IMPACT OF FLOW QUALITY IN TRANSONIC CASCADE WIND TUNNELS: MEASUREMENTS IN AN HP TURBINE CASCADE

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Abstract

This study presents measurements made in a transonic linear turbine cascade to assess the impact of flow quality on the desired results. The experiments were performed in the transonic blow-down wind tunnel at Carleton University. Variations in the inlet flow quality were induced by displacing the inlet test section walls. Measurements were made mainly for incidence values of -10.0^o, 0.0^o *and* $+10.0^o$ *relative to the design incidence and for transonic Mach numbers. The measurements include spanwise losses, deviation and blade loading. The results demonstrate that the cascade outlet flow periodicity alone cannot be used as a reliable criterion for judging the inlet flow quality. The inlet flow uniformity is shown to have a significant impact on the measured cascade performance.*

Nomenclature

$AVDR$	Axial Velocity Density Ratio, $\left(=\frac{\int_0^1 (\rho_2 C_{(ax)_2})_{MS} d(y/s)}{\int_0^1 (\rho_1 C_{(ax)_1})_{MS} d(y/s)}\right)$
c	blade chord length
C	flow velocity
C_b	base pressure coefficient, $\left(=\frac{(P_b-P_2)}{q_2}\right)$
C_{P0}	total pressure coefficient, $\left(=\frac{(P_{02}-P_{01})}{q_2}\right)$
H	blade Span
i_{eff}	effective incidence, in degrees, $(=\alpha_1-(\alpha_1)_{des}=i-i_{des})$
M	Mach number
o	throat opening
P_o	total pressure
q	dynamic pressure, $\left(\frac{1}{2}\rho C^2\right)$
Re	Reynolds number, $\left(\frac{\rho C_2 c}{\mu}\right)$
s	pitch distance
W	design inlet duct width
We	wedge angle
We	wedge angle
y	pitchwise location
Y_t	total pressure loss coefficient, $\left(=\frac{(P_{01}-P_{02})}{q_2}\right)$
α	flow angle measured from the axial direction
ζ	stagger angle measured from the axial direction
μ	air dynamic viscosity
ρ	air density
θ_u	uncovered turning angle

Subscripts

1	cascade inlet
2	cascade outlet
ax	axial
des	design
MS	midspan

1 Introduction

Cascade testing has proved to be a valuable tool over the years for gaining a better understanding of the flow behaviour in turbine blade passages and thus for improving the performance of gas turbine engines. Today, with the advent of numerical tools to predict turbomachinery flows, cascade testing has gained an additional use in the validation of these Computational Fluid Dynamics (CFD) codes. However, for the cascade results to be useful, great care must be exercised to ensure that the flow simulates as accurately as possible the conditions in the "infinite" blade row being modelled. Among the flow quantities that must be considered are the inlet boundary layer thickness, the inlet flow uniformity, the outlet flow periodicity and the Axial Velocity Density Ratio (AVDR). However, relatively little guidance is provided in the literature as to what constitutes acceptable flow quality for transonic cascade measurements. This is especially true for off-design incidence.

Methods for obtaining good flow quality in terms of inlet flow uniformity and outlet flow periodicity have been discussed by a few authors.

Gostelow [3] briefly discussed in his book on cascade aerodynamics the question of good flow quality in cascade wind tunnels. Starken & Lichtfuss [19] presented a more detailed discussion on cascade flow adjustments. They describe procedures for obtaining good flow periodicity for different flow conditions (e.g.. compressible-incompressible, subsonic-supersonic) at the inlet and exit of a blade passage. However, the authors do not present any example results to demonstrate what is considered good flow quality. Furthermore, the effect of inlet flow non-uniformity on the results is not discussed. Starken & Lichtfuss suggest that it is sufficient to measure the static pressure by means of wall static taps in a plane upstream of the cascade and to verify the flow angle at one point to assess the uniformity of the inlet flow. This procedure appears to be well accepted since it is used by several other research groups. For example, in 1986 Kiock et al. [9] presented turbine cascade measurements made in four different European wind tunnels for the same blade row geometry. Inlet flow uniformity checks were made at the cascade inlet by measuring the static pressure over several pitches. The inlet flow angle was also measured in some of the facilities.

Once good inlet flow uniformity has been established, outlet flow periodicity is usually achieved easily in subsonic flow. Therefore, very little information is found in the literature concerning methods of obtaining outlet flow periodicity. However, if compressible outlet flow is present periodicity can be harder to achieve due to the presence of reflected shocks, as mentioned by Sieverding [18]. Sieverding discusses the different type of boundaries that can be used at the extremities of the cascade to achieve periodic flow. In order to assess the periodicity, Starken & Lichtfuss [19] suggest using the same procedure as for the inlet flow: that is, measuring the endwall pressures along the cascade outlet. This procedure was followed by Mee et al. [13]. However, a review of the literature reveals that other methods have also been used to assess periodicity. Midspan wake traverses over several pitches are often performed to verify periodicity. This was the procedure followed by Kiock et al. [9]. Another method consists of comparing the loading distributions for adjacent blades in the cascade. This was the approach used by Langston [10] and Langston et al. [11].

In nominally two-dimensional cascade studies, it is necessary that the inlet flow should exhibit a significant region of uniform flow around midspan in the spanwise direction. However, very little guidance exists as to what constitutes acceptable inlet boundary layer characteristics. In the open literature, data concerning the inlet boundary layer to actual turbines is scarce. However, the inlet boundary layer characteristics for a model turbine are given by Hunter [5] and those for a cascade by Hodson & Dominy [4] and Langston et al. [11]. Marchal & Sieverding [12] performed a cascade study on secondary flows. They tested a turbine rotor blade in a cascade wind tunnel having a thick and a thin inlet boundary layer. It was found that the increase in inlet boundary layer thickness had no effect on the downstream midspan losses and the secondary losses.

