse turbine is greatly affected by rotational speed. This feature is a typical characteristic of supersonic turbines originating from the unique-incidence condition. At a fixed rotational speed, maximum turbine efficiency is found at the reference turbine pressure ratio at which the turbine nozzle is fully expanded.

2) The linearly estimated efficiency gradient of the subject supersonic impulse turbine is 0.09 at the reference test point. This value is about 3 times smaller than that of subsonic shrouded impulse turbines. This result well supports the argument that only a small portion of the total loss is due to clearance loss in the supersonic impulse turbine.

3) The efficiency of the shrouded supersonic impulse turbine changes nonlinearly with tip clearance. The efficiency gradient is relatively larger at small tip clearances and higher rotational speed. With large tip clearance ($c/h > 10.7\%$), the turbine efficiency variation with respect to tip clearance is almost negligible.

4) For a fixed turbine pressure ratio, the efficiency gradient varies linearly with the cube of rotational speed.

5) For a fixed rotational speed, the efficiency variation due to the tip clearance is at a minimum when the supersonic impulse turbine operates near the reference turbine pressure ratio.

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