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TIP LEAKAGE LOSSES IN SUBSONIC AND TRANSONIC BLADE-ROWS

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ABSTRACT

In this paper the effect of blade-exit Mach number on unshrouded turbine tip-leakage flows is investigated. Previously published experimental data of a high-pressure turbine blade are used to validate a CFD code, which is then used to study the tip-leakage flow at blade-exit Mach numbers from 0.6 to 1.4. Three-dimensional calculations are performed of a flat-tip and a cavity-tip blade. Two-dimensional calculations are also performed to show the effect of various squealer-tip geometries on an idealized tip-flow. The results show that as the blade-exit Mach number is increased the tip leakage flow becomes choked. Therefore the tip-leakage flow becomes independent of the pressure difference across the tip and hence the blade-loading. Thus the effect of the tip-leakage flow on overall blade loss reduces at blade-exit Mach numbers greater than 1.0. The results suggest that for transonic blade-rows it should be possible to raise blade loading within the tip region without increasing tip-leakage loss.

NOMENCLATURE

C_d	discharge coefficient ($m_{tip}/m_{tip,s}$)
g	tip clearance gap height
m	mass flow rate
M	Mach number
PR	inlet total pressure to exit static pressure ratio
s	entropy
T	temperature
V	velocity
w	tip stream-wise width
ξ	mixed-out loss coefficient $\xi = T\Delta s \big/ \tfrac{1}{2} V_{exit,s}^2$

Subscripts

0	zero-clearance
exit	blade-exit
m	for mainstream passage flow
ps	pressure-surface
s	isentropic
ss	suction-surface
tip	for tip flow

INTRODUCTION

Blade-tip leakage flows are a significant source of loss, especially for low aspect ratio unshrouded blading. Tip-leakage losses can account for up to 30% of the total stage losses in unshrouded high-pressure (HP) turbines. Typically, HP turbine blades will operate with exit Mach numbers in the range $0.8<M_{exit}<1.1$. Recent work has shown that for exit Mach numbers within this range, the tip flow is largely transonic [1]. Thus, if blade-exit Mach numbers are high enough, the leakage-flow will become choked and the leakage mass-flow rate will become largely independent of the pressure ratio across the blade. Since tip-leakage losses tend to be proportional to the tip-leakage mass-flow rate, this raises important questions regarding the losses associated with transonic tip-flows, namely: At what blade-exit Mach number does the tip-flow become choked?; Beyond this point does the tip-leakage loss become independent of further increases in blade-exit Mach number and thus blade-loading?; To what extent does the blade-tip geometry play a role in controlling the tip-leakage loss once the tip is choked?

Harvey [2] gives a comprehensive review of the work on the effect of tip-clearance on turbine aerodynamics and performance, much of which has been performed within subsonic blade-rows or cascades. There has been much work on the effects of tip geometry on blade loss in subsonic blade-rows and of these one of the most detailed recent studies was that of Schabowski and Hodson [3]. However, as stated above HP unshrouded blades can often be transonic and the effects of compressibility on the tip flow have not been so widely studied. There have been some cascade experiments of transonic blade-tip aerodynamics, for instance Key and Arts [4] and Hofer and Arts [5] have compared squealer-tips and flat-tips at transonic conditions. Rotating-rig measurements of the aerodynamics of tip flows at transonic conditions have also been performed, often with the focus on the aerothermal

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performance of the turbine (see [6] to [11]). Recently there have been computational studies of the tip flow at engine-scale conditions such as [12][13]. These engine-scale investigations suggest that the aerothermal behaviour of the tip flow is strongly linked to the transonic nature of the flow.

The water table experiments of Moore et al. [14] and Moore and Elward [15] showed that the formation of the vena-contracta at the entrance to the tip gap was able to accelerate the flow to supersonic conditions when the gap exit Mach number exceeded 0.8. Therefore the vena-contracta acts in a similar way to a converging-diverging nozzle creating a high Mach number tip flow. Furthermore, the experimental and numerical tests of Chen et al. [16] on a two-dimensional tip gap in transonic flow showed that for an exit Mach number of 1.0, the peak Mach number in the gap was 1.4. Krishnababu et al [17] used a similar approach to investigate computationally the effects of transonic flows on tip heat-transfer.

Wheeler et al. [1] shows that when the tip flow is transonic, there is a significant change in the structure of the tip flow, and this in turn causes regions of supersonic flow to have substantially lower heat-transfer than regions of subsonic flow. The fundamental differences between a subsonic tip flow and a transonic tip flow are shown Figure 1. As the flow enters the tip-gap, the vena-contracta formed by the boundary-layer separation on the pressure-side edge accelerates the flow. In a subsonic tip-flow, the flow downstream of this separation decelerates as there is a pressure-recovery due to turbulent mixing. In a transonic tip flow, the separation-bubble sets-up a choked throat, downstream of which the flow can accelerate to a supersonic condition. In this case the rapid acceleration downstream of the separation causes the separation to be much smaller and shorter than would occur in a subsonic tip-flow. Shock-waves form within the tip which cause large local variations in pressure gradient and heat-transfer. The amount of supersonic flow within the tip-gap will vary depending on the pressure ratio across the tip. As the tip pressure-ratio increases, the position of the normal shock, which terminates the region of supersonic flow, will move from the separation-bubble reattachment zone to the exit of the tip gap.

