Some Issues and Developments in Analytical and Experimental Work on Turbine Blade Flows

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Abstract

Areas where substantial research on planar turbine cascades is ongoing, or is still needed, are identified. Compressibility effects are particularly important and are addressed in the three main sections. The modeling of the shock-boundary layer interaction is not yet reliable. For supersonic speeds the agreement is excellent apart from the crucial region downstream of the shocks. At subsonic speeds the vortices were shed in a classical von Kármán vortex street. This resulted in strong base pressure deficits causing high wake losses and energy separation in the wake. The base pressure deficit and the measurements of wake energy separation coincide and it is concluded that the two phenomena are both manifestations of von Kármán vortex shedding. At Mach numbers above unity the vortex shedding was found to be one of a number of transient shedding patterns.

Keywords

Shock-boundary layer interaction — base pressure energy separation — exotic shedding

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INTRODUCTION

For the prediction of flows over turbine blades it is clearly essential that attention is paid to the modeling of three dimensional (3-D) flows. Arguably all turbomachinery flows are three-dimensional and unsteady. However this should not be at the expense of adequate attention to the physics of two-dimensional (2-D) flows that provide the foundation and are the subject matter of this paper. These flows have generally been treated as 2-D but are not strictly 2-D as recent publications on stationary streamwise vorticity make clear. Many details of these quasi 2-D flows are not yet fully understood. Only when these are fully represented will we acquire more confidence in blade design. An emphasis on representing the flow physics is needed, not only for code validation, but also to predict laminar boundary layers, transition to turbulence, separation, heat transfer, base pressure etc. These all affect performance and efficiency.

In this paper some obscure features of the 2-D flow over turbine blades are identified and three high speed cases are discussed in more detail. The planar cascade of blades is a model that gives valuable information and understanding for the flow through all turbomachinery blade rows. Although the flows through a blade row are essentially 3-D and unsteady, the 2-D cascade can still give detailed information on the flow physics that is otherwise not well-predicted. Some gaps in knowledge will be identified, covering entire blade and nozzle vane surfaces, from leading edge to trailing edge and beyond. To give improved prediction capability, these gaps require improved understanding.

The focus of this work is on turbine cascades. Specifically the emphasis is on transonic and low supersonic flows. Similar behavior has been observed between tests under strong adverse pressure gradients on triggered spots, wake-perturbed flat plate boundary layers, and on turbine blading. The open questions in the physics of blade flows start ahead of the leading edge and continue to the trailing edge and into the wake. Figure 1 gives the layout of a 2-D turbine nozzle passage, indicating remaining gaps in knowledge. In this paper, an attempt is made to identify areas where substantial research on planar turbine cascades is ongoing or is still needed. As an example, the question of shock-boundary layer interaction is addressed here, followed by the listing of some other phenomena.

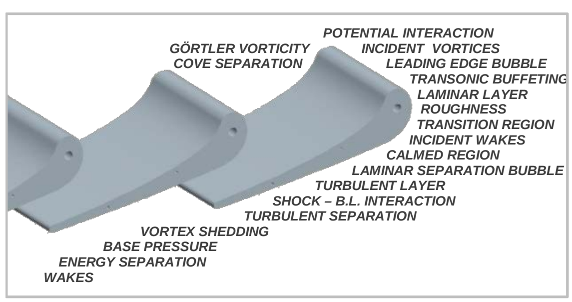

Figure 1. Some Physical Features in the Flow over Turbine Nozzle Blading.

The purpose of this investigation is to raise awareness of some features in blading aerodynamics that are not yet clearly understood. The emphasis is on the quasi two-dimensional flows covering the entire nozzle vane surfaces. Many of these features can also be found on compressor and fan blades. An attempt is made in this paper to identify some of the areas where substantial research on planar turbine cascades is ongoing or is still needed.

It is obviously also essential that attention is paid to the modeling of three dimensional flows. It is arguable that all turbomachinery flows are essentially three-dimensional and unsteady [1]. Computational grids need to be refined. Boundary layers and separation need detailed three-dimensional attention; also secondary flows, clearance, purged flows, sweep effects, cross-flow instabilities etc. need to be incorporated. However this should not be at the expense of adequate attention to predictions of two-dimensional flows that provide the foundation, and are the subject matter, of this paper.

