Mid-Span Losses in Turbine Blades at Subsonic and Supersonic Speeds

J. Paul Gostelow[1]*, Aldo Rona[2].

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Abstract

The effects of compressibility are intrinsic to many axial flow turbomachines, is. Both subsonic and supersonic speed ranges are considered in this investigation. Subsonic surface base pressures, and wake energy separation, are a direct result of periodic von Kármán vortex shedding. This is the principal cause of both wake energy separation and the related subsonic base static pressure deficit. At high subsonic speeds a 17^{o}C temperature difference across the wake was observed. This time-averaged temperature separation was a manifestation of the energy separation (Eckert-Weise) effect. At supersonic speeds the trailing edge base pressure, and the wake energy separation, exhibit different characteristics from the subsonic behavior. Shock waves from the trailing edge may impinge on the adjacent suction surface adversely affecting the downstream boundary layer. Supersonic flows usually cause shock and expansion waves and this may occur in steady flows. Other wake modes may also involve von Kármán vortex shedding from the confluence region of the wake. This is not the only form of shedding and anomalous, or exotic, shedding may also play an important role.

Keywords

Mid-Span 1 — Subsonic 2 — Supersonic 3

[1,2] *University of Leicester, Leicester, United Kingdom*

***Corresponding author**: jpg7@le.ac.uk

INTRODUCTION

The design emphasis of the blading of most axial flow machines, whether expanding or contracting, and regardless of the flow medium, is the blade aspect ratio. This parameter determines whether the principal research and design emphasis is to be directed to the quasi two dimensional flows of mid-span or the interaction of flows between the end wall and the blade boundary layers with associated vorticity. To make the designer's role even more challenging the appropriate aspect ratio may change drastically from inlet to outlet within the one machine so that a comprehensive approach is needed.

The aspect ratio is defined as the blade height divided by the chord length. A high blade aspect ratio (often defined as one above three) places most of the design emphasis on a two dimensional approach. With this approach the emphasis has been on blade, or cascade, flows. Traditionally the low aspect blading had been covered by correlations of experimental data. Attempts involving purely experimental results enjoyed a measure of success but were not always reliable especially in the regions of hub and casing. This changed with the improved resolution of CFD in the blade hub and tip regions. The design emphasis, particularly on the casing, has seen considerable improvement. In that scenario it is understandable if the improvement of mid-span flows has also seen the reduction of losses.

However the prediction of both end wall and mid-span regions needs continuing improvement. The purpose of this presentation is to highlight some of the physical aspects of mid-span flows that need ongoing attention if losses are to be further reduced.

A useful summary of the situation has been given by Saravanamuttoo *et al.* [1]: "An overall blade loss coefficient … must account for the following sources of friction loss:

(a) Profile loss – associated with boundary layer growth over the blade profile (including separation loss under adverse conditions of extreme angles of incidence or high inlet Mach number).

(b) Annulus loss – associated with boundary layer on the inner and outer walls of the annulus.

(c) Secondary flow loss – arising from secondary flows which are always present when a wall boundary layer is turned through an angle by an adjacent curved surface.

(d) Tip clearance loss – near the rotor blade tip the gas does not follow the intended path, fails to contribute its quota of work output, and interacts with the outer wall boundary layer."

Traditionally there has been a tendency to use cascade data for the main stream of the flow and correlation-based approaches for flows in the wall region where interactions between the end-wall and a passage vortex prevail. This approach has been refined as a result of the capabilities of modern computers. Whilst the computational approach has enjoyed some success the cascade approach in the main stream has more recently been neglected. The objective of this paper is to demonstrate that the physics of much of the blading is worthy of closer attention. This includes blade wake regions, often with unsteady phenomena such as suction surface flows and shock interactions.

Most of the experimental work described here was performed on the tri-sonic turbine cascade at the National Research Council of Canada (Figure 1). This Ottawa (CNRC) facility is amply described elsewhere [2, 3, 4]. The approach of this new presentation is more phenomenological and is focused on the results and their implications.