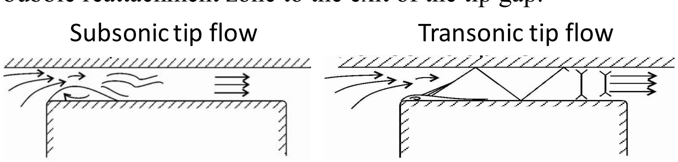

Figure 1: Schematic of subsonic and transonic tip flows

Denton [18] shows that tip-leakage losses arise mainly due to the mixing of the tip-flow with the mainstream, and so the loss associated with this is proportional to the tip-mass flow and the velocity components between the mainstream and tip-leakage stream; this is analogous to the mixing of a jet in crossflow. For subsonic blade-rows this leads to the conclusion that the tip-loss will tend to increase with blade-loading, due to the increase in the driving pressure difference across the tip. In this case, the leakage-flow jet velocity leaving the gap will be similar to that of the local suction-surface velocity. But this is not necessarily the case for a transonic tip-flow, since when the tip-flow is choked the mass flow rate becomes independent of changes in the suction-surface pressure. Furthermore, if the flow leaving the tip-gap is supersonic then the velocity of the flow leaving the tip-gap will be largely independent of the suction-surface pressure.

This paper aims to determine how tip-leakage losses vary when the tip-flow becomes transonic. This paper describes an investigation of the effect of blade-exit Mach number (M_{exit}) on HP turbine tip-leakage losses. Fully 3D RANS simulations are performed of the HP blade-profile described by Kiock et al [19] (see Figure 2). The computational predictions are validated using the Kiock et al experimental data of loading and loss for exit Mach numbers from 0.6 to 1.2 at mid-span. Flat-tip and cavity/squealer-tip geometries are tested with a gap-to-chord ratio of 3%. Two-dimensional simulations are also performed to show how discharge-coefficient varies with pressure-ratio in an idealized tip flow. The results show that for $M_{exit} > 1.0$, the tip-leakage flow remains relatively invariant to increases in blade exit Mach number. As blade-exit Mach numbers are increased beyond the tip-choking point, while the mid-span loss continues to increase, the contribution of the tip-leakage loss reduces significantly.

COMPUTATIONAL METHOD AND EXPERIMENTAL VALIDATION

The computational work detailed here involved the use of the commercial RANS CFD package FLUENT© using meshes created using the GAMBIT© software. The code was used to solve the flow for turbine-blade cascade geometries with a flat-tip and a cavity-tip (see Figure 3). The high-pressure turbine blade tested was that described by Kiock et al [19]. This blade profile has been widely experimentally tested by several research groups and Kiock et al. describe these results. The blade profile and loading distribution is shown in Figure 2. The CFD predictions are to be discussed later but it is useful to note at this point that the predicted loading distribution matches well with the range of experimental results reported by Kiock et al. [19]. The Kiock et al. measurements were obtained at a blade-exit Reynolds number of $8x10^5$ and the computational predictions matched this; there is some range to the experimental results since they were obtained from a wide range of research rigs with different endwall flows and downstream tail-board arrangements. The cascade flow inlet and exit angles were 30deg and 67.8deg respectively. The gap-to-chord ratio was chosen to be 3%. In this case the span-to-chord ratio was chosen to be 2.0 so the gap-to-span ratio was 1.5%. For the cavity-tip geometry the squealer width-to-gap ratio was 1.0, and the squealer height-to-gap ratio was 3.0.

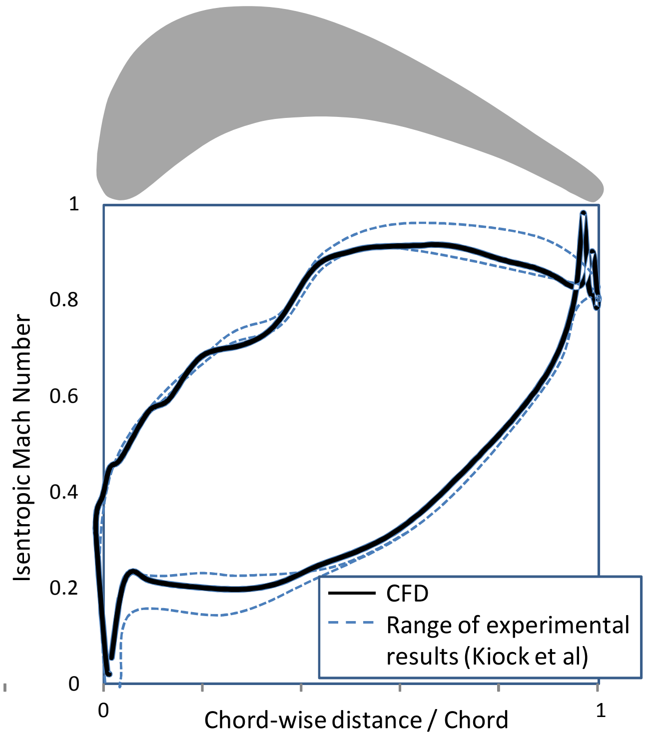

Figure 2: Mid-span Mach number distribution at M_{exit}=0.8 for the Kiock *et al.* blade