Testing on planar (rectilinear) cascades has continued in laboratory facilities around the world and is still providing valuable information. Although much of this testing is nominally two-dimensional, planar cascade tunnels are not limited to this and work on the three-dimensional aspects of the flow and on unsteady flows with wake interaction is also widespread. It should be mentioned that the testing of annular cascades and of complete stages is also undertaken, mainly in industrial laboratories. There is, therefore, a continuum from the canonical models of flat plates and circular cylinders through rectilinear cascades to annular cascades and complete rotating machines. Factors governing the choice of model are often cost and versatility but the specific purpose of investigations may also be crucial.

A principal aim is to validate the prediction of computational results. These themselves may have a variety of aims, from basic physics to direct design and code validation. The codes available take on a variety of forms, from two-dimensional and time-marching, through the most usual Reynolds-averaged Navier Stokes (RANS) codes, to Direct Numerical Simulation (DNS). In all of this a most important objective is the understanding of the basic flow physics. The ideal way of attaining this is to have a high quality planar cascade in a stable environment with good instrumentation back-up that can be worked on continuously, or at least when new staff, ideas or instruments arrive. The authors are fortunate to have had such accessibility at the National Research Council of Canada (NRC) in Ottawa and most of the results presented in this paper will be drawn from that facility. Some of the issues raised by cascade tunnel testing are listed below. The question of shock-boundary layer interactions is one on which progress is imminent as new compressible models and codes are developed.

1. SHOCK–BOUNDARY LAYER INTERACTION

High loading requirements in modern axial flow machines often call for transonic and supersonic flows. Outer regions of the fan blades of high by-pass engines operate with supersonic relative inlet flows and these result in a shock-boundary layer interaction in the leading edge region. This interaction, involving a thin boundary layer, mainly affects the flow rate but otherwise such interaction effects are relatively benign. This cannot be said for turbine nozzle vanes where high loadings may call for supersonic discharge flows. The modeling of such shock-boundary layer interactions is not yet reliable. This can affect flow predictions downstream of the shock impingement and hence the loss. It is particularly difficult when a laminar separation bubble is triggered or when the shock is oscillating under the influence of vortex shedding.

In Fig. 2 schlieren photographs of the flow through a representative highly loaded nozzle vane are shown for a range of Mach numbers. In turbine blading the shock wave emanating from the trailing edge of one vane may impinge on the adjacent vane at around 45% of true chord (70% axial chord). There is the potential for 55%

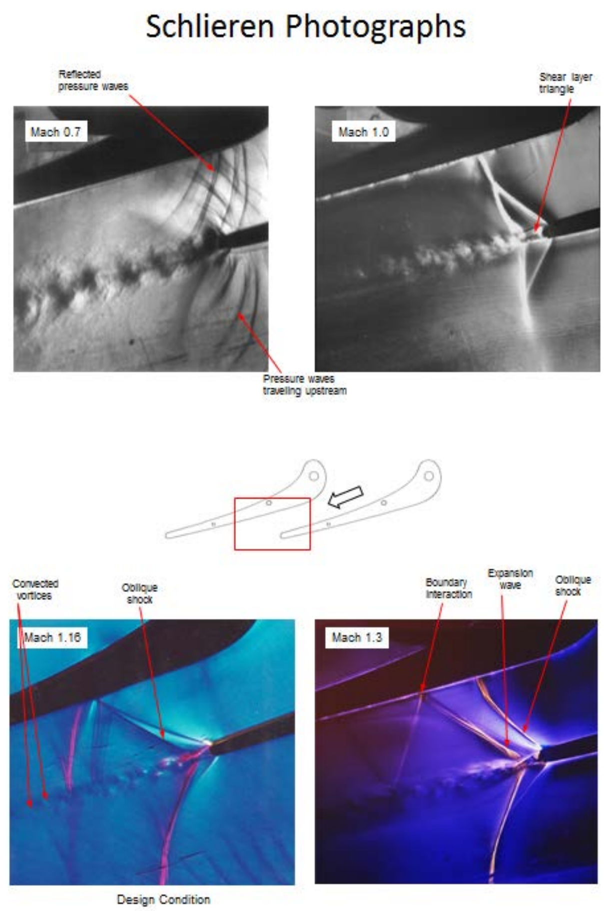

Figure 2. Schlieren Images of Flow at Ma = 0.7, 1.0, 1.16 and 1.3 .