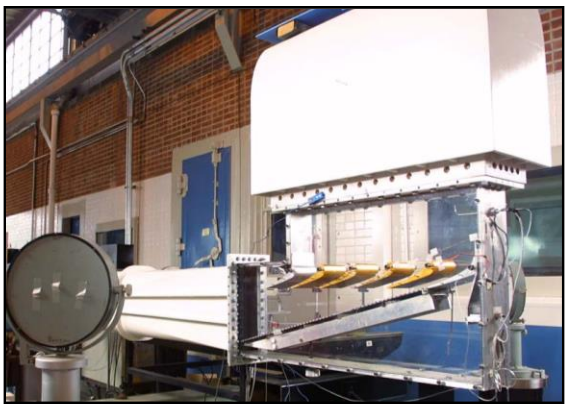

Figure 1 The Transonic Turbine Cascade Tunnel

1. SUBSONIC FLOWS

High pressure turbines, having low aspect ratio blading, may be affected by substantial secondary flow losses. On the other hand low pressure turbines, having high aspect ratio blading, can be expected to sustain high mid-span losses.

Bodies having a blunt trailing edge are likely to shed vortices in a von Kármán vortex street. Trailing edges are often blunt for blade cooling and stressing reasons; this may incur a high loss penalty. Awareness of vortex shedding, in most flow regimes, is essential to minimize the adverse impact of energy separation and base drag. The loss penalty is greater than might be expected from a simple backward facing step and remained unexplained until high speed schlieren photography was used on cascades of blades. The high losses were clearly associated with the vortex shedding. The purpose of this paper is to raise awareness of some features in blading aerodynamics that are not yet clearly understood.

1.1 Energy Separation in Subsonic Blade Wakes

In 1943 Eckert and Weise [5] observed that the surface temperature over the rear portion of a circular cylinder in cross flow dropped by as much as 20°C compared with the upstream total temperature, resulting in a negative recovery factor. These findings were substantiated in the time-averaged experiments of Ryan [6] suggesting that vortex shedding from the bluff bodies might be responsible for the phenomenon. Further work by Eckert and subsequently by Kurosaka *et al.* [7] and Ng *et al.* [8] provided further evidence for the Eckert-Weise effect. This is now referred to as ‘energy separation’ when dealing with the relationship between wake temperatures and vortex shedding. A further confirmation has been provided in highly resolved computational work by Hummel [9] predicting temperature variations across a turbine blade wake that agree closely with results presented in this paper. Similar total temperature redistributions were observed in both planar and annular cascades. The vortex shedding effects described here are equally applicable to annular cascades and are likely to be present in both circular cylinders and rotating machines.

It is argued that von Kármán vortex shedding is the principal cause of both the deficit in subsonic base pressure and the related energy separation in the wake. Subsonic base pressures and Eckert-Weise energy separation are principal manifestations of the same phenomenon. Both are a direct result of von Kármán vortex shedding. A non-uniform total temperature distribution has been observed in the wake of a circular cylinder. This also occurs downstream of turbine blades with thick trailing edges. This was investigated on a time-average basis by Carscallen and Oosthuizen [10] and on a time-resolved basis by Carscallen *et al.* [2] and Gostelow *et al.* [3, 4].

While good progress has been made experimentally and computationally, that is mainly confined to subsonic flows. This paper will indicate that further work is required both for subsonic flows and for supersonic flows. This includes anomalous vortex shedding that extends well beyond Eckert’s original discovery for circular cylinders and subsequent consideration of turbine blade flows. There is scope for more analytical and computational work. The experimental discoveries not only serve to provide test cases for ongoing computational work but will also shed light on the important physics of trailing edge and wake flows.

The objective of an early collaboration between Pratt and Whitney, Canada and the CNRC was to produce a gas generator for the PT6 engine with an aggressive turbine design. The single-stage, highly-loaded, high flow turning transonic turbine had a low wheel speed and was designed for a stage pressure ratio of 3.8 and stage loading of 2.5. This program was supported by a cold flow turbine rig that was three times engine size and matched the engine Mach and Reynolds numbers at design condition. Rig testing was carried out over a range of exit Mach numbers between 0.67 and 1.2.

