20TH SYMPOSIUM OF THE INDUSTRIAL APPLICATION OF GAS TURBINES COMMITTEE
BANFF, ALBERTA, CANADA
OCTOBER 2013

13-IAGT-305

EXPERIMENTAL INVESTIGATION OF THE INFLUENCE OF SERVICE EXPOSURE UPON THE AERODYNAMIC PERFORMANCE OF TRANSONIC TURBINE VANES

R.Woodason*†, A. Asghar, W.D.E.Allan****

***StandardAero(†ray.woodason@standardaero.com)**
****Royal Military College of Canada***

Keywords: *transonic cascade, turbine vane, repair*

Abstract

The airfoil profile of turbine nozzle guide vanes can be unintentionally altered due to service exposure, repair activities or manufacturing variability. This unwanted profile variation causes loss of turbine efficiency and may confound compressor to turbine matching after engine maintenance.

An experimental investigation into the aerodynamic consequences of small airfoil profile variations is described. Post-overhaul profiles from two real world turbine vanes were obtained and compared to a nominal new profile. To investigate their performance differences, a transonic two-dimensional linear cascade rig was designed and commissioned. Experimental data collection techniques included shock pattern visualization by schlieren imagery, and high-frequency measurement of flow direction and total pressure at the cascade exit.

Test results showed a significant increase in total pressure loss and a flow capacity reduction for off-design profiles. Boundary layer growth, flow separation in the boundary layers and shock boundary layer interactions, observed on the service-exposed and repaired profiles, were not present on the reference vane profile. The geometry deviations being explored were, in some cases, small and difficult to measure with conventional tools. Consequently their disproportionate contribution was notable. Conclusions are drawn regarding the aerodynamic performance influences of subtle geometric adjustments or minor damage and the consequent implications on engine overhaul practice.

1 Introduction

Unwanted variation of airfoil profile on turbine blades and vanes may be encountered during gas turbine engine maintenance. This may result from service condition-induced damage, from part rework and repair, or manufacturing variability. Turbine nozzle guide vane (NGV) airfoils are particularly prone to cracking and distortion due to operating under severe thermal gradients.

Since many current turbine designs require NGVs made with superalloys, sophisticated cooling schemes and protective coatings, their fabrication and replacement cost is high. Consequently, there is considerable economic incentive to repair and reuse this materiel during maintenance. A wide range of NGV airfoil repair techniques have been implemented, and some examples follow:

- Cracks may be repaired by manual welding or wide-gap braze followed by manual contour blending.
- Wall thinning and cracks may be restored using what is known is a *laminate repair*. This involves brazing an overlay or pre-form to the damaged airfoil surface, followed by blending original and repair surface contours manually.
- Missing or burned sections may be repaired using a coupon repair, in which a section or even entire airfoil would be cut out, and replaced with a manufactured insert or coupon
- Straightening distortion or adjusting gas flow area may be accomplished by bending the airfoil metal.
- Recently developed repair schemes tend to exploit adaptive machining for better control of airfoil profile.

It should be clear from the above that airfoil shapes may be influenced by NGV service and repair. Turbine efficiency depends strongly on profile losses and secondary losses which are linked to airfoil shapes. In addition, overall engine efficiency can be influenced by turbine nozzle flow capacity due to compressor matching effects. Increased turbine nozzle flow capacity would decrease pressure ratio over the turbine, which results in reduced compressor speeds and work output.

The study of transonic turbine blade profile loss mechanisms and performance prediction is the subject of a large body of literature. Corriveau and Sjolander [1] showed that mild variation of loading distribution for given blade profile affected pressure loss by more than 10%. Li *et al*. [2] studied two turbine blade profiles and noted significant differences in pressure loss for transonic exit flow conditions. Mee *et al*. [3] examined the contribution of blade boundary layers, wake-mixing and shocks to the overall loss of a transonic cascade. The mechanism of losses associated with the trailing edge flow and shock structure is discussed in some detail by Denton and Xu [4].