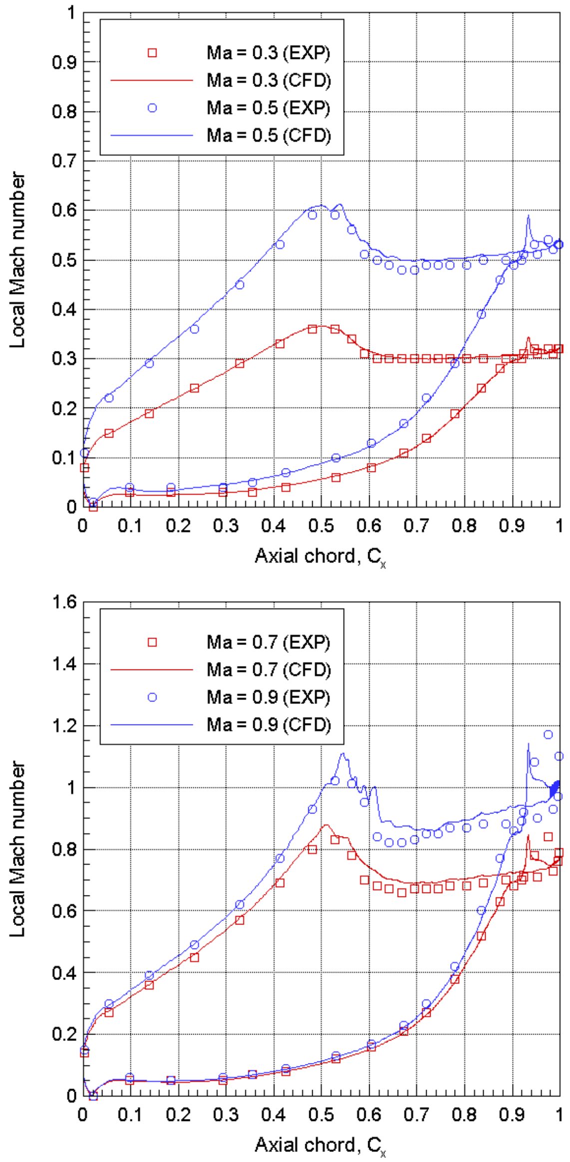

Figure 3. Agreement between Experiment and Computation for NRC Nozzle Cascade at Four Subsonic Discharge Mach Numbers.

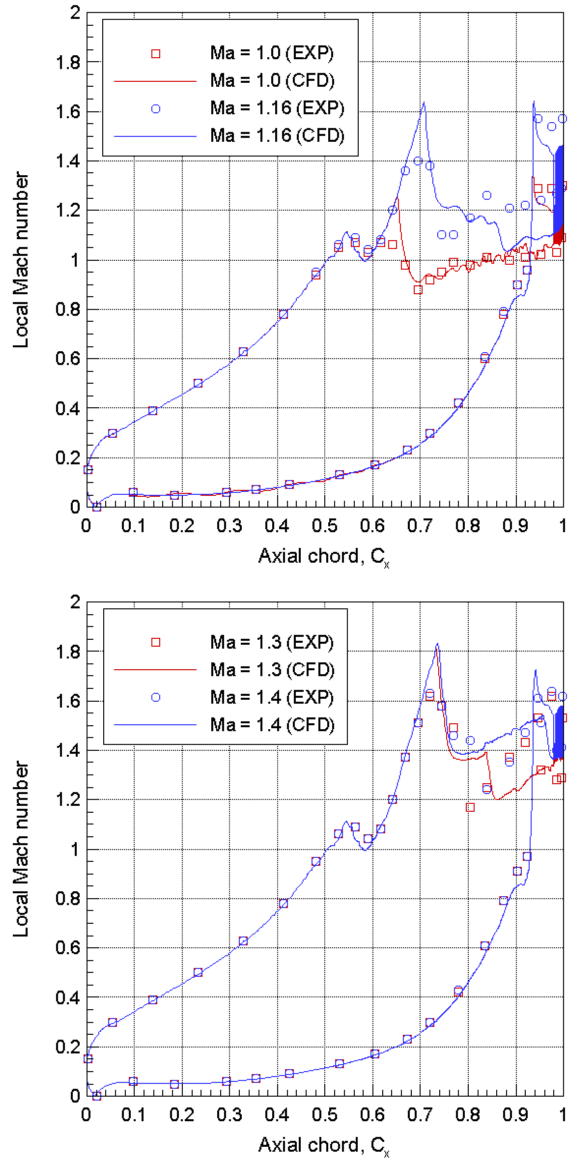

Figure 4. Agreement between Experiment and Computation for NRC Nozzle Cascade at Four Supersonic Discharge Mach Numbers.

of the suction surface to be wrongly predicted if the representation of flows, in the interaction region and further downstream, is not correctly modeled**.**

Results from the subject test case are given in Figs. 3 and 4 and have been used for validating a number of codes. The most recent two-dimensional time-accurate numerical simulations of the mid-span flow were performed over the speed range to Ma = 1.4; these also are given in Figs. 3 and 4.