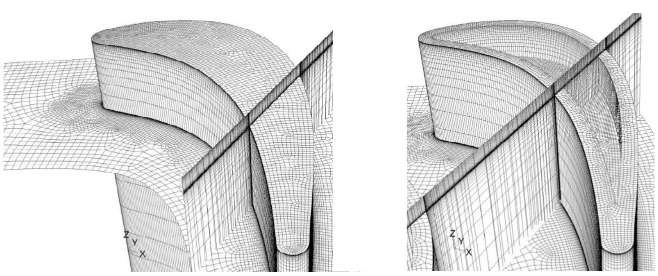

Figure 3: Cascade blade computational geometries

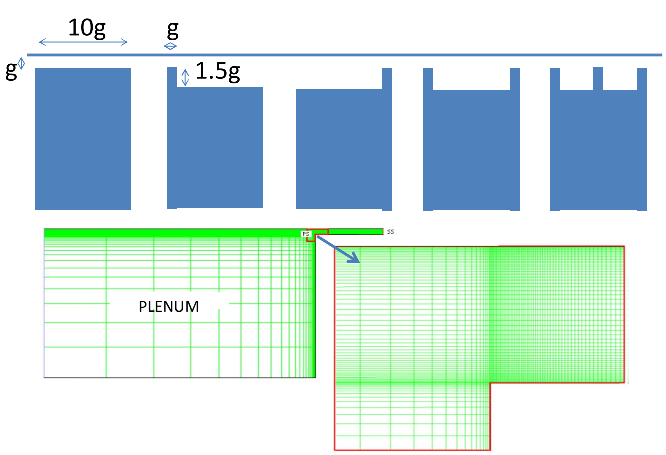

Figure 4: 2D computational domain and geometries tested

The computational grids used for the blade calculations were structured in the spanwise direction and unstructured in the blade-to-blade plane, apart from near the blade surface where a structure O-mesh resolved the boundary-layer (see Figure 3).

Two-dimensional calculations of an idealized tip flow were also performed with various tip geometries shown in Figure 4. For these calculations the Reynolds number based on tip width used was 2×10^5. Stagnation conditions were specified at the inlet to the plenum, and a static pressure specified at the gap exit (see Figure 4). A gap-to-width ratio of 10 was chosen which is typical of the shape of the gap around mid-chord on a blade.

Fully turbulent calculations were performed and the Spalart-Allmaras turbulence model was used throughout. The wall distances of the first cells on the tip surface were kept within $y^+<5$ in all cases tested. A density-based implicit 2[nd] order solver was used for all calculations.

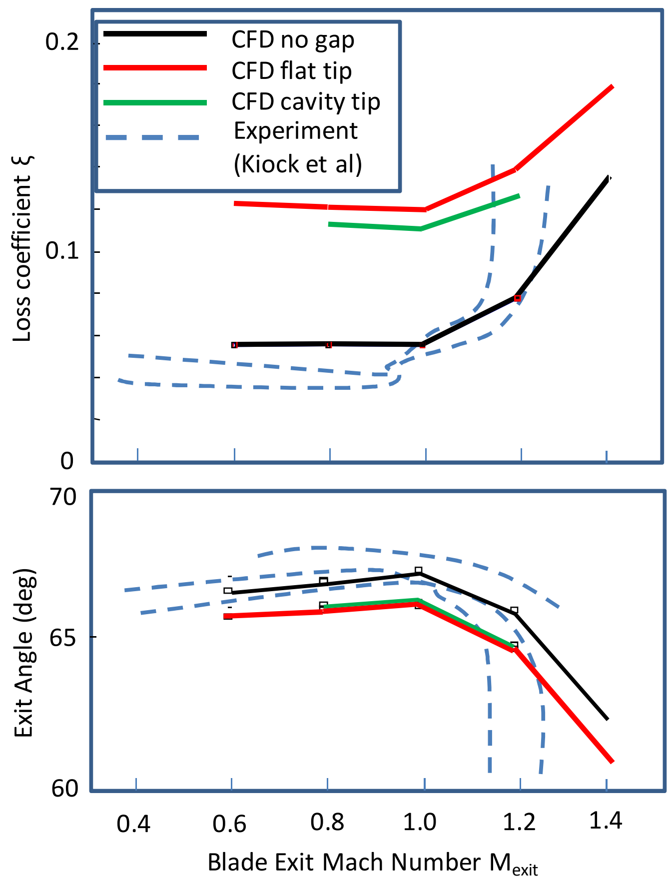

Figure 5: Variation of blade loss coefficient and exit angle with Mach number

The CFD predicted blade performance in terms of flow exit angle and loss can be seen in Figure 5. This figure will be discussed in more detail later but now serves to demonstrate the veracity of the predictions. The losses are determined based on constant-area mixing, conserving mass, momentum and energy. For cases where the flow is locally supersonic, the mixing calculation has two possible solutions, and the solution which created the most entropy was the one taken. The results for the zero-clearance blade (*CFD no-gap*) show that the predicted losses in the range M_{exit}=0.6-0.8 are about 20% higher than the experimental data range. The CFD losses include the endwall boundary layers which raise losses slightly and the CFD is also fully turbulent. The experimental data was obtained at mid-span, and it was mentioned by Kiock et al. that for some of the experimental measurements transition was enforced using a trip at 60% chord-length on the blade-suction surface, implying some laminar flow which will also tend to reduce losses. For M_{exit}>0.8 the CFD predictions match well with experiment as the effects of shock-losses and base-pressure dominate the loss generation.

The predicted blade-exit angles are within the range of experimental data for M_{exit}<1.2. For higher exit Mach numbers the effects of shock and expansion waves in the exit flow lead to high levels of supersonic deviation and the exit angle becomes very sensitive to small changes in exit Mach numbers (see [20]).

The effect of blade-exit Mach number on performance for blades with a flat-tip and cavity-tip are also shown in Figure 5 and these will be discussed later. Before this it is useful to show how changes in blade-exit Mach number influence the overall flow-field of the blade.