Colantuoni *et al*. [5] investigated the causes of a high reject rate for low power during the acceptance test of overhauled PT6 twinpac power sections. A statistical model based on correlations between build variables and engine performance showed higher probability of success if new rather than used turbine nozzles were installed. Part condition details were not available.

Bölcs and Sari [6] performed transonic cascade studies on a turbine rotor blade that had been heavily fouled by operation with a heavy fuel, and a clean one. Thicker suction side boundary layers and thicker wakes with the fouled blade were shown. The location of the sonic point along the suction surface was found to advance with the fouled blade. Part condition details and loss data were not available.

Sjölander *et al*. [7] examined the effect of trailing edge damage on blades using a low speed cascades. Trailing edge cutouts were found to affect flow turning more than total pressure loss. The influence of transonic flow was not explored.

Duffner [8] conducted an analytical investigation into the effects of turbine NGV manufacturing variation using measured profiles from 25 manufactured specimens. The predicted results showed negligible affect on flow turning angle, but pressure loss could exceed design tolerance due to geometry deviation at the throat and trailing edge regions.

The effect of repair modification to turbine vane profiles on pressure loss and flow capacity is the subject of this paper. The present study examines the aerodynamic performance of service-exposed transonic turbine vanes experimentally. Airfoil profiles from both new and service exposed engine components were measured, and the profiles were replicated for testing in a transonic 2D-cascade rig. Flow structures were investigated using schlieren optics, and cascade losses were mapped using a pressure probe traverse.

2 Experimental Method

Transient Blow-Down Rig. The experimental results presented here were obtained from a short duration transonic blowdown rig, which has been constructed at the Royal Military College of Canada (RMC).

A schematic diagram of the test rig is shown in Figure 1. At the sudden perforation of a membrane, atmospheric air was drawn through the cascade and discharged into the vacuum tank. Choked flow was obtained at the cascade throat for duration of about 1200 ms, during which all measurements were taken. The average cascade inlet Mach number was 0.30 and exit flow isentropic Mach number was approximately 1.05.

A photograph of the cascade is shown in Figure 2. The cascade had four replaceable airfoils and five passages. The 18-mm thick, acrylic end-walls provided optical access for schlieren imaging. This cascade rig is described in more detail by Woodason *et al.* [9]

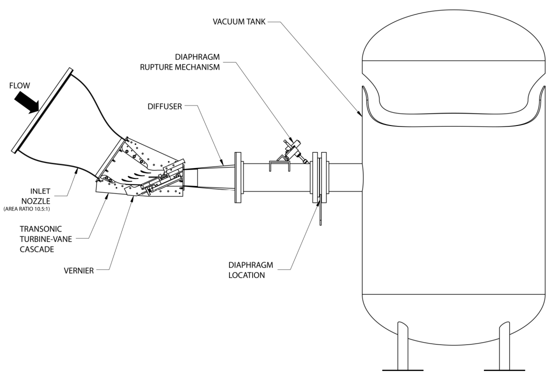

Figure 1: Schematic of RMC blow-down rig

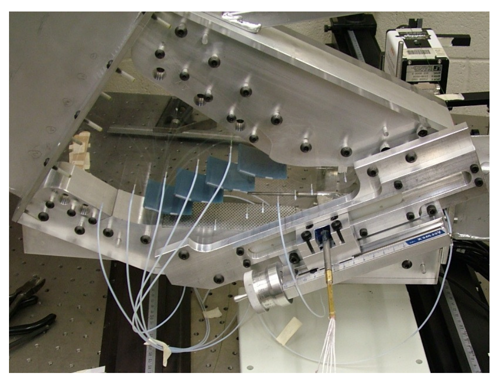

Figure 2: Transonic cascade working section

Turbine Vane Profiles: Three different parameterized turbine vane profiles were obtained from real-world engine hardware and submitted for wind tunnel testing. One newly manufactured nozzle was measured for reference, and two other nozzles that had been repaired for return to service were chosen. These airfoil profiles were designated NV (new vane), RV1 (repair vane #1) and RV2 (repair vane #2). The airfoil profiles are plotted for comparison in Figure 3; and differences are highlighted in Figure 4 (b) and (c), later in this work.