During testing, the turbine stage gave some inexplicable results with a redistribution of the downstream total temperature field. In this ostensibly adiabatic arrangement the vane wakes exhibited a significant decrease in total temperature and their edges showed an unexpected increase. In order to resolve these anomalous results and obtain more mid-span section of this high pressure turbine nozzle was tested in a large scale, low aspect ratio transonic planar cascade. The turbine nozzle profile had a 5.4mm thick trailing edge. Schlieren imaging at high subsonic speeds showed intense von Kármán vortex shedding from this blading. It was clear that the wake energy redistribution was associated with the vortex shedding.

Downstream wakes, at the mid-span of the cascade middle vane, were traversed with fast response temperature and pressure probes to quantify any entropy increase. 'Hot spots' of increased total temperature were discovered at the edge of the wake and 'cold spots' of decreased total temperature were located close to the wake center line. The non-uniform downstream total temperature and total pressure distributions were a source of entropy production, and hence of additional loss.

At high subsonic speeds, the thermo-acoustic effect of energy separation was present. At the outer edges of the wake the stagnation temperature was 5^{o}C higher than that of the incoming fluid whilst on the wake center line the stagnation temperature was 12°C lower than the incoming fluid. This time-averaged temperature separation was a manifestation of the Eckert-Weise effect [5].

Investigation of this phenomenon involved measuring time-resolved temperature variations within the fluctuating wake and relating these to the previously observed time-average total temperature variations. Hitherto attempts to obtain such time-resolved measurements had been limited by the inadequate bandwidth of the available temperature instrumentation.

Using innovative wide bandwidth temperature probes from Oxford University [11] the anticipated fluctuations were detected. The frequency of vortex shedding temperature from the blades was of the order of 10 kHz and it was considered necessary to make total temperature measurements with a bandwidth approaching 100 kHz for the energy separation phenomenon to be resolved and identified. Phase-averaged contours of total temperature and pressure were constructed from simultaneous fast-response measurements of the quartz rod mounted thin film gage, and a Kulite pressure transducer respectively.

From these measurements, contours of time-resolved entropy increase at the measurement location, downstream of the trailing edge, were calculated from the Gibbs' entropy relation:

$$s_2 - s_1 = C_p \ln\left(T_{02}/T_{01}\right) - R\ln\left(p_{02}/p_{01}\right) \qquad (1)$$

States 2 and 3 are taken to be the inlet and downstream measuring planes respectively. As an example the total temperature contours are shown in Figure 2 and the entropy contours in Figure 3 for *Ma* = 0.95. Positive y values refer to the suction surface and negative y values the pressure surface. The relatively cool vortical structures on the wake centerline are seen, as are the hot spots on the edge of the vortex wake. The entropy plot of Figure 3 shows that the entropy generation is more or less concentrated in the wake center region resulting from the coalescence of the suction surface and pressure surface boundary layers. The hot spots of Figure **2** are essentially outside of this entropy-laden wake.

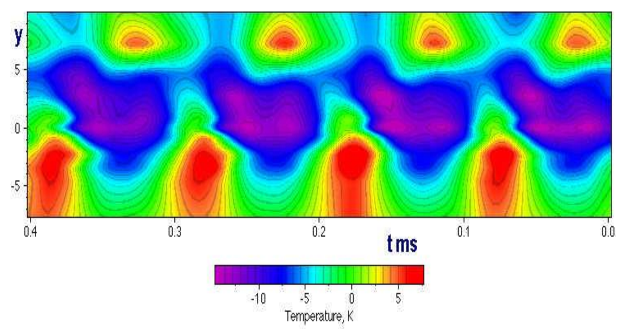

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Figure 2 Time-resolved temperature contours