A value of 1.0 for the axial-velocity-density ratio (AVDR) is a necessary but not sufficient condition for two-dimensional flow at the midspan of a cascade. The influence of AVDR on turbine cascade results under low-speed conditions has been examined by Rodger et al. [16]. They found that AVDR had a significant effect on the losses at higher incidence where boundary layer separation was present. However, the effect of AVDR on transonic cascade results is still somewhat unclear. Kiock et al. [9] concluded that the AVDR had no effect on the losses or deviation in the range of 0.9 to 1.0. Sharma & Graziani [17] concluded that the AVDR in itself could not explain the effect of the endwall flow on the aerodynamics and heat transfer on midspan blade surface. More recently, Jouini et al. [7] [8] observed that the AVDR increased with incidence for measurement made in a transonic cascade. They also concluded that the losses are affected by the varying AVDR.

AVDR is a function of the aspect ratio of the blades, among other things. For three-dimensional effects to be kept as small as possible the aspect ratio of the cascade blades must be high. However this requirement must be balanced with the need for large chord lengths, to give wider, more easily measured wakes and to allow the blades to be instrumented with static taps. Sieverding [18] recommends a minimum aspect ratio for reliable two-dimensional performance in a turbine cascade as a function of the velocity ratio across the cascade.

The present paper describes an experimental study that was carried out to assess the impact of flow quality on the aerodynamic measurements obtained in an high-speed cascade wind tunnel. The emphasis is placed on the effect of inlet flow uniformity and outlet flow periodicity at both design and off-design values of incidence. Three different values of incidence were investigated in detail: 0.0^o, -10.0^o and $+10.0^o$. A few results were obtained at $+12.0^o$. Detailed flow field measurements were made upstream and downstream of the cascade. Blade loading measurements were also performed to assist in the interpretation of the results. The objective of the paper is to assess the importance of flow quality in the wind tunnel on the experimental results obtained.

2 Experimental Apparatus and Procedures

2.1 High Speed Wind Tunnel

The measurements were obtained in the High Speed Wind Tunnel at Carleton University. A schematic of the wind tunnel is shown in Figure 1. The wind tunnel is of the blow-down type. Prior to each run, the storage tanks are filled with air at a pressure of about 8 atmospheres. When the tanks are full, the control valve is opened and the air is discharged through the test section. For typical transonic cascade testing, blowing pressures of the order of 2 to 3 bars are required. The test section blowing pressure is controlled using a Proportional-Integral pressure control system. Runtimes between 30 and 60 seconds are achieved depending on the blowing pressure and cascade outlet Mach number. The turbulence intensity in the test section is about 4%. The outlet of the cascade test section is fitted with an ejector-diffuser system. This system allows variation of the cascade outlet Mach number independently of the Reynolds number. The diffuser outlet exhausts to the laboratory at atmospheric conditions. A more detailed description of the wind tunnel is given by Jeffries [6].

2.2 Test Section and Test Cascade

The linear cascade test section used to make the measurements is shown in Figure 2. The cascade is mounted on a turntable. By rotating the turntable, incidences between -10^o and $+15^o$ can be obtained. For the current study, measurements were made chiefly at three values of incidence, namely , 0.0^o, -10.0^o and $+10.0^o$. Adjustments to the flow to obtain good inlet flow uniformity and outlet flow periodicity are performed by moving the inlet test section side walls shown in Figure 2.

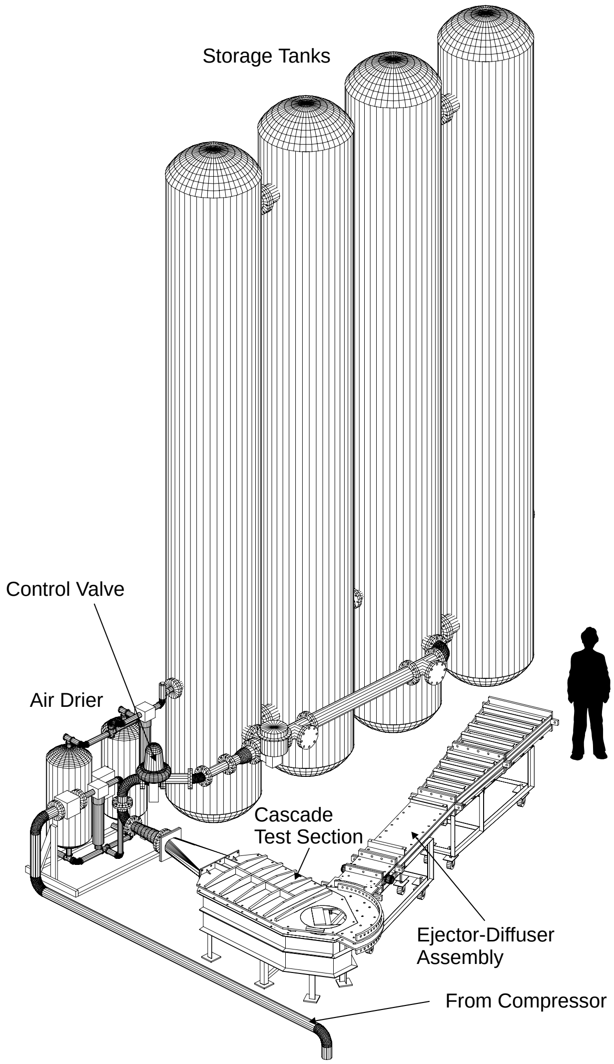

Fig. 1 Pratt & Whitney Canada High Speed Wind Tunnel (Jeffries [6]).