The RV1 profile had a subtle depression on the suction surface near 40% chord, but a significant bend beginning near 80% chord. The exit metal angle β_2 is 3 degrees higher on RV1. It was believed that this is a result of hot working used by maintenance workers to adjust a turbine vane's throat area, a process known as *tweaking*.

The RV2 profile has an eroded and blunter leading edge. About 5% of the chord length is missing, and it was estimated that the inlet flow effective incidence angle would be nearly 13 degrees higher than the reference vane. This airfoil may have had weld repairs for cracking followed by manual blending.

The replaceable airfoils were fabricated using a rapid prototyping process. Inspection of the test airfoils after fabrication showed that net-shape accuracy was generally better than 0.07 percent of chord, but deteriorated to 0.30 percent of chord in the vicinity of the leading edge radius.

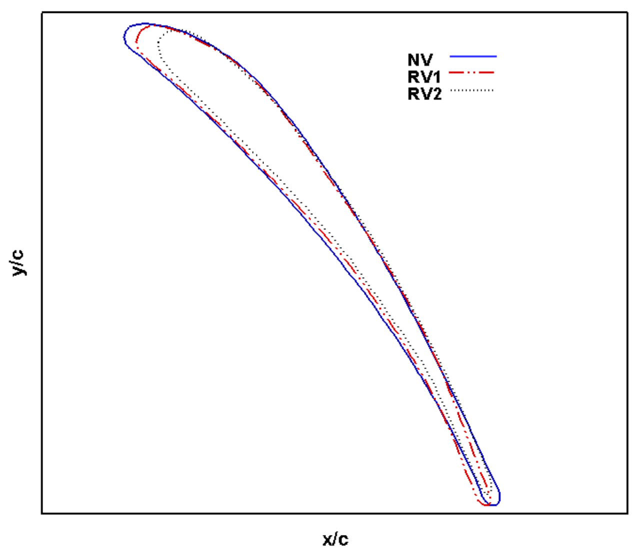

Figure 3: Turbine vane profile comparison

Experimental Procedure. For each airfoil profile (NV, RV1, and RV2), the following data were collected:

- Cascade mass flow capacity from wall static pressure measurements, along with ambient temperature and stagnation pressure.
- Cascade exit surveys from a pressure probe housing high frequency response Kulite transducers. The probe traverse plane was ½ axial chord downstream of the exit, and at the midspan height. The probe position was fixed for each tunnel run, and manually advanced between runs using a

precision vernier. The survey plan entailed 35 stops across two full-vane pitches. The probe travel limits spanned the centre passage, plus ½ pitch on either side.

- Visualization of shock patterns within the cascade with schlieren.

Estimated measurement uncertainties for derived quantities are listed in Table 1.

Table 1: estimated Measurement Uncertainties

Parameter	Uncertainty
Inlet Mach	±3%
Exit Mach	±2%
Total pressure ratio p_{t2}/p_{t1}	±0.61%
corrected mass flow	±0.17%

3 Experimental Results and Discussion

Rig test results for each vane profile are compiled into Figure 4. The flow characteristics are now discussed.

NV Cascade. The trailing edge flow shown in Figure 4 (d) had a normal shock emanating from the wake. Expansion waves ran from the trailing edge metal to the normal shock. This structure has been described by previous researchers such as Deitrichs [11] and Denton and Xu [4]; and is considered to be typical of current transonic designs.

The total pressure ratio in the NV cascade was near unity across the passage, and the wake showed a narrow, low-pressure core – see Figure 4 (g). The NV cascade exit pressure profile implied negligible shock loss and thin, attached boundary layers.