The spatial derivatives were discretized with a second-order accurate upwind Roe flux difference-splitting scheme. The temporal terms were treated with the second-order implicit method. The *k-ω* turbulence model was used for closure. Convergence was accelerated; using multi-grid techniques the mesh was refined such that the minimum value of y^+ was less than unity. No wall functions were used and the turbulence model was integrated all the way to the wall.

At discharge Mach numbers below sonic (Fig. 3) the agreement between computational prediction and experimental measurements of local Mach number is reasonable. At a Mach number of unity it is not clear whether the shock impingement is accurately predicted. At discharge Mach numbers of 1.16, 1.3 and 1.4 the agreement on both surfaces is very good apart from the crucial region downstream of the shock. Shock impingement here results in a significant discrepancy between computation and experiment. The prediction is clearly adversely affected and at a

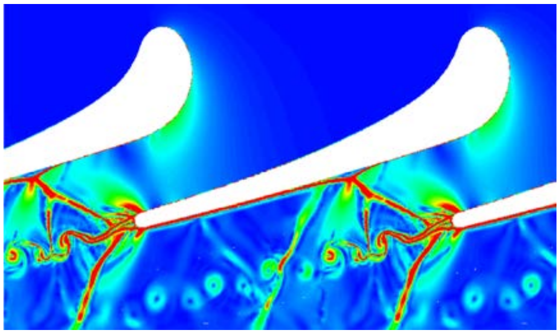

Figure 5. Instantaneous Computational Schlieren. View of Shock Wave – Boundary Layer Interaction at Ma =1.16 .

discharge Mach number of 1.16 the computation under-predicts the strength of the expansion and of the subsequent recovery. It may be noted that prediction of the flow regime upon shock interaction at transonic speeds is notoriously sensitive to small changes in Reynolds number.

Figure 5 shows the numerical schlieren corresponding to the experimental result for a Mach number of 1.16. The experimental image shows that the experimental shock appears to directly impinge on the blade surface whereas the numerical schlieren indicates impingement on a separated flow region or a bubble. This is consistent with the rapid expansion fan following the experimental shock that is not predicted numerically. The experimental flow then appears more capable of recovery than the computed flow. The impingement and the flow on the downstream surface are not being correctly predicted.

It may be concluded that over the subsonic speed range (Fig. 3) the flow throughout the blade passage region is correctly predicted. In this case the approaches to turbulence modeling and transition modeling are working well and existing techniques are adequate.

For supersonic flows, although flows upstream of the impinging shock are modeled quite well, for the remaining 55% of true chord the observed suction surface flow is not modeled correctly. Since this is the critical region for blade profile loss generation the need for improved modeling of the shock-boundary layer interaction region is clear.

The discrepancy when strong shocks are present appears to be a failure to model the shock-boundary layer interaction correctly. There is a need to investigate and improve the modeling of shock-boundary layer interactions, and their influence on the downstream flow, particularly when a laminar separation bubble is predicted or when the shock oscillates under the influence of vortex shedding.

2. VORTEX SHEDDING

Vortex shedding is endemic for blading having a blunt trailing edge. Trailing edges are often blunt, for blade cooling and stressing reasons, and carry a high loss penalty. This loss penalty is greater than would be expected from a simple backwards-facing step and remained unexplained until high speed schlieren photography was applied to cascades [2]. The unexplained losses were clearly associated with the shedding process.

Base Pressures on Turbine Blades

A detrimental flow phenomenon affected by vortex shedding is low base pressure. Blades with thick trailing edges have an area of reduced static pressure around the trailing edge creating a considerable increase in base drag at subsonic speeds and reducing the blade row's efficiency. Sieverding *et al.* [3] conducted an investigation into the effect vortex shedding had on the base region flow. It was found that the pressure in this region fluctuated by as much as 8% of the downstream dynamic head near separation and by 4.8% in the base region. The instantaneous base pressure could be significantly different from the time-averaged value. Computations for blading designed using steady state methods will be erroneous for much of the vortex shedding cycle.