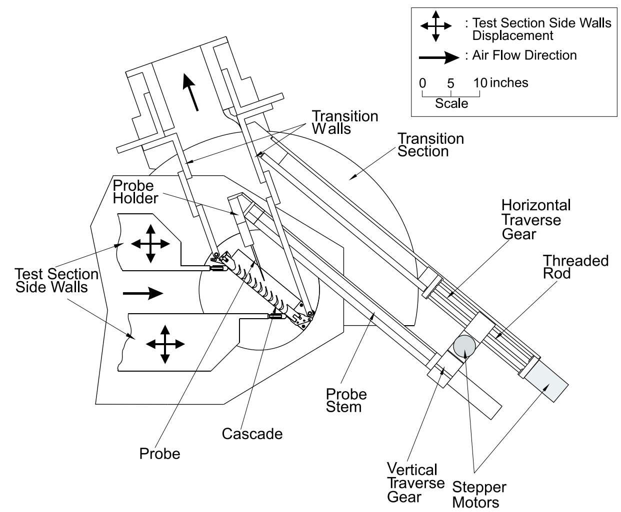

Fig. 2 Plan view of the cascade test section (Adapted from Jouini et al. [7]).

Parameter	Blade HS1A
Chord Length, C	40.0mm
Blade Span, H	61.0mm
Blade Pitch, s	29.14mm
Trailing Edge Thickness, t	1.25mm
Aspect Ratio, H/C	1.525
Inlet Metal Angle, β_1	50.5°
Outlet Metal Angle, β_2	59.0°
Leading Edge Wedge Angle, We_{le}	38.0°
Trailing Edge Wedge angle, We_{te}	6.0°
Design Incidence, i_{des}	-4.5°
Stagger Angle, ξ	25.1°
Throat Opening, o	15.3mm
Unguided Turning, θ_u	11.5°

Table 1 HS1A cascade and blade geometry.

The blade and cascade geometry are summarized in Table 1. The blade is scaled from the midspan section of a high pressure turbine from Pratt & Whitney Canada. The cascade is composed of seven blades. The blade span is 61*mm*. Two of the blades at the center of the cascade were instrumented with static taps for loading measurements.

Experiments were performed for exit Mach numbers between 0.5 and 1.2. The corresponding Reynolds numbers varied from about 4×10^5 to 10^6.

2.3 Instrumentation and Experimental Procedures

The flow field measurements were made with pressure probes. The upstream spanwise measurements were made with a custom-made Pitot probe. The probe tip is 0.635*mm* in diameter. The location of the spanwise traverses is shown in Figure 3. The inlet flow angle was determined with a United Sensor three-hole wedge probe used in the nulling mode. The inlet static pressure distribution in the pitchwise direction was obtained from a row of static taps located one chord length upstream of the blade leading edge. The inlet static taps cover the whole cascade width. The taps have a spacing of 7.3*mm*, giving four taps per blade pitch.

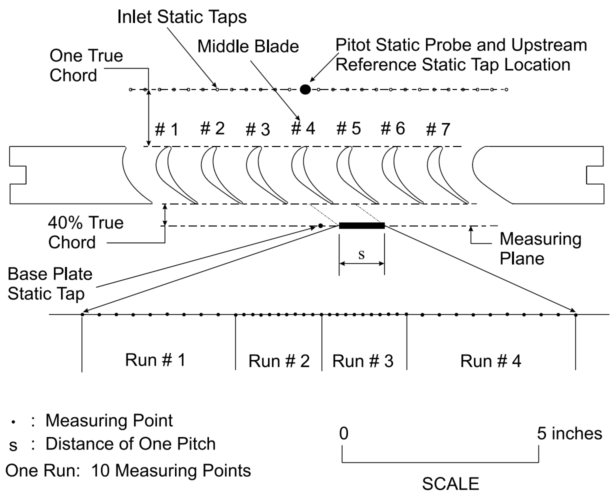

Fig. 3 Cascade blade row measurement locations (Adapted from Jouini et al. [7]).

The downstream flow field measurements were obtained with a three-hole pressure probe used in non-nulling mode. The probe tip has a width of 1.37*mm*, which corresponds to 4.7% of the blade pitch, and a thickness of 0.46*mm*. The probe was calibrated in 1 degree steps over a range of $\pm 10^o$ of flow misalignment in the yaw direction. Static-pressure probe measurements were also made downstream of the cascade. The cylindrical probe has a tip cone angle of 15^o and a diameter of 1.02*mm*. For the analysis of the results, the static-pressure measurements obtained with the static-pressure probe were combined with the flow angle and total pressure measurements from the three-hole probe. Using the method described by Amecke & Safarik [1], fully mixed-out loss values, as well as the other relevant quantities, were calculated from the collected data.

The pressure measurements were obtained using a 48 port Scanivalve system. A miniature fast-response Kulite transducer model number XCQ-062-25A was mounted in the Scanivalve housing to measure the pressure. The full scale range of the transducer is 0 to 25 psi absolute. The output from the transducer was recorded using a Hewlett-Packard high-speed data-acquisition system controlled by a microcomputer.

The locations of the upstream and downstream pressure measurement planes are shown in Figure 3. The static pressure measurements upstream of the cascade are made in one run. For the downstream static and three-hole probe traverses, four runs are required to cover one blade pitch. For each run, 10 measurements are made for a total of 40 measurements for one blade pitch.