RV1 Cascade. Similar to the NV cascade, the RV1 shock structure also had expansion waves from the trailing edge and a shock emerging from the wake behind the vane - see Figure 4 (e). But in addition, an oblique shock originating from the suction surface near x/c=0.80 swept across the passage, merging downstream with the main shock. Both shocks appeared to have higher intensity than the NV cascade based on schlieren comparisons

In the RV1 cascade, the total pressure loss across the passage was ~2% higher than the NV– see Figure 4 (h). The oblique plus normal shock system described above was believed to cause the higher pressure loss measured outside the wake. The oblique shock was believed to be caused by boundary layer separation, which was further caused by the trailing edge bend or *tweaking* for throat area.

The RV1 exit pressure survey showed less momentum deficit in the wake relative to the NV cascade, and wider wake, see Figure 4 (h). This would be consistent with a turbulent boundary layer which separated from the suction surface near x/c=0.80.

RV2 Cascade. The RV2 shock structure is shown in Figure 4 (f). A normal shock attached to the suction surface at 95% chord was observed, with no shock on the pressure side. The normal shock intensity was thought to be higher relative to the NV cascade by inspection of the schlieren. A reason why the shock moved forward into the passage could be related to boundary layer thickness. Bölcs and Sari [6] reported a similar suction side shock structure in a turbine cascade as explained below. In their study of off-design blade profiles, they described a connection between thickened suction surface boundary layers and a redistribution of Mach numbers within the passage.

The RV2 cascade exit pressure traverse showed a noticeable pressure gradient across the passage; with higher loss near the suction side and lower loss along the pressure side. Refer to Figure 4 (i). This could be explained by two contributing factors:

- One is energy dissipated in the turbulent boundary layer of the suction surface. The boundary layer would have been turbulent along much of the suction surface length following a separation bubble at around 20% chord, due to the blunt leading edge profile. Typical behavior of leading edge separation bubbles was shown by Walraevens and Cumpsty [15].
- Another is the pressure probe tip crossing the normal shock wave. Since the probe tip follows the same line as the row of wall static taps visible in Figure 4 (f), it can be seen that the probe tip would cross through the shock. Some shock-induced pressure loss near the pressure side wake may not be measured.

The remaining momentum deficit at the core of the wake was less than either the NV or RV1 cascade, which suggested more vigorous mixing. This would be consistent with a turbulent suction surface boundary layer, which had developed downstream of the leading edge separation bubble.

Loss Coefficient. The total pressure loss profiles were integrated to enable overall comparison using a pressure loss coefficient (Y_N) defined by Equation 1.

$$Y_N = \frac{p_{t1} - p_{t2}}{p_{t2} - p_{s2}} \qquad \text{Eqn 1}$$

Three alternative averaging techniques were used, namely area-averaging, mass-averaging and mixed-out loss. From the results listed in Table 2, it can be seen that loss with the RV1 profile was nearly double that of the NV. The loss coefficient for the RV2 profile appears similar to the NV profile, but the reader is reminded that the pressure probe tip unluckily crossed the front of an observed normal shock. Consequently actual shock losses and loss coefficient for the RV2 cascade were understated by the present survey.

Table 2: Comparison of pressure loss coefficients

Vane Profile	Y_N area-average	Y_N mass-average	Y_N mixed-out
NV	0.056	0.055	0.078
RV1	0.105	0.105	0.109
RV2	0.054	0.054	0.079