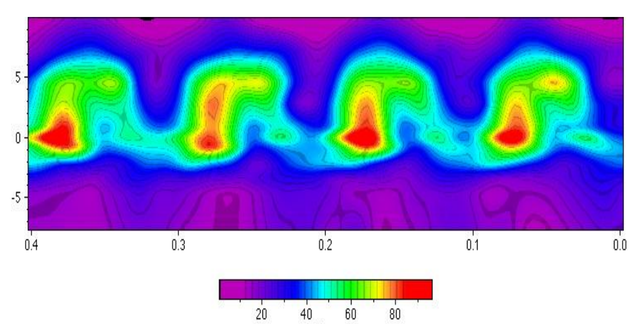

Figure 3 Time-resolved entropy contours downstream of the cascade trailing edge.

The separation of total temperature and pressure is essentially an inviscid process, related by equation (1). The cold spots between the hot spots are expected from the conservation of total energy, resulting in the unavoidable overlapping of the cold spots with the wake core. An indication was that the time-averaged measurements were in agreement with previous thermocouple measurements showed very good agreement. The vortex shedding fluctuations were in excellent agreement with the time-averaged measurements.

1.2 Base Pressure Losses on Subsonic Blades

The base pressure is strongly dependent on Mach number. At subsonic speeds, shocks only begin to play a role as the velocity reaches critical levels. In general, the unsteady process of vortex shedding is more important. At supersonic speeds, the main cause of low base pressure is the strong spatial progression of pressure through shocks and expansions. There are therefore two distinct compressibility regimes.

The highest base pressure losses coincided with the strongest wake energy separation. The experimental results indicated that, at subsonic speeds, energy separation and base pressure deficit were caused by vortex shedding. Coincidence was observed between the most active vortex-shedding behavior and the strongest energy separation and base drag.

At subsonic speeds vortex shedding is the principal cause of a base pressure deficit. Turbine blades with thick trailing edges have an area of reduced static pressure creating a considerably increased base drag, reducing the efficiency of the blading. Cicatelli and Sieverding conducted an investigation into the effect vortex shedding had on the base region flow [12]. They 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. Fluctuations in base region pressure indicate that the instantaneous base pressure could differ from the time-averaged value; this inadequate representation resulted in poor computational results if steady state methods were used. Time-resolved pressure distributions give information on fluctuations and corresponding drag coefficients. Computations for design using steady state methods will be erroneous for much of the vortex shedding cycle. MacMartin and Norbury 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" [13].

At subsonic speeds the unsteady vortex-shedding process is the most important cause of base drag; a relationship that was investigated in the measurements. For subsonic speeds, low pressures at the trailing edge are an essential facet of the vortex shedding process resulting in increased drag for bluff bodies and turbine blades. Base pressures were measured at the extreme trailing edge of the turbine blades. The results were supplemented by earlier results obtained by Carscallen and Oosthuizen [10] who presented contour plots of time-averaged total temperature differences between the inlet and outlet gas streams and total pressure loss coefficients for three isentropic exit Mach numbers. The similarity between the contour plots of time averaged total temperature difference and loss coefficient indicated a strong correlation between both phenomena.

2. UNSTEADY FLOW EFFECTS

A significant temperature variation across the wake involves the impingement of shock and expansion waves and this can be a steady flow effect. However other modes in the wake are possible. These include von Kármán vortex shedding from the confluence region of the wake. This is not the only form of shedding and at times anomalous (or "exotic") vortex shedding plays an important role. Intrinsic to many axial flow turbomachines is consideration of the effects of compressibility. Both subsonic and supersonic speed ranges are considered in this investigation. Subsonic surface base pressures, and wake energy separation are principal manifestations of the same phenomenon and are a direct result of periodic von Kármán vortex shedding (Figure 4). This is the principal cause of both wake energy separation and the related subsonic static pressure deficit.

At high subsonic speeds the wake flow was supposedly isothermal. Instead a 17^{o}C temperature difference between the wake outer edge and its center line was observed. This time-averaged temperature separation was a manifestation of the energy separation (Eckert-Weise) effect.