For subsonic speeds low base pressure is an essential facet of the vortex shedding process resulting in increased drag for bluff bodies and efficiency losses in turbine blades. The base pressure depends strongly dependent on Mach number. At supersonic speeds, the main causes of low base pressure are the strong spatial variations of pressure through shocks and expansions; this tends to be a relatively steady process. At subsonic speeds, shocks only begin to play a role as the velocity reaches critical levels and, in general, the unsteady process of vortex shedding is more important. These are therefore two distinct compressibility effects. The main focus of this subsection is on the subsonic speed range.

Base pressure loss is an important contributor to a turbine blade's total loss. Work by Xu and Denton [4] and by Mee *et al.* [5] showed that the base pressure contributed a significant proportion of the total loss at high speeds. MacMartin and Norbury had concluded that, for bluff body flows, "calculation methods which neglect base pressure effects are incapable of accurately calculating the flow patterns or the total pressure loss" [6]. Carscallen *et al.* [7] found that low base pressure was accompanied by the strongest amplitude of vortex shedding. The most comprehensive base pressure correlation is that of Sieverding *et al.* [3]. The base pressure results are compared with the Sieverding correlation by Gostelow e*t al.* [8]. There is a significant discrepancy between the two base pressure correlations.

Energy Separation in Blade Wakes

Associated with the vortex shedding was the energy separation effect that was particularly strong at high subsonic speeds. On a time-averaged basis the wake center line stagnation temperature was found to be 12°C lower than for the incoming fluid. Meanwhile the stagnation temperature at the edges of the wake was 5°C higher than that of the incoming fluid. This effect had had a major adverse impact on the development of a new high-loading turbine design. It was demonstrated that this was a manifestation of the Eckert-Weise effect [9]. In energy separation the vortex cores emerge colder than the surrounding fluid and are associated with hot spots at the edge of the wake. On a time-averaged basis this results in substantial total temperature redistribution.

Investigation of this phenomenon involved measuring time-resolved temperature variations within the fluctuating wake and relating these to the previously observed time-average stagnation temperature variations. The frequency of vortex-shedding from the blades was of the order of 10 kHz. This was a requirement to measure total temperature fluctuations with a bandwidth approaching 100 kHz for the energy separation phenomenon to be resolved and identified. This was achieved using novel quartz rod-mounted thin film gages supplied by Oxford University [10]. A Kulite pressure transducer was mounted alongside the quartz rods enabling total pressure to be measured simultaneously. It was therefore possible, using phase averaging, to construct contours of total pressure, total temperature and entropy increase at the measurement location in the vortex wake. As an example, the total temperature contours are shown in Fig. 6 and the entropy contours in Fig. 7. The relatively cool vortical structures on the wake center line are seen, as are the hot spots.

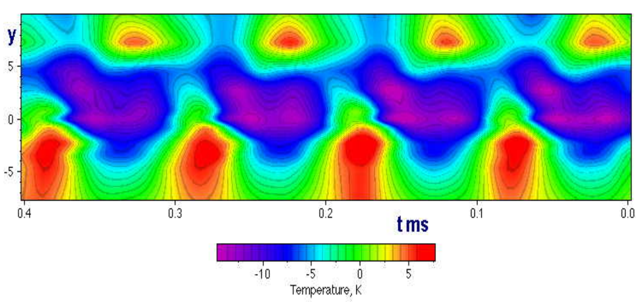

Figure 6. Time-resolved Temperature Contours Downstream of the Blade Trailing Edge.

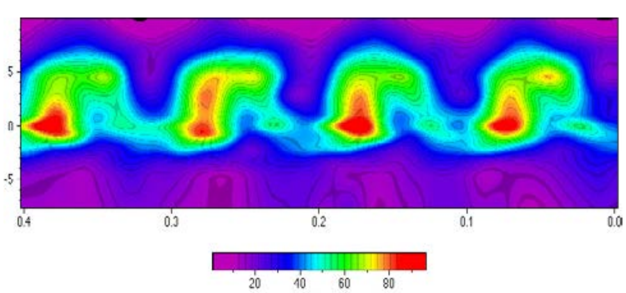

Figure 7. Time-resolved Entropy Contours Downstream of the Blade Trailing Edge.

Energy Separation and Base Pressure

The finding that the distribution of the total temperature differences was correlated with the distribution of total pressure loss coefficients meant that the energy separation phenomenon not only caused the redistribution of the total temperature field within the wake but also affected the magnitude of the wake losses.