EFFECT OF BLADE EXIT MACH NUMBER ON TIP FLOW FIELD

Figure 6 shows how the flow-field changes at midspan when the blade-exit Mach number is increased. At M_{exit}=0.8 the flow at mid-span is entirely subsonic. When M_{exit} is increased to 1.0, the peak Mach number rises to 1.3 and shocks form close to the trailing-edge on both the suction and pressure surfaces. When M_{exit} is increased to 1.2, the peak Mach number rises further to 1.7. The shock formed close to the trailing-edge on the pressure side now creates a pattern of oblique waves as it reflects off the aft suction surface. Thus over the aft portion of the blade, the blade-surface is subject to strong stream-wise pressure gradients. Correspondingly the driving pressure difference across the tip will also be varying significantly from leading-edge to trailing-edge of the blade.

Figure 7 shows Mach number contours in the tip region for both the flat-tip and cavity-tip blades. Four axial planes are shown in this figure and their positions are also indicated in Figure 6 for comparison. The leakage flow in the flat-tip gap accelerates over a pressure-side separation bubble. In the aft portion of the tip, this separation is able to accelerate the flow through the sonic condition. This is even the case when the blade-exit Mach number is as low as M_{exit}=0.8. Thus, the pressure-side separation sets up a sonic throat, which controls the mass flow through the tip.

For the cavity-tip blade, the flow over the pressure-side squealer rim remains subsonic for all exit Mach numbers. In contrast, the flow over the suction-side squealer is transonic. In this case it is the separation on the suction-side squealer which sets up the effective throat area of the tip. Thus peak Mach numbers in the tip tend to be higher than the peak blade Mach numbers, for both the flat-tip and the cavity-tip blade.

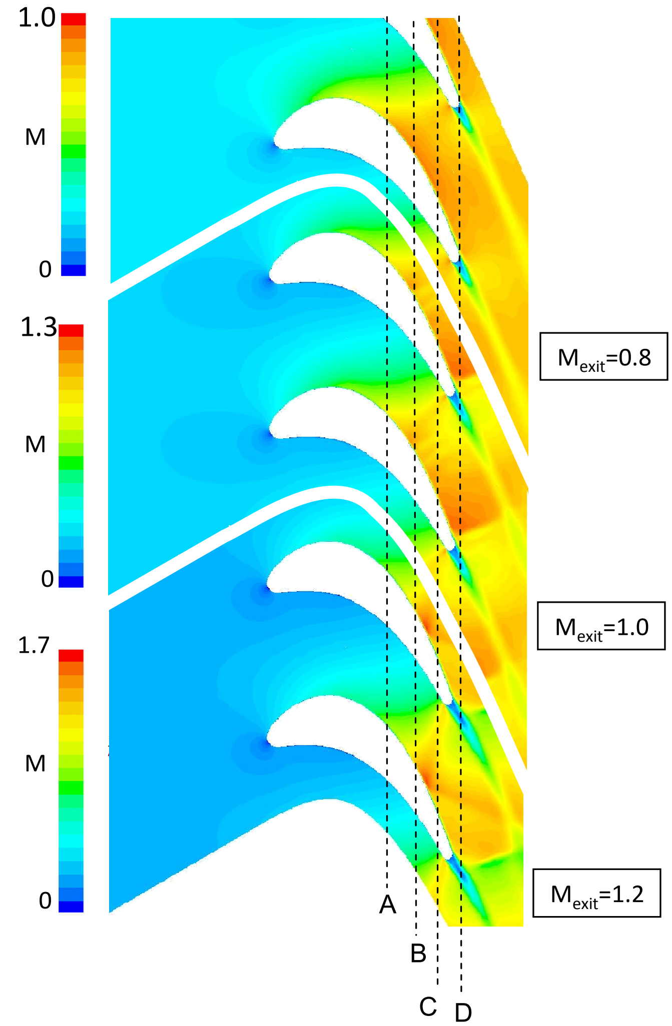

Figure 6: Contours of Mach number at mid-span with different exit Mach numbers

Figure 8 shows the variation of Mach number along a mid-gap contour around the tip-gap for the flat-tip blade (shown in black). The figure also shows the variation of free-stream Mach number around the blade close to the tip at 90% span (shown in red). As the blade-exit Mach number is increased from 1.0 to 1.4, the peak free-stream Mach number on the suction-surface rises from around 1.2 to 2.1. Although the suction-surface Mach number changes significantly with M_{exit}, the Mach number of the flow leaving the tip-gap from the suction-surface edge remains relatively constant once the exit Mach number is raised above M_{exit}=1.2. When M_{exit} is increased from 1.2 to 1.4, the Mach number of the flow leaving the tip gap only varies appreciably near the trailing-edge of the blade (>90% chord). Thus, the flow leaving the tip-gap becomes largely invariant to changes in blade-exit Mach number when $M_{exit} > 1.2$.