The measurement uncertainty for the inlet and outlet angle flow angles is $\pm 1.0^o$. The uncertainty on the static pressure measurements is $\pm 2\%$ of the local dynamic pressure. The uncertainty in the cascade inlet Mach numbers is ± 0.015. The cascade exit Mach number uncertainty is about ± 0.005 for Mach numbers greater than 0.8. For lower Mach numbers the uncertainties in the Mach number increases. The uncertainty for the mixed-out total-pressure loss coefficients is estimated as ± 0.006 for Mach numbers between 0.85 and 1.1. For higher transonic Mach numbers the uncertainties are higher due to the formation of complex shock structures. The uncertainty in the AVDR values is ± 0.04. The uncertainty values were estimated using the method of Moffat [15] for single-sample uncertainty analysis.

3 Results and Discussion

3.1 Cascade Inlet Flow

3.1.1 Inlet Boundary Layer

The inlet flow was traversed in the spanwise direction with a boundary layer probe at the location shown in Figure 3. The integral parameters of the boundary layers are summarized in Table 2. They were obtained using the compressible form of the appropriate equations. The results show that the inlet boundary layer is turbulent with shape factors, H, of about 1.4 for both choked and unchoked inlet flow. This shape factor is typical of that found in other cascade wind tunnels. Marchal & Sieverding's [12] study of secondary flows within turbine blade passages compared the results obtained with thin and thick inlet boundary layers. The thick boundary layer used in their study is very similar to the one observed in the present experimental facility in terms of the ratio of boundary-layer thickness to blade span. Marchal & Sieverding found that the midspan losses for a rotor blade of low aspect ratio (0.79) were essentially the same for the thin and thick inlet boundary layers tested at design incidence. Therefore, it appears that the inlet boundary layer thickness has only a limited effect on the midspan results as long as a significant region of two-dimensional flow is present at midspan. However, where nominally two-dimensional midspan results are the goal, the thickness of the inlet boundary layer should nevertheless be kept to a minimum. This issue will be discussed further in a later section.

Parameter	Unchoked Outlet Flow	Choked Outlet Flow
Inlet Mach Number	0.39	0.52
Displacement Thickness, δ^*	2.3mm	2.0mm
Momentum Thickness, θ	1.6mm	1.4mm
Shape Factor, H	1.4	1.4
Boundary Layer Thickness, $\delta_{99\%}$	17.7mm	17.7mm

Table 2 Inlet boundary layer parameters.

3.1.2 Inlet Flow Uniformity

In order to obtain good inlet flow uniformity and downstream flow periodicity, the wind tunnel control surfaces must be adjusted such that the mass flow rate of air in each passage is equal.

A review of the literature has shown that different research groups in turbine aerodynamics use different means for adjusting the flow in their wind tunnels. Langston [10] uses adjustable bleed at the two extremities of his cascade together with adjustable tailboards downstream of the cascade. Other researchers, such as Mee et al. [13], use adjustable shutters to control the amount of air flowing through the end passages.

In the current facility, inlet flow adjustment is achieved by moving the test section side walls, as shown in Figure 2. No provision is made for bleeding the inlet side wall boundary layers. Furthermore, no tailboards are used downstream of the cascade. This setup is similar to that used at the Von Karman Institute (see Kiock et al. [9]). Through experimentation, it was found that good inlet flow uniformity could be achieved by setting the side walls parallel to each other and by aligning the test section side walls with the leading edge of the cascade end blocks. The required inlet duct width, or design inlet flow area, can be calculated as follows. For a cascade composed of blades having a pitch (s) and operating at an incidence α_1, the distance (w) between the bounding streamlines for the streamtube entering a particular passage is given by

$$w = s\cos\alpha_1. \tag{1}$$

Thus, for an arbitrary cascade composed of N blades and N+1 passages, the required design inlet duct width (W)is given by

$$W = (N+1)w \tag{2}$$

and the design inlet flow area is obtained by multiplying the duct width W by the blade span H. This calculation neglects the blockage due to the displacement effect of the sidewall boundary layers. Since the flow over much of the sidewall length is highly accelerated, the sidewall boundary layers are expected to be very thin.

Pitchwise wall static pressure measurements were made at three different values of incidence and for different upstream passage widths. The aim of these measurements was to determine the effect of the side walls alignment on the quality of the inlet flow.

The variation of the static pressure in the pitchwise direction is presented in Figure 4 in the form of an inlet static pressure coefficient. The results are for roughly the design outlet Mach number of the cascade.

The results show that for the cases where the side walls were aligned with the end passages (design inlet flow area), the inlet uniformity is very good for the five centermost passages. Non-uniformity in the inlet flow is only present for the outermost passages, due to the test section sidewall effects. On the other hand, for the case where the inlet flow area was increase by moving the right side wall (looking downstream) outward, a pressure gradient can be clearly observed across the cascade inlet. This pressure gradient is an indication that the inlet streamlines are curved. If the streamlines are curved then the inlet flow is not aligned with the wind tunnel axis, giving rise to erroneous and probably varying values of incidence across the cascade. The impact of this on the results will be discussed in the following sections.