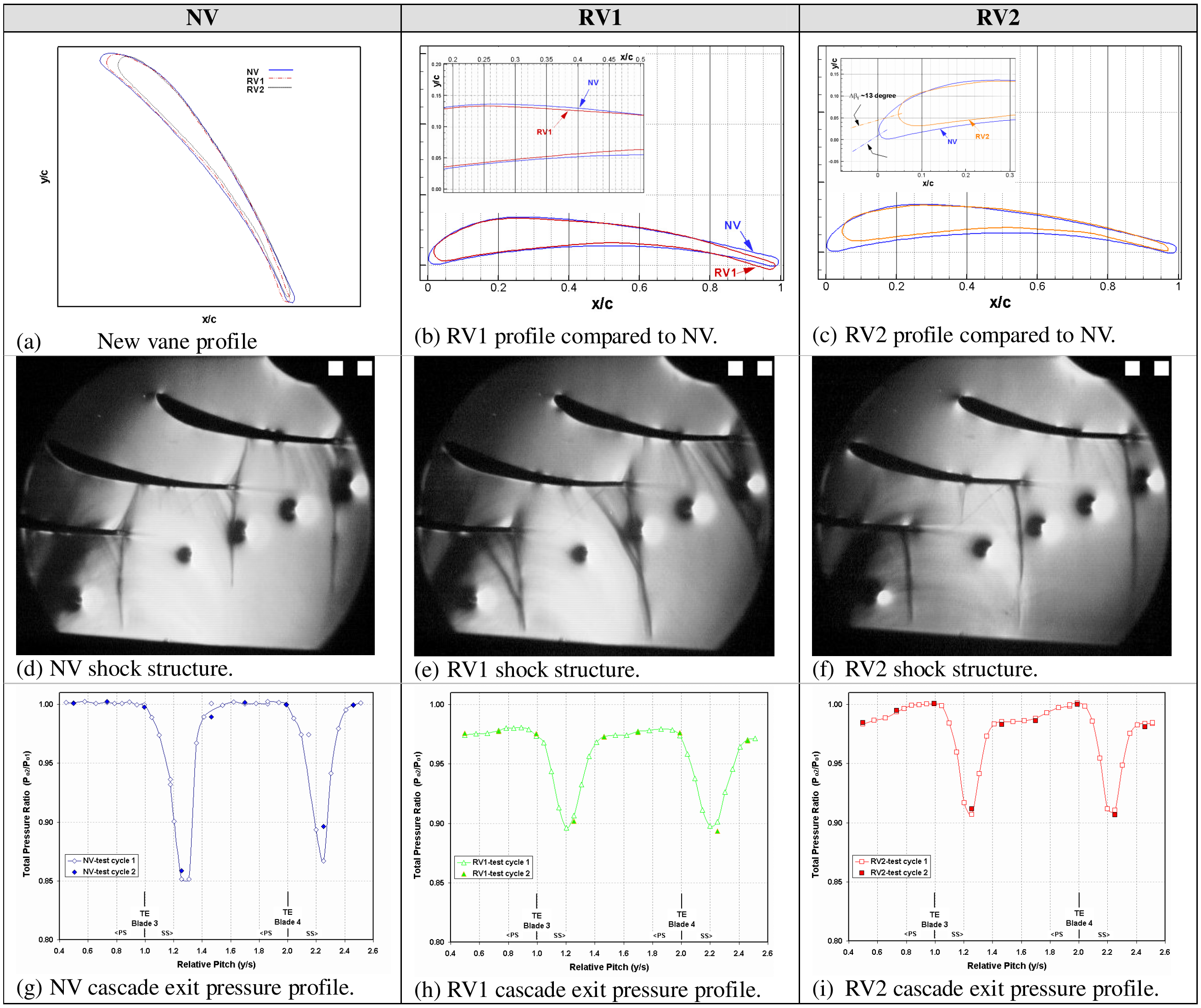

Figure 4: Summary of experimental results for surface flow visualization, schlieren imaging and pressure survey.

Flow Capacity. Due to airfoil profile differences the cascades had small differences in throat width. The throat, illustrated in Figure 5, is the narrowest passage width between adjacent airfoils and is widely used to derive a turbine nozzle's geometric flow area (GFA).