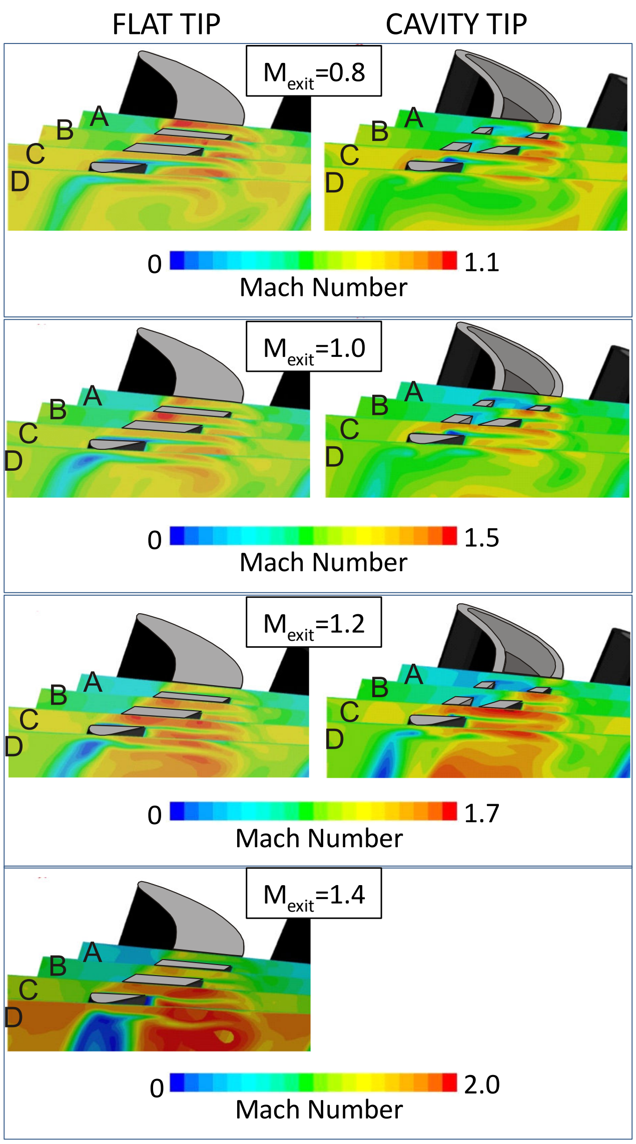

Figure 7: Contours of Mach number within the aft portion of the tip at different axial stations

EFFECT OF BLADE EXIT MACH NUMBER ON TIP MASS FLOW RATE

Consider the idealized two-dimensional tip flow shown in Figure 9. If the conditions at the tip throat are sonic the discharge coefficient is simply given by:

$$C_d = {g^*}/{g} \tag{1}$$

Where g^* is the effective throat size set by the height of the separation bubble. If the flow accelerates isentropically downstream of the separation, the Mach number will be simply a function of the discharge coefficient. Therefore changes in the discharge coefficient will change the peak Mach number in the tip as well as the tip mass flow rate; if C_d=1.0 the peak tip Mach number cannot exceed 1.0 but a value of C_d<1.0 will create peak Mach numbers in the tip which can be significantly higher than the peak Mach number on the blade surface.

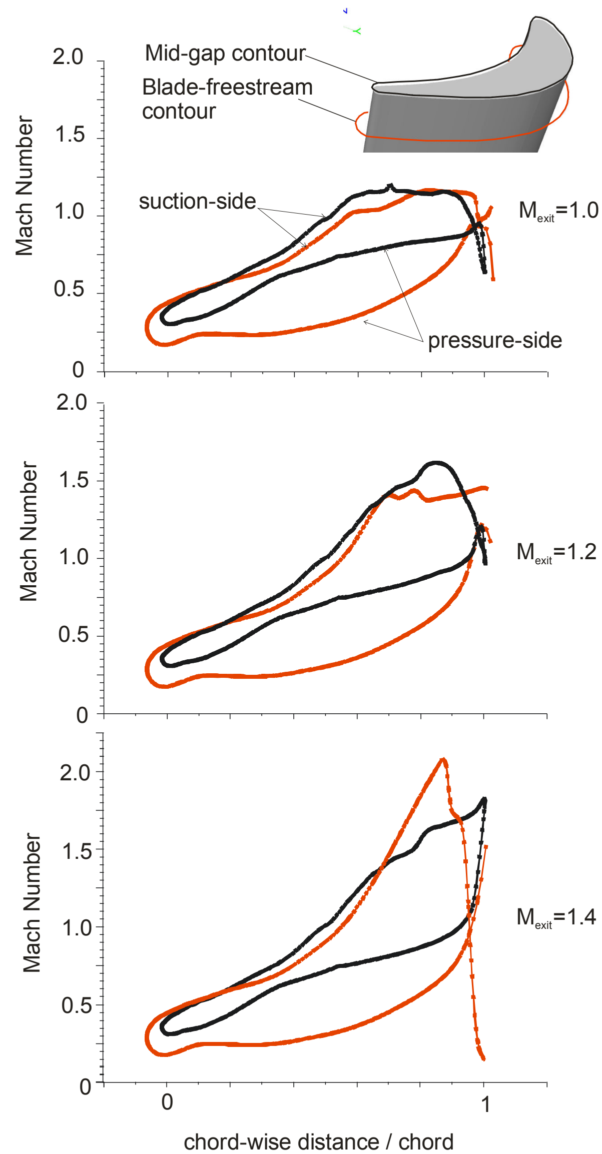

Figure 8: Variation of Mach number along a mid-gap contour around the tip, and along a free-stream contour at 90% span and 5% chord away from the blade surface (flat-tip blade)

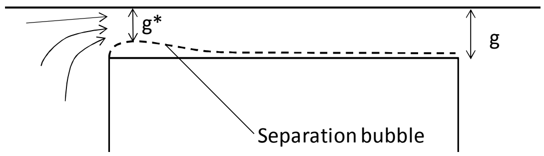

Figure 9: Schematic of idealized choked tip flow

It is well known that pressure-ratio affects the discharge-coefficient of orifice plates [21], and in a similar way the pressure ratio across the blade-tip will also affect discharge-coefficient (as shown previously by [16][17]). In order to demonstrate these effects for various tip geometries, Figure 10 shows predicted discharge coefficients for flat-tip and squealer-tip geometries at different total-to-static pressure ratios. The calculations are two-dimensional predictions which show the effect of pressure ratio on discharge coefficient for an idealized tip flow although these effects are also seen within the blade tip-flow.