Both subsonic and supersonic speed ranges were considered in this investigation. The subsonic flow past a turbomachine blade with a thick trailing edge is still not well predicted. This results from a lack of understanding of trailing edge flows. Subsonic surface base pressures, and energy separation in the wake, are principal manifestations of the same phenomenon. Both are a direct result of periodic von Kármán vortex shedding; this is the principal cause of both wake energy separation and the related subsonic base static pressure deficit. At the same high subsonic speeds vortex shedding was found to be the principal cause of a deficit in blade surface and wake static pressure. For turbine blades the increased base drag deficit results in a considerable area of reduced static pressure and a consequent reduction in blading efficiency.

The principal cause of unsteady flow was von Kármán vortex shedding and the vortex shedding frequency increased with Mach number. The highest base pressure losses coincided with the strongest wake energy separation. The experimental results indicated that, at subsonic speeds, energy separation and base pressure deficit were caused by vortex shedding. Coincidence was observed between the most active vortex-shedding behavior and the strongest energy separation and base drag.

It is argued that von Kármán vortex shedding is the principal cause of both the deficit in subsonic base pressure and the related energy separation in the wake. Subsonic base pressures and Eckert-Weise energy separation are principal manifestations of the same phenomenon. Both are a direct result of von Kármán vortex shedding. At supersonic speeds, both base pressure deficit at the trailing edge and anomalous energy separation in the downstream wake exhibit some different phenomenological characteristics from the subsonic behavior and need to be treated differently. Vortex shedding may still be present but is governed by strong pressure forces across the wake rather than from the blade itself. At supersonic speeds shock waves from a blade trailing edge may impinge on the adjacent suction surface and adversely affect the downstream boundary layer. The physics of supersonic flows specifically involves shock and expansion waves; these flows, and anomalous vortex shedding, need particular awareness and treatment.

Energy separation and base pressure, and their strong interactions, have been observed in subsonic bluff body flows whenever suitable techniques were deployed. At supersonic speeds anomalous vortex shedding modes were in good agreement with computational predictions.

Awareness of vortex shedding in all flow regimes is essential to minimize the adverse impact of energy separation and base drag. The purpose of this paper is to raise awareness of some features in blading aerodynamics that are not yet clearly understood.

3. SUPERSONIC FLOWS

At the sonic condition vortex shedding may still be present but is governed by strong pressure forces across the wake rather than from the blade itself. Both base pressure deficit at the trailing edge and anomalous energy separation in the downstream wake exhibit some different phenomenological characteristics from the subsonic behavior and need to be investigated and treated differently.

3.1 Transonic and Supersonic Flows

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, as shown in Figures 4 and 5. Only free-stream disturbances are effective in provoking the vortex shedding instability. The lateral distance between the incipient vortices at the downstream location is shortened. Observed Strouhal numbers need to be based on these shorter distances for supersonic flow. Based on the CFD results, the shedding frequency was predicted to increase; the effective length of the shear layers was clearly reduced and the shedding frequency was increased.

An increase in Reynolds number brings transition to the primary laminar separation line in an