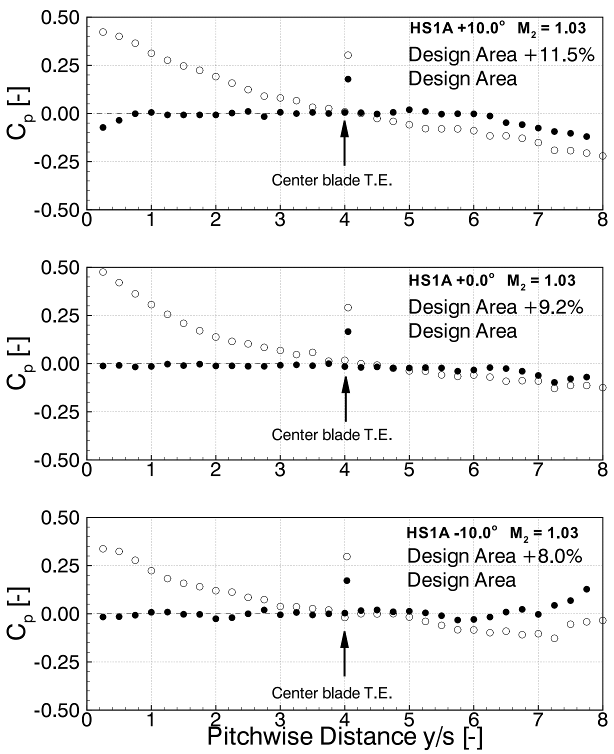

Fig. 4 Variation of the static pressure coefficient across the cascade inlet plane.

Similar results were obtained for the cases where the left side wall was moved inward. The results showed that the pressure gradient across the cascade inlet was reversed when the flow area was reduced relative to the design value.

3.2 Cascade Outlet Flow

3.2.1 Outlet Flow Periodicity

The cascade outlet flow periodicity is somewhat weakly linked to the inlet flow uniformity, particularly near design incidence. It should be noted that the current experimental facility has no control surfaces available downstream of the cascade to adjust the flow: the cascade outlet flow discharges into a plenum of the same height but considerably wider dimensions compared to the cascade. Figure 5 shows the variation of the midspan outlet flow Mach number and the total pressure loss coefficients together with the inlet static pressure coefficients for the full cascade width at an incidence of $+10.0^o$. The results are shown for good (design inlet flow area) and poor (design inlet flow area +8%) inlet flow uniformity.

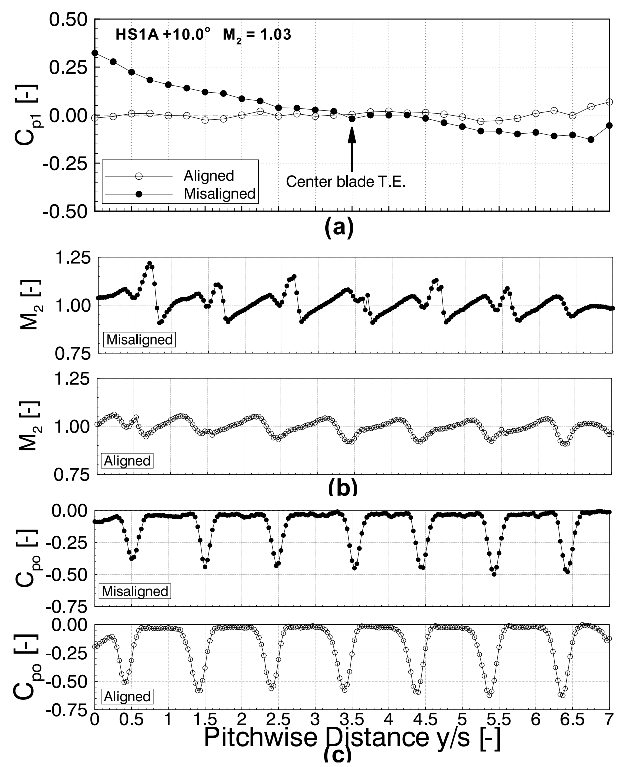

Fig. 5 Effect of inlet flow uniformity on outlet flow periodicity. (a) Inlet pitchwise static pressure coefficient (b) Outlet pitchwise Mach number variation (c) Outlet pitchwise total pressure loss coefficient.

It is noticeable that the non-uniformity in the inlet flow is not readily detectable in the cascade outlet flow, which appears to have good periodicity for both cases. The clear indication is that the cascade outlet flow cannot be used reliably to detect problems with the cascade inlet flow. The most significant difference between the two cases is the depth of the wakes. The reasons for this will be discussed later.

3.2.2 *Flow Two-Dimensionality*

Cascade measurements are often conducted to determine the two-dimensional aerodynamic behaviour of a particular blade profile. The two-dimensionality of a cascade flow can be assessed in several ways. A region of constant profile losses near midspan is a necessary condition for two-dimensionality of the flow. Sieverding [18] recommended a minimum aspect ratio for reliable two-dimensional performance in a turbine cascade as a function of the velocity ratio across the cascade. A minimum aspect ratio is required in order to obtain reasonably two-dimensional midspan flow for typical values of inlet endwall boundary layer thickness. Based on Sieverding recommendations, the current cascade would required an aspect ratio of about 1.8 at design incidence and Mach number, given that the velocity ratio equals 0.53 at these conditions. This is somewhat higher than the present cascade aspect ratio of 1.53. Figure 6 shows that the low aspect ratio for the current cascade does not prevent the formation of a two-dimensional flow region at design incidence. However, the upper part of the figure shows that for $+12.0^o$ of incidence there is essentially no region of two-dimensional flow at midspan, even though the endwall boundary layer had essentially the same thickness at the cascade inlet for both cases.

The inlet endwall boundary layer is the source of the secondary vortex that wraps around the blade leading edge. This vortex is augmented by the cross-channel flow inside the passage. By controlling the inlet boundary layer thickness, one can limit to some degree the extent of the secondary flow in the cascade.