Figure 10 shows that discharge coefficient rises with pressure ratio for all tip geometries, as is expected from seal theory. The cavity-tip and double cavity-tip show discharge coefficients which are about 10-15% lower than the flat-tip for the range of pressure-ratios tested here, showing a clear advantage for these geometries. However both the single-squealer geometries show quite a significant rise in C_d at high pressure ratios. Both the pressure-side squealer and the suction-side squealer are beneficial at low pressure ratios since they give lower discharge coefficients than the flat-tip, however at high pressure ratios (PR>2.0) the discharge coefficients are no better than that of a flat-tip.

The cause of these increased discharge coefficients at high pressure ratio can be observed in Figure 11, which shows contours of Mach number for a flat-tip and a pressure-side squealer tip at different pressure ratios. The figure shows that as pressure ratio is increased, the pressure-side separation reduces in both height and length. This was previously shown by Wheeler et al [1] and Chen et al [16]. For the pressure-side squealer, at low pressure ratios (PR<2) the separation is longer than the squealer width and so does not reattach. This open separation leads to a low discharge-coefficient. At high pressure ratios (PR>2) the separation accelerates the flow through the sonic condition and the separation reattaches within a supersonic accelerating pressure gradient. This causes a short separation which is able to reattach onto the squealer tip and thus the discharge-coefficient rises significantly. Strong local pressure gradients are playing a significant role on the tip flow. This differs significantly from a subsonic tip flow where the bulk pressure difference across the tip is primarily the controlling parameter.

Therefore the effect of pressure ratio on a transonic tip flow can still be important if it affects the tip discharge coefficient, which in turn controls both the Mach number in the tip and the tip mass-flow rate.

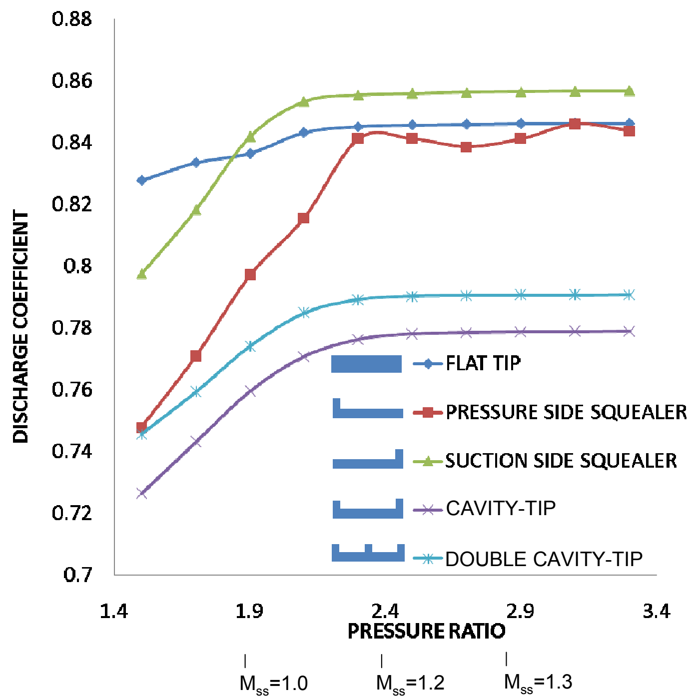

Figure 10: Predicted discharge coefficients for 2D idealized tip flows (w/g=10)

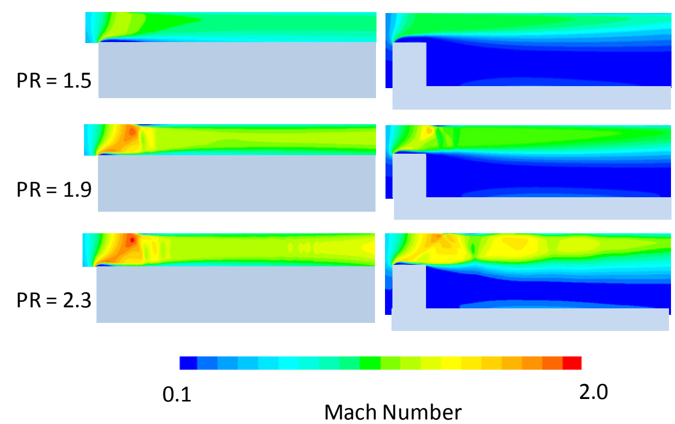

Figure 11: Predicted Mach number contours for 2D flat-tip and pressure-side squealer-tip flows (w/g=10)

For the three-dimensional blade-tip flow, when the blade-exit Mach number is raised the pressure ratio across the tip increases. The effect of this on the blade-tip leakage mass flow rate is shown in Figure 12. This figure shows the variation of the proportional tip-leakage mass flow rate (m_{tip}/m_m) with M_{exit} for both the flat-tip and the squealer-tip blades from the 3D calculations. This figure shows that the cavity-tip has about a 20% lower leakage flow rate compared to the flat-tip and this is to be expected due to the lower discharge coefficient for the cavity-tip.

As M_{exit} is increased from 0.8 to 1.2, the proportional tip-leakage flow rate rises by 4% for the flat-tip and 7% for the squealer-tip. Since the tip flow is largely transonic, the increase in tip mass flow is essentially due to the changes in the tip discharge coefficient seen above. When $M_{exit}>1.2$ the tip mass-flow rate becomes constant and thus the tip flow can be considered to be fully choked beyond this point.

Since the tip leakage loss is proportional to the tip-leakage flow rate, choking of the tip flow will also affect the tip-leakage loss and this is discussed next.