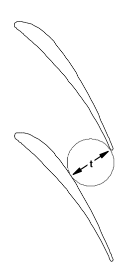

Figure 5: Cascade throat definition sketch

Rig testing showed that mass flow was not proportional to the cascade's throat or GFA. For example, RV2 had GFA 1.8% higher than NV, but mass flow was 1.3% lower. Using flow-per-unit-area of the new vane as a reference value, differences in effective flow capacity of the repaired vanes became more apparent. Comparison of GFA, observed mass flow, and relativized flow-per-unit-area are given in Table 3.

Table 3: Cascade flow capacity summary

Vane Profile	GFA/GFA_{NV}	$flow/flow_{NV}$	*Relativized flow/area* $\left(\frac{\dot{m}}{GFA_{cascde}}\right) \Big/ \left(\frac{\dot{m}}{GFA_{cascde}}\right)_{NV}$
NV	1.000	1.000	1.000
RV1	0.982	0.960	0.977
RV2	1.018	0.987	0.969

The differences were believed to be due to variation of aerodynamic blockage caused by boundary layer thickening, and boundary layer separation in a certain case. This lack of unique relation between a nozzle's geometric or metal area, and effective flow capacity under operating conditions may confound choice of vane area during engine maintenance.

Estimated effect upon Engine Performance. The impact of turbine vane loss variation upon overall engine performance depends on several factors.

Pressure loss across a vane would show up as turbine inefficiency. The net effect depends on particulars including local flow mach number, stage loading, and number of stages. Cycle models for selected current engines were estimated and used to predict the effect of doubling a nozzle's pressure loss coefficient (from Y_N=0.05 to 0.10). Resulting shaft power loss at constant firing temperature varied from 0.5% to 1.5% for different engine types.

The impact of flow capacity variation depends on interaction with other engine components and compressor-turbine rematching considerations. Turbine nozzle area changes can be used to invoke small changes to cycle pressure ratio, compressor operating efficiency, compressor surge margin, and gas generator spool speeds. Consequently a flow capacity change may or may not be helpful to net engine performance.

4 Conclusions

An experimental study of the effect of service exposure on the performance of transonic turbine vanes has been presented. Performance comparison of three different vane profiles, measured from actual engine components, has been made using a linear, transonic cascade. The profiles designated RV1 and RV2 represent typical alteration after exposure to operating service and repair activities.

Boundary layer growth, flow separation in the boundary layers, and shock-boundary layer interactions observed on the service-exposed profiles were not present on the reference vane profile. Small changes to airfoil profile affected by service exposure and repair can dramatically change the shock structure of the transonic flow. A repaired NGV was shown to have twice the pressure loss of a new part in the present study.

Turbine operating efficiency would be affected by these changes. Predicted shaft power loss due to increased NGV pressure loss ranged from 0.5-1.5% depending on engine configuration.

Mechanical tweaking of airfoils for NGV throat area control has been shown to increase aerodynamic losses. Geometric flow area may not be proportional to effective flow area due to aerodynamic-blockage of the boundary layer.

5 Nomenclature

b	span
c	true chord length
GFA	geometric flow area
$\dot{m}$	mass flow of air
M	Mach number
NGV	Nozzle guide vane
p	pressure
Re	Reynolds Number
s	pitch
t	cascade throat width
v	velocity
x/c	non-dimensional chord
y	pitchwise position index
Y	total pressure loss coefficient

Greek

$\boldsymbol{\beta}$	metal angle of blades
$\boldsymbol{\gamma}$	stagger angle

Subscripts

1	values at cascade inlet
2	values at cascade exit
N	nozzle
s	static pressure
t	total pressure
x	axial direction

6 References

[1] Corriveau, D., and Sjolander, S.A., "Influence of loading distribution on the performance of transonic high pressure turbine blades," Journal of Turbomachinery, Vol. 126, No. 2, 2004, pp. 288-296.