In Fig. 8 the overall loss coefficient and total temperature separation are compared directly by suitable normalization. The loss coefficient is the total pressure loss divided by the upstream dynamic pressure; it is normalized by the difference between the value at Mach 1.0 and at the lowest measured Mach number of 0.32. For the total temperature separation in the wake the inverse of this denominator is used. With this normalization, 12°C of total temperature separation in the wake corresponds to a loss coefficient difference of 0.113. The good agreement of the curves in the high subsonic regime gives heuristic justification to the relationship between energy separation in the wake and the loss coefficient of the blade. The losses rose by over 200% as the Mach number increased from 0.3 to 1.0 and then fell as the Mach number further increased to 1.3. Once again there is a peak in area averaged losses at or just below a Mach number of unity. A linkage therefore exists between the energy separation in the wakes of some turbine blades and the base drag emanating from the blade surface pressures. The phenomena of energy separation and of base pressure deficit are inextricably linked to, and are caused by, vortex shedding. For design purposes alleviation of the problems of energy separation and base drag should begin with the suppression of the vortex shedding, which is seen to be the causal factor.

At subsonic speeds acoustic waves propagated upstream and affected the blade surface and trailing edge base pressures. Under transonic flow conditions, the origin of the vortex shedding moved from the blade trailing edge to the confluence of the two trailing edge shear layers as shown in Fig. 5. Under these conditions

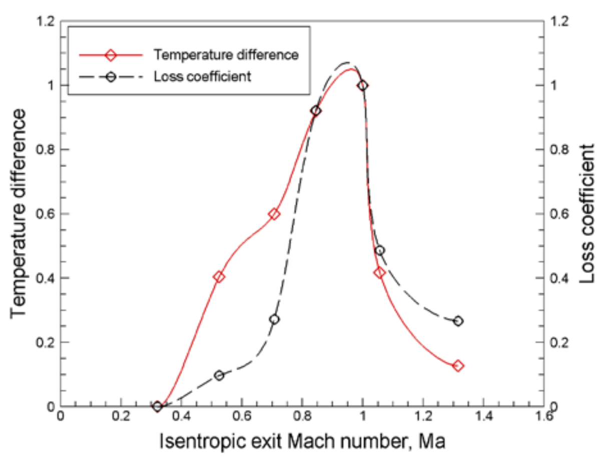

Figure 8. Normalized Loss Coefficient and Total Temperature Difference as a Function of Mach Number.

conditions schlieren observations revealed vortex shedding structures varying intermittently between the usual von Kármán mode and more exotic modes. The resultant vortex shedding was also responsible for an oscillating shock that impinged on the suction surface of the adjacent blade.

The Relationship

At subsonic speeds the link between energy separation and base pressure is von Kármán vortex shedding. For the turbine blades the amplitude of oscillations, the energy separation and the base drag are all at their most severe at exit Mach numbers around 0.9 and, as Fig. 8 shows, fall off steeply at exit Mach numbers above unity. A wide range of energy separation phenomena had been reviewed by Eckert [11] who concluded that energy separation was primarily caused by pressure forces, acting on fluctuating curved streamlines, with only a minor contribution from viscous forces.

The evidence of the results is that the driving force behind both energy separation in the wake and base drag on the blade at subsonic speeds is clearly the strong von Kármán vortex shedding. Under vortex shedding conditions, the dynamic action of the vortices produces strong total temperature differences between the wake's cold core and the hot outer regions. The same process demonstrates that the dynamic action of the vortices produces strong total pressure fluctuations in the trailing edge region. This manifests itself as the low static pressure (base pressure deficit) on the wall surface. This is the principal cause of subsonic base drag.

It has therefore been demonstrated that both phenomena are the inevitable consequences of the strong von Kármán vortex shedding at high subsonic speeds. The analysis indicates that the phenomena of energy separation and of base pressure deficit are inextricably linked to, and are caused by, vigorous von Kármán vortex shedding.

The best practical approach to alleviating energy separation and base drag is not to attempt to address these issues separately or directly but rather to address their cause, namely the global stability of the von Kármán vortex shedding. Quite subtle changes in trailing edge geometry can minimize or even eliminate vortex shedding. The main cause of von Kármán vortex shedding behind a turbine blade is the bluntness of the trailing edge.