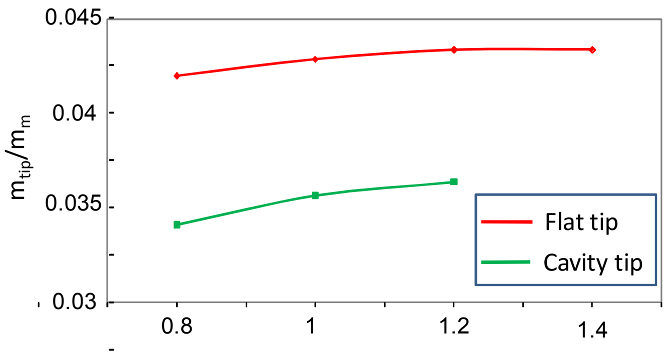

Figure 12: Variation of tip leakage mass flow rate with blade-exit Mach number for the flat-tip and cavity-tip blades

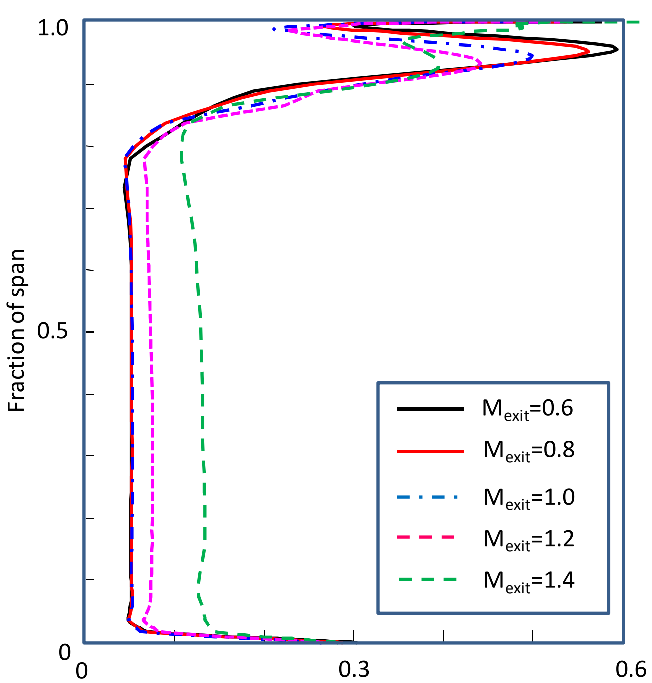

Figure 13: Spanwise profiles of blade-exit loss-coefficient for flat-tip blade

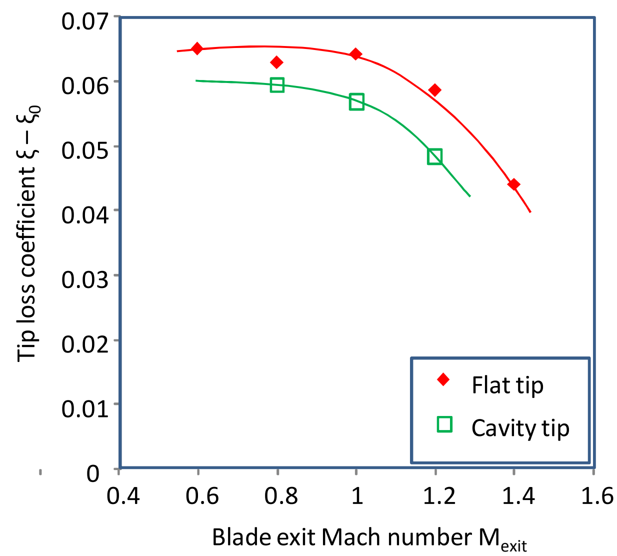

Figure 14: Variation of tip loss coefficient ($\xi_{tip}=\xi-\xi_0$) with M_{exit}

EFFECT OF BLADE EXIT MACH NUMBER ON TIP LEAKAGE LOSS

The tip leakage loss is generally accepted to be mainly a result of the mixing of the leakage flow with mainstream flow. Denton (1993) suggests that, for a particular element of tip-leakage flow passing over the tip (dm_{tip}), the tip-loss is approximately given by:

$$\frac{T\Delta s}{1/2V_{exit}^2} = 2\left(\frac{V_{ss}^2}{V_{exit}^2}\right)\left(1-\frac{V_{ps}}{V_{ss}}\right)\frac{dm_{tip}}{m_m} \qquad (2)$$

This assumes that the leakage flow mixes immediately with the suction-surface flow as it leaves the suction-side of the tip gap.

The analysis of Denton is based on the loss created due to the mixing of two streams of the same velocity magnitude but having different directions i.e., $V_{ss} \approx V_{tip}$. For a subsonic tip flow this will generally be true, since as the tip flow passes through the tip-gap it will be accelerated to the same static pressure as the suction-surface flow. Since the total pressure drop across the tip is normally small, the tip flow velocity will be roughly equal to the suction-surface velocity at the point the tip flow exits the gap.

The same is not necessarily true for a transonic tip flow, especially when the flow leaving the tip gap is supersonic, since in this case the velocity of the fluid leaving the tip will be independent of the static pressure on the suction-side of the blade, and the tip mass-flow rate will also be invariant to changes in suction-surface pressure. This means that the assumptions on which Equation 2 are based are no longer appropriate. Figure 5 shows the variation of blade loss-coefficient with exit Mach number for the zero-clearance blade, the flat-tip blade and the cavity-tip blade. The difference between the no-gap (zero-clearance) loss and the loss for the flat-tip and squealer-tip blades shows the effect of M_{exit} on the tip leakage loss. In the range M_{exit}=0.6 to 1.0, the tip-leakage flow effectively doubles the blade-loss for the flat-tip blade. The cavity-tip blade has a 10% lower loss than the flat-tip, since it has a lower tip-leakage flow rate (see Figure 12). For high exit Mach numbers (M_{exit}>1.0) the blade losses rise significantly. The increase in loss is well known, and due to increased shock related losses and reduced base-pressure. It is interesting to note that the contribution of the tip-leakage loss to the overall blade-loss appears to reduce when M_{exit}>1.0 i.e, the difference between the zero-gap and the flat-tip and squealer-tip loss reduces at high Mach numbers.