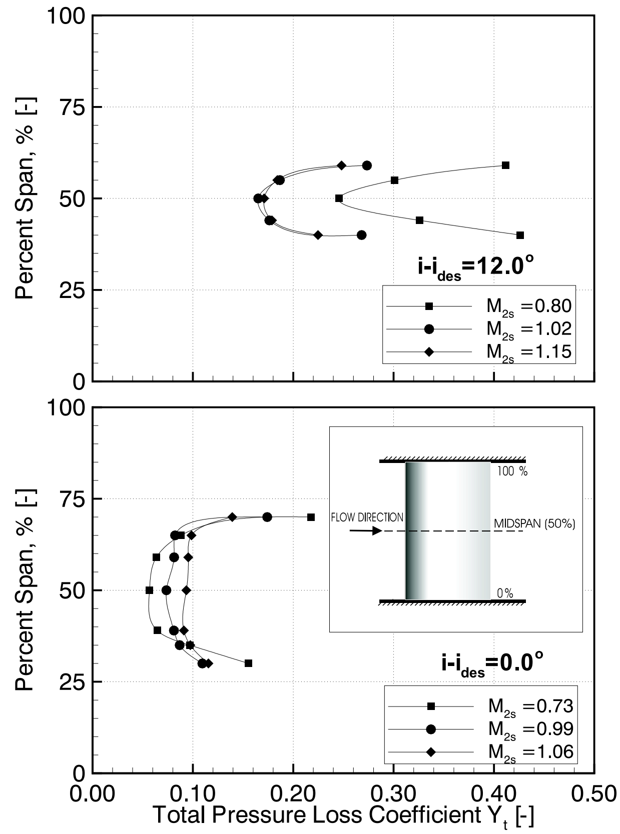

Fig. 6 Spanwise distribution of total pressure losses.

The extent of the secondary flow is also a function of the flow acceleration through the cascade. High acceleration tends to stretch the secondary flow vortex and thus limit its spanwise dimension. In a typical turbine cascade the streamwise acceleration in the passage decreases as the incidence increases. This explains the reduction in the spanwise extent of uniform midspan flow shown in Figure 6. Thus, it appears that aspect ratios that are adequate for studies at design incidence may be too low for measurements at positive, off-design values of incidence.

3.3 Axial Velocity Density Ratio (AVDR)

The increased extent of the region of three-dimensional flow for higher values of incidence calls for a closer examination of the two-dimensionality of the flow through the cascade. A necessary but not sufficient condition for two-dimensional midspan flow is that the AVDR be equal to 1.0 at midspan. Measurements of AVDR where made at 0.0^o, -10.0^o and $+10.0^o$ of incidence for different outlet Mach numbers. The results are presented in Figure 7 for uniform and non-uniform inlet flow. It can be observed that for the design incidence the AVDR is equal to 1.0 over the whole range of Mach numbers tested when the inlet flow is uniform. On the other hand, for an incidence of $+10.0^o$ the AVDR is about 1.1. This is mainly the result of the increased blockage caused by the enlarged secondary flows. As noted earlier, the larger secondary flows are due to the reduced channel acceleration at positive values of incidence.

There is also greater uncertainty in the values of AVDR for positive incidence due to the greater uncertainties in the outlet angle measurements at these values of incidence. At $+10.0^o$, significant boundary layer separation occurs and therefore the deviation angles are much higher. The flow separation together with the presence of secondary flow vortices at $+10.0^o$ contribute to the increase in uncertainty for the flow-angle measurements. Baines et al. [2] have shown that the inferred values of AVDR are very sensitive to the inlet and outlet angle measurements. It can be shown that a 1^o variation in the outlet angle results in a variation in the value of AVDR of the order of 0.04.

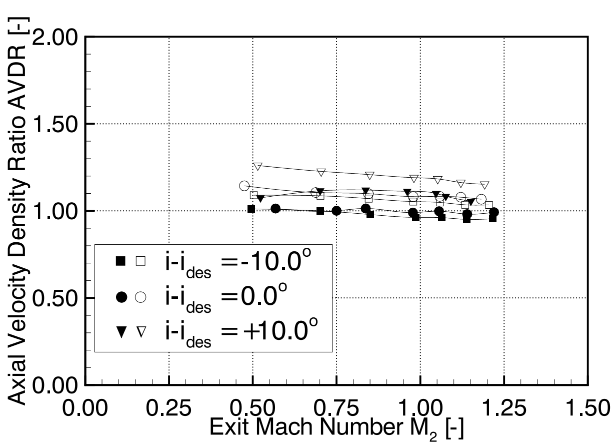

Fig. 7 Effects of incidence and Mach number on the axial velocity density ratio (AVDR). Filled symbols •: uniform inlet flow; Open symbols ∘: non-uniform inlet flow.

The non-uniformity of the inlet flow also has an influence on the inferred values of AVDR, as shown in Figure 7. The differences between the cases where the flow is uniform versus non-uniform are due to the fact that the AVDR is a function of the inlet flow angle. When calculating the AVDR, the inlet flow is assumed to be aligned with the wind tunnel axis. As noted earlier, in the cases where the inlet flow is not aligned a pressure gradient exists across the cascade inlet. This pressure gradient is associated with streamline curvature that alters the effective inlet flow angle at the cascade. The precise change in inlet angle seen by the cascade is not known. However, the changes in the direction of the inlet angle implied by the direction of the observed pressure gradients are consistent with the differences in AVDR shown in Figure 7.