3. EXOTIC VORTEX SHEDDING AT TRANSONIC SPEEDS

Although a link between energy separation and base drag at subsonic speeds has been demonstrated the shed vortices may become intermittent at supersonic speeds. The configurations are no longer solely of the conventional von Kármán kind but adopt a number of different patterns. This behavior is well-known for vortex shedding at low speeds when the wake is subjected to lateral static pressure variations. In the case of the blunt trailing edge of the turbine blade at transonic speeds the pressure fluctuations do not originate on the blade surface but rather in the instability of the confluence region downstream of the trailing edge.

The most common vortex shedding mode, that predicted by von Kármán, is not the only shedding mode. Not all vortex shedding takes form of a classical vortex street; a wide range of 'exotic' shedding modes exists [12, 13]. Carscallen and Gostelow [7] also discovered these anomalous patterns behind transonic turbine blading prompting an investigation of when they might occur. Two other applications were found in the vortex-induced vibrations of bluff bodies and research on oscillating airfoils. Findings from the vortex-induced vibration work of Williamson and Roshko [12] and others clarified the shedding modes.

For some of the time vortices were shed simultaneously from the two sides of the wake, rather than alternately. This behavior can be observed in Fig. 9 for the discharge Mach number of 1.09. Other modes were observed in which vortex pairing appeared to be taking place on one side only as in Fig. 10. Since the passage shock behavior is determined by the vortex shedding mode this anomalous behavior could have consequences for predicting the shock position, blade loading and dynamics. None of these additional transonic speed modes are explained by conventional stability theory. However Ponta and Aref [13] have performed an analysis that appears to predict the observed data well and extend them to a wider range of Reynolds numbers.

As the discharge Mach number becomes supersonic the trailing edge shocks become oblique and the origin of the vortex street migrates from the trailing edge to the confluence of the two trailing edge shear layers. Previously available evidence had suggested that only free-stream disturbances are effective in provoking vortex-shedding instability. In the present example the visible existence and fixed location of acoustic waves precludes such a path for anti-symmetric upstream-travelling pressure waves. This has the effect of reducing the lateral distance between incipient vortices to the relatively short wake width at the downstream shock location. Nevertheless, significant free shear layer instabilities are thought to be propagated downstream through a Kelvin-Helmholtz mechanism.

These phenomena, caused by vortex shedding, also play an important role in the loss-generation due to low base pressures behind blades with thick trailing edges. They can also have a role in vortex-induced vibration of the resulting airfoil, which is effectively a bluff body.

High speed schlieren and traverses of total pressure fluctuations have established that, although strong von

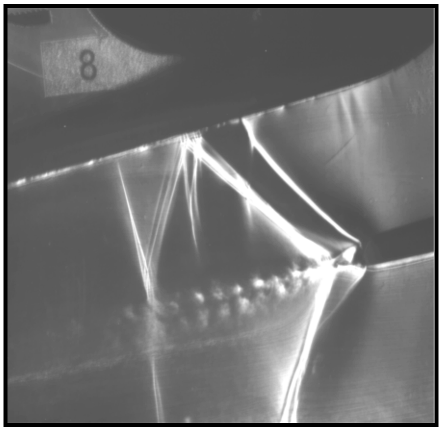

Figure 9. Schlieren View of Vortex Couples.

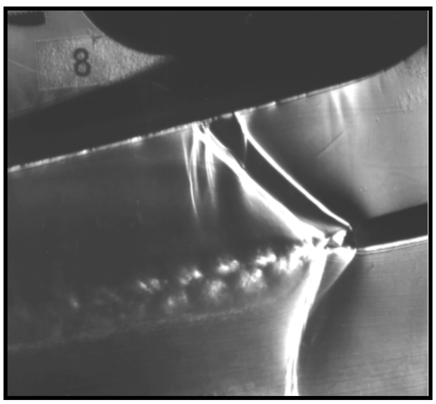

Figure 10. Schlieren View of Vortex Doublets.

Kármán vortex shedding occurred throughout the subsonic range. Above sonic the wake vorticity distribution was intermittent with vortices being shed in one of a number of transient, yet distinct, shedding modes. These vortex-shedding modes were characterized as classical von Kármán, couples, hybrid and doublets. Broadly corresponding designations from the field of vortex-induced vibration were identified in terms of the single and pairs definitions 2S, 2P, 2P* and P+S.

Schlieren photographs from transonic cascades showed that the interaction between the base flow shear layers and the shock waves are the likely mechanism causing the changes in observed vortex-shedding patterns. There was strong interaction between the downstream shock waves and the vortex shedding process but the coupling mechanism was not understood.