The tip-leakage loss coefficient is defined here as the change in the mixed-out loss coefficient that occurs when the tip clearance is introduced

$$\xi_{tip} = \xi - \xi_o \,. \qquad (3)$$

The tip-loss coefficient is plotted in Figure 14 for both the flat-tip and cavity-tip blades. The mixed-out spanwise profiles of blade-loss coefficient for the flat-tip blade are plotted in Figure 13 for comparison.

Figure 14 shows that in the range M_{exit}=0.6 to 1.0, the tip leakage loss does not vary significantly, while when M_{exit}>1.0 the tip loss coefficient reduces as exit Mach number is increased. An increase of M_{exit} from 1.0 to 1.4 leads to a reduction in the tip loss coefficient of 30%. The reduction in tip-loss is observed for both the flat-tip and the cavity-tip blades. The spanwise profiles of loss coefficient shown in Figure 13 also show a significant drop in the loss core in the tip related to the tip-leakage flow as M_{exit} is increased.

Choking of the tip-flow at high Mach numbers will limit increases in the tip-leakage flow rate and hence loss, however it is interesting to note that the tip-leakage loss coefficient actually drops at high Mach numbers. The cause for the drop in loss coefficient is also related to the transonic nature of the tip flow, which will be shown next.

Consider again the idealized tip flow shown in Figure 9. If the flow leaving the tip-gap is supersonic, its Mach number will be invariant to changes in suction-surface pressure and blade-exit Mach number. This was shown previously in Figure 8, which showed that increases in blade exit Mach number above M_{exit}>1.2, have very little effect on the Mach number of the flow leaving the tip-gap, although the suction-surface pressure does vary significantly. This means that the kinetic-energy of the tip flow, which is lost during the mixing process with the mainstream flow, is also fixed although the kinetic energy of the exit flow is still increasing. Thus the ratio of lost-kinetic energy to mainstream kinetic energy (i.e., the loss coefficient) will drop as M_{exit} is increased since $\xi = T\Delta s / 0.5V_{exit,s}^2$. In this case the entropy-rise due to the tip-leakage mixing loss will be fixed and therefore the loss coefficient will be approximately inversely proportional to the square of the blade-exit Mach number (i.e., $\xi_{tip} \propto 1/M_{exit}^2$). The results shown here in Figure 14 appear to support this, since when M_{exit} increases above 1.0, the tip-loss coefficient drops with Mach number.

CONCLUSION

This paper has described an investigation of the effect of blade-exit Mach number on tip-leakage flow and loss for different high-pressure turbine blade-tip geometries. A number of important results were observed:

(1) The tip flow was largely transonic for blade-exit Mach numbers greater than 0.8. Despite this, small changes in tip mass flow-rate were observed as blade-exit Mach number was increased because the tip-discharge coefficient increased at high tip pressure ratios. The tip mass-flow rate did not vary significantly for blade exit Mach numbers greater than 1.0.

(2) Single-squealer tip geometries, either on the pressure-side or suction-side edge, were shown to perform poorly at high pressure ratios. This was because the tip discharge coefficients increased to a level which was similar to a flat-tip. The reason for this was that the boundary-layer separation which formed on the squealer was able to reattach onto the squealer within the strong accelerating pressure gradient in the bubble reattachment zone. This created a small separation-bubble with low blockage. In this case the squealer-width-to-gap ratio was 1.0, and thus it is likely that single-squealer tip geometries will need to be thinner than this if they are to perform well at high Mach numbers. This may make certain squealer designs impractically thin for HP turbine applications.

(3) The results showed that the tip-leakage loss coefficient dropped at high blade-exit Mach numbers. This was in-part due to the tip flow choking, which limited the tip-leakage mass flow rate. In addition, at high blade-exit Mach numbers, the Mach number of the flow leaving the tip-gap became invariant to changes in blade-exit Mach number. This meant that the contribution of the tip flow to the overall loss coefficient dropped significantly. Moreover, since the loss-coefficient associated with the leakage flow is essentially proportional to the ratio of the kinetic energy of the flow leaving the tip-gap to the mainstream kinetic energy, the loss coefficient associated with the tip-leakage flow also dropped.

The results suggest that tip-leakage flows in transonic blade-rows differ significantly from those in subsonic blade-rows. The results show that the effects of pressure ratio on discharge coefficient mean that blade-tip geometries which may operate well at low Mach numbers (such as a single pressure-side squealer) will not necessarily be beneficial for transonic blade-rows. Crucially, in transonic blade-rows the tip flow is either choked, or near the choking point and thus the tip-leakage loss is much less dependent on the blade-loading than for a subsonic blade. This suggests that further increases in blade loading will not lead to an increase in tip loss and thus it may be advantageous to raise blade-exit Mach numbers or blade loading in the tip region.

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At the time of writing this paper the currently unpublished work of Zhang & He [22] was brought to the authors' attention. It should be noted that this work has also demonstrated tip-choking and has shown the potential for this to reduce tip-leakage losses in HP turbines.

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