[2] Li, S.-., Chu, T.-., Yoo, Y.-., "Transonic and low supersonic flow losses of two steam turbine blades at large incidences," Journal of Fluids Engineering, Transactions of the ASME, Vol. 126, No. 6, 2004, pp. 966-975.

[3] Mee, D.J., Baines, N.C., Oldfield, M.L.G., "An Examination of the Contributions to Loss on a Transonic Turbine Blade in Cascade," Journal of Turbomachinery, Vol. 114, No. 1, 1992, pp. 155-162.

[4] Denton, J.D., and Xu, L., "Trailing edge loss of transonic turbine blades," Journal of Turbomachinery, Vol. 112, No. 2, 1990, pp. 277-285.

[5] Colantuoni, S., Mainiero, G., and Esposito, A., "A Method to Reduce the Rejection Rate for Low Performance at the Acceptance Test of PWC PT6T-6 Overhauled Power Sections," Journal of Engineering for Gas Turbines and Power, Vol. 118, No. 2, 1996, pp. 229-235.

[6] Bolcs, A., and Sari, O., "Influence of deposit on the flow in a turbine cascade," Journal of Turbomachinery, Vol. 110, No. 4, 1988, pp. 512-519.

[7] Sjolander, S.A., Isaacs, D., and Klien, W.A., "Aerodynamics of Turbine Blades with Trailing-Edge Damage: Measurements and Computations," Eleventh International Symposium on Air Breathing Engines, Vol 2, ISABE, Tokyo, Japan, 1993, pp. 1327.

[8] Duffner, J.D., "The Effect of Manufacturing Variability on Turbine Vane Performance," Massachusetts Institute of Technology, MS Thesis, Cambridge, Massachusetts, 2008.

[9] Woodason, R., Asghar, A., and Allan, W.D.E., "Assessment of the Flow Quality of a Transonic Turbine Cascade," Proceedings of ASME Turbo Expo 2009, ASME Paper GT2009-60164, Orlando, FL, USA, 2009.

[10] Sieverding, C.H., Richard, H., and Desse, J., "Turbine blade trailing edge flow characteristics at high subsonic outlet mach number," Journal of Turbomachinery, Vol. 125, No. 2, 2003, pp. 298-309.

[11] Dietrichs, H.J., Hourmouziadis, J., Malzacher, F., "Flow Phenomena in Transonic Turbine Cascades - Detailed Experimental and Numerical Investigation," 8th ISABE, International Symposium on Air Breathing Engines, Cincinnati, Ohio, 1987,

[12] Hourmouziadis, J., "Aerodynamic design of low pressure turbines," Blading Design for Axial Turbomachines AGARD-LS-167, Publ by AGARD, Neuilly-sur-Seine, Fr, 1989.

[13] Mee, D.J., Baines, N.C., and Oldfield, M.L.G., "Detailed Boundary Layer Measurements on a Transonic Turbine Cascade," Journal of Turbomachinery, Vol. 114, No. 1, 1992, pp. 163-172.

[14] Hodson, H.P., and Dominy, R.G., "Off-Design Performance of a Low-Pressure Turbine Cascade," Journal of Turbomachinery, Vol. 109, No. 2, 1987, pp. 201-209.

[15] Walraevens, R.E., and Cumpsty, N.A., "Leading edge separation bubbles on turbomachine blades," Journal of Turbomachinery, Transactions of the ASME, Vol. 117, No. 1, 1995, pp. 115-125.

7 Copyright

Papers are considered part of the public domain and may appear in Symposium handouts, CD ROM and website postings. If there exist any restrictions on the sharing of the material, instructions to that effect should be provided at the time of draft submission or otherwise consent will be considered granted. In addition, with the submission of the final paper, the author(s) confirm that they, and/or their company or institution, hold copyright on all of the original material included in their paper. They also confirm they have obtained permission, from the copyright holder of any third party material included in their paper, to publish it as part of their paper.