3.4 Effect of Flow Quality on Results

The changes in inlet flow angle alter the effective incidence seen by the blades. For example, the variations of the static pressure across the inlet for the cases shown in Figure 4 are consistent with a reduction in effective incidence. Such changes in incidence can have significant effects on the aerodynamic performance of the cascade. These effects are examined next.

3.4.1 Profile Losses

Figure 8 shows the variation of profile losses with Mach number at -10.0^o, $+0.0^o$ and $+10.0^o$ of incidence. The results are presented for both uniform and non-uniform inlet flows.

At design and -10.0^o incidence, it is seen that the influence of the inlet flow uniformity on the losses is limited. Both curves follow the same trend and the losses are similar. The variations in losses with Mach number also resemble those observed by other research groups, such as Mee et al. [14].

On the other hand, at an incidence of $+10.0^o$ the influence of the inlet flow uniformity is clearly seen, especially at lower Mach numbers. The high losses observed at $+10.0^o$ incidence for the uniform inlet flow case are due to a flow separation on the blade suction surface. The losses for non-uniform inlet flow are much closer to those observed at design incidence, suggesting a reduction in the extent of the separation. This is consistent with the reduction in inlet flow incidence associated with the streamline curvature that occurs due to the presence of the pressure gradient.

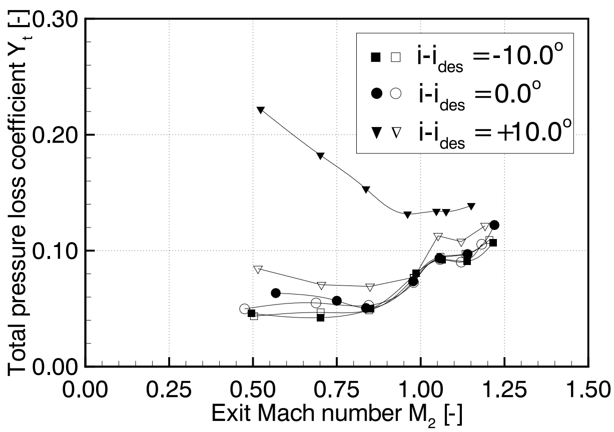

Fig. 8 Effects of incidence and Mach number on the total pressure losses. Filled symbols •: uniform inlet flow; Open symbols ○: non-uniform inlet flow.

3.4.2 Deviation

The variation of exit flow angle with Mach number and incidence is shown in Figure 9 for uniform and non-uniform inlet flow. As for the losses, the influence of the inlet flow uniformity is primarily seen at high positive incidence. As mentioned previously, at $+10.0^o$ of incidence boundary layer separation occurs on the suction surface of the blade. This results in smaller exit flow angles for both inlet flows, as shown in Figure 9. However, for the case where the inlet flow is non-uniform, the outlet flow angles are closer to those observed at design incidence. This is an indication that the boundary layer separation occurring at this condition is considerably less severe. Again, this is in agreement with a reduced incidence resulting from the streamline curvature at the cascade inlet.

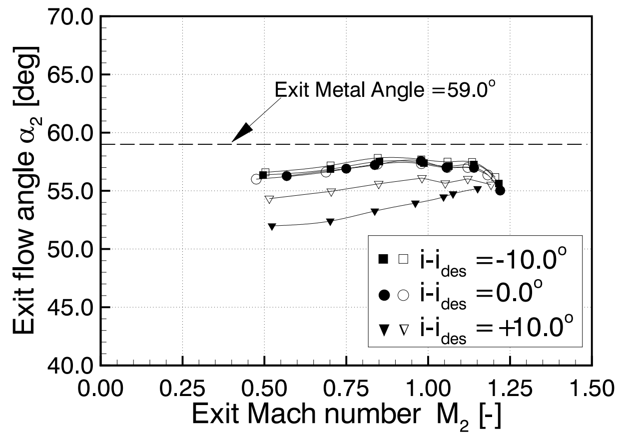

Fig. 9 Effects of incidence and Mach number on the exit flow angle. Filled symbols •: uniform inlet flow; Open symbols ○: non-uniform inlet flow.

3.4.3 Blade Loading and Base Pressure

Loading measurements were also performed for uniform and non-uniform inlet flows. For the design incidence no significant effect of the inlet flow uniformity can be observed on the blade's pressure distribution. However, as with the losses and deviation, the uniformity of the inlet flow had an influence on the loading when the blade was at incidence, particularly at high positive values of incidence. The results are shown in Figure 10 for an incidence value of $+10.0^o$ and in Figure 11 for -10.0^o, both for an exit Mach number of 1.03. The isentropic Mach number is calculated from the ratio of the measured surface static pressure to the upstream total pressure. For the positive incidence, the pressure distribution is not affected on the pressure surface by the non-uniformity of the inlet flow. However, on the suction surface, it can be observed that the pressure distributions are significantly different. The suction surface pressure distribution is somewhat flatter on the rear part of the blade for the case where the inlet flow is uniform. This is an indication that flow separation occurs at this location, which is consistent with the higher losses and smaller outlet flow angles observed previously for this case. At -10^o of incidence, mild discrepancies between the pressure distributions for uniform and non-uniform inlet flow are observed, as shown in Figure 11. The differences are confined to the forward part of the blade but affect both the pressure and suction surfaces. The differences result from the increased negative incidence induced by the non-uniformity of the inlet flow. However, the differences in the pressure distributions had little impact on the losses, as shown previously. This is presumably because they are quite localized and there seem to be no separations associated with them.