Observations of how the shocks interact with shear layers suggest that the observed changes in vortex shedding from the blunt trailing edges of the transonic cascade in the Mach number range between 0.9 and 1.3 are caused by a similar self-induced oscillation mechanism. As shown in Figs. 9 and 10, shocks are generated at the confluence of the shear layers; the shocks interact with the shear layers in a manner similar to the mechanism described by Mabey [14] for the biconvex airfoil.

Findings, from schlieren visualization, computational work and a separate hydraulic analogy experiment, have shown the shock wave / wake interaction structure at the confluence of the shear layers to be particularly dynamic and mobile. As a result an oscillatory flow is set up which causes the observed changes in vortex shedding.

The base pressure recovered significantly in transonic flows, where the vortex street changed its character. The anomalous vortex shedding patterns were therefore associated with a reduction in loss.

4. SUMMARY

For the prediction of flows over turbine blades it is important that attention be paid to the modeling of three dimensional flows. All turbomachinery flows are essentially 3-D and unsteady. Computational grids need to be refined. Boundary layers and separation need detailed three-dimensional attention; also secondary flows, clearance, purged flows, sweep effects, cross-flow instabilities and streamwise vortices need to be incorporated.

However this should not be at the expense of adequate attention to the 2-D flow physics that provides the foundation and the subject matter of this paper. Many details of these quasi 2-D flows are not yet fully understood. Only when these are fully represented will there be more confidence in blade design. An emphasis on representing the flow physics is needed, not only for code validation, but also to predict laminar boundary layers, transition to turbulence, heat transfer, separation etc. These will all affect performance and efficiency.

Figure 1 gives the layout of a turbine nozzle passage, indicating regions where there are gaps in knowledge. These cover the entire surface from leading edge to trailing edge and beyond. Many such features can also be found on compressor and fan blades. In this paper an attempt is made to identify areas where substantial research on planar turbine cascades is ongoing or is still needed. Compressibility effects are particularly important and are addressed in the three main sections of this paper.

High loading requirements in modern axial flow machines often call for transonic and supersonic flows. The fan blades of high by-pass engines operate with supersonic inlet velocities and these result in a shock-boundary layer interaction in the leading edge region. This shock interaction involves a thin boundary layer, such that the interaction effects are relatively benign. This cannot be said for turbine nozzle vanes, where high loadings may call for supersonic discharge flows. The modeling of the shock-boundary layer interaction is not yet reliable. This can affect flow predictions downstream of the shock impingement and hence the loss. It is particularly difficult when a laminar separation bubble is triggered or when the shock is oscillating under the influence of vortex shedding.

In turbine blading the shock wave emanating from the trailing edge of one vane may impinge on the adjacent vane at around 45% of true chord (70% axial chord). There is the potential for 55% of the suction surface to be wrongly predicted if the physical representation of flows in the interaction region and further downstream are not correctly modeled. This test case has been used for validating a number of codes. 2-D time-accurate numerical simulations of the mid-span flow were performed over the speed range to Ma = 1.43 and are used in Fig. 2.

At subsonic discharge speeds the agreement between prediction and measurements is reasonable. For supersonic discharge speeds the agreement on both surfaces is excellent apart from the crucial region downstream of the shock. The prediction is clearly adversely affected and the computation under-predicts the strength of the expansion and of the subsequent recovery.

At subsonic speeds the vortices were shed in a classical von Kármán vortex street. This resulted in strong base pressure deficits causing high wake losses and energy separation in the wake. The base pressure deficit and the measurements of wake energy separation are coincident and it is concluded that the two phenomena are both manifestations of the von Kármán vortex shedding.

At Mach numbers above unity the von Kármán vortex street was found to be but one of a number of transient, yet distinct, shedding patterns. These corresponded with similar patterns observed in the field of vortex-induced vibration, The occurrence of similar changes in vortex shedding from transonic cascades suggests that the existence of an oscillating body is not a fundamental requirement. The wake will be under lateral pressure and its instability could be caused by an oscillating flow mechanism. Shock-induced transonic flow oscillations could also change the modes of vortex shedding.

The transonic cascade schlieren photographs showed that the interaction between the base flow shear layers and the shock waves, which form at Mach numbers between 0.97 and 1.2, is the likely mechanism causing the changes in observed vortex-shedding patterns.

In all this work an emphasis should be retained on representing the flow physics. More work is needed, even to predict laminar boundary layers, heat transfer and separation. Experimental work is needed for analytical understanding and code validation. Computer modeling will then be able to proceed with confidence.

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