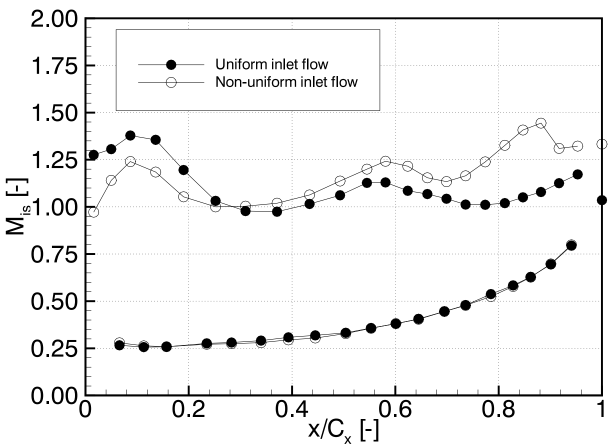

Fig. 10 Effect of inlet flow uniformity on the blade loading at $Ma = 1.03$ and an incidence of $+10.0^o$.

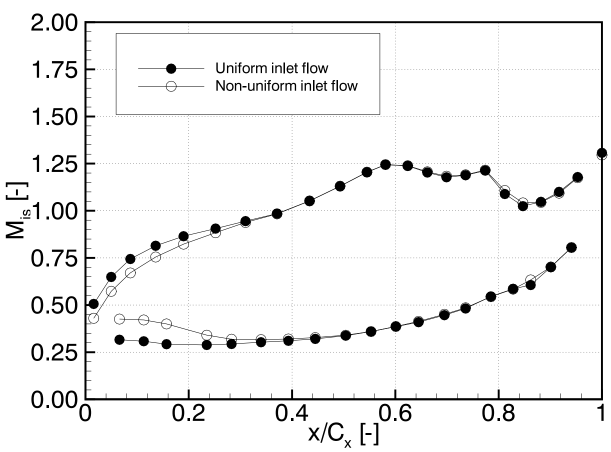

Fig. 11 Effect of inlet flow uniformity on the blade loading at $Ma = 1.03$ and an incidence of -10.0^o.

The base pressure is known to have a strong influence on the losses. Therefore, if the changes in inlet flow uniformity are reflected in the base pressures this would provide part of the explanation for the differences in losses noted earlier. In Figure 12 the base pressure coefficient was plotted against the outlet Mach number for incidences of $+10.0^o$ and -10.0^o. The lines connecting the data are included mainly to guide the eye. The results are shown for both uniform and non-uniform inlet flow. Results at design incidence are omitted for clarity. At design incidence, the inlet flow uniformity had very little influence on the base pressure. The variation of the base pressure at design followed essentially that observed at -10.0^o for uniform inlet flow.

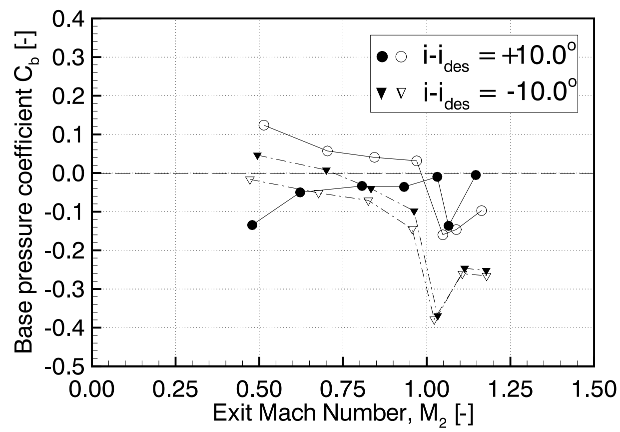

Fig. 12 Effects of incidence and Mach number on the base pressure coefficient. Filled symbols •: uniform inlet flow; Open symbols ○: non-uniform inlet flow.

At an incidence of $+10.0^o$, a significant difference exists between the values of the base pressure coefficient for uniform and non-uniform flow. This is especially true at lower Mach numbers. Again, this can be explained by the fact that at $+10.0^o$ of incidence with uniform flow, the boundary layer on the suction surface of the blade was separated, whereas the degree of separation was much reduced for the non-uniform flow case. Both the thickness of the blade surface boundary layers at the trailing edge and the presence of trailing edge separation are known to influence the base pressure. For an incidence of -10.0^o, the base pressure appears to be influenced by the inlet flow uniformity primarily at the low Mach numbers.

4 Conclusions

Results obtained from detailed measurements performed on a turbine cascade at transonic Mach number for both design and off-design condition were presented. The aim of these experiments was to investigate the effect of the overall flow quality in the wind tunnel on the aerodynamic performance of the turbine cascade.

Data were obtained at three incidences, namely, -10.0^o, 0.0^o and $+10.0^o$ as well as for a wide range of transonic Mach numbers.

The results show the importance of carefully monitoring the quality of the flow both upstream and downstream of the cascade. The results presented in this paper have shown that the lack of inlet flow uniformity cannot be readily detected by measurements made downstream of the cascade. Such measurements should only be used to assess the flow periodicity in the cascade.

Lack of good inlet flow uniformity yields erroneous results. This is especially true at positive off-design incidence for which the cascade becomes sensitive to changes in the effective incidence. Detailed pitchwise measurements of wall static pressure made close to the leading edge of the cascade are essential for verifying the uniformity of the inlet flow.

Finally, Sieverding's recommendations concerning the required blade aspect ratio for making two-dimensional cascade measurements appear to be satisfactory, and perhaps even a little conservative. However, it also appears that considerably higher aspect ratios may be needed to obtain a sufficient width of uniform flow near midspan for studies conducted at large positive values of incidence.

5 Acknowledgement

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