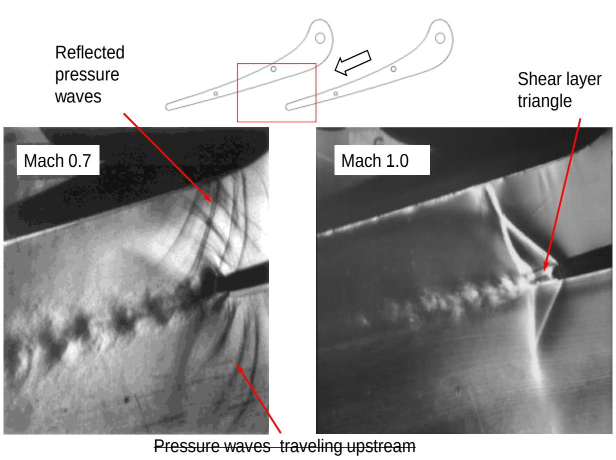

Figure 4 Subsonic and Transonic Schlierens

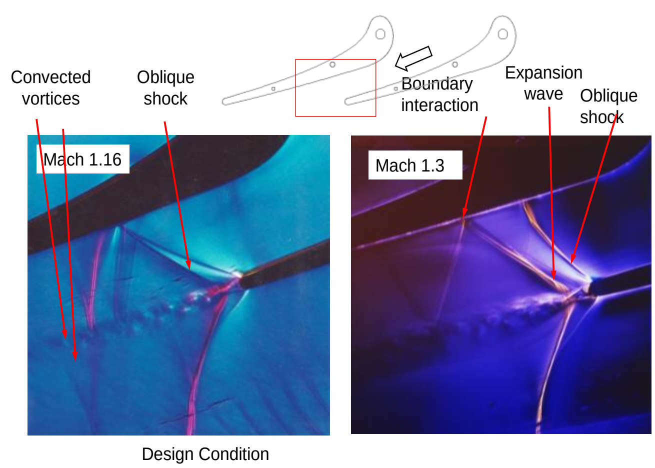

Figure 5 Transonic and Supersonic Schlierens

irregular manner. This leads to the disruption and fragmentation of separation bubbles along the span. The irregularly fragmented separation line prevents vortex separation. This absence of vortex shedding permits a high level of pressure recovery. At the sonic condition vortex shedding may still be present but is governed by strong pressure forces across the wake rather than from the blade itself.

3.2 Energy Separation on Turbine Blades at Supersonic Speeds

At supersonic speeds both base pressure deficit at the trailing edge and energy separation in the downstream wake exhibit some different phenomenological characteristics from the subsonic behavior. Vortex shedding may still be present but is governed by strong pressure forces across the wake rather than from the blade itself.

At supersonic speeds shock waves from a blade trailing edge may impinge on the adjacent suction surface and adversely affect the downstream boundary layer. The physics of supersonic flows specifically involves shock and expansion waves; these flows, and various unsteady interactions, need particular awareness and treatment.

As the discharge Mach number becomes supersonic the trailing edge shocks become oblique. In addition the wake behavior downstream of the trailing edge at supersonic speeds is entirely dependent on the confluence region. The shedding origin of the vortex street migrates from the trailing edge to the confluence of the two trailing edge shear layers. Only free-steam disturbances are effective in provoking the vortex shedding instability. The lateral distance between the incipient vortices at the downstream location is shortened. Observed Strouhal numbers need to be based on these shorter distances for supersonic flow. Based on the CFD results, the vortex shedding frequency was calculated to increase from 7.91 kHz at Ma=0.7 to 13.91 kHz at an exit Mach number of 1.16. The effective length of the shear layers was clearly reduced and the shedding frequency was increased.

3.3 Base Pressures on Turbine Blades at Supersonic Speeds

A detrimental flow phenomenon affected by vortex shedding is low base pressure. Blades with thick trailing edges have an area of static pressure deficit in the trailing edge region. This creates a considerable increase in base drag at subsonic speeds and reduces the blade row's efficiency.

Sieverding *et al.* [14] 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. Instantaneous base pressures could differ significantly from the time-averaged value.

The base pressure is strongly dependent on the Mach number. 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. 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. At supersonic speeds, the main causes of low base pressure are the strong spatial variations of pressure through shocks and expansions. These are therefore two distinct compressibility effects.

Denton and Xu [15] and Mee *et al.* [16] showed that a significant proportion of the total loss at high speeds could be attributed to the base pressure. Carscallen *et al.* [2] found that a strong base pressure deficit was accompanied by the strongest amplitude of vortex shedding. Motallebi and Norbury [17] measured the base pressure and shedding frequency over a range of Mach numbers and found that a large drop in base pressure was accompanied by an increase in shedding frequency. The most comprehensive base pressure correlation is that of Sieverding *et al.* [14].

Experimental and analytical work on a high speed planar cascade was examined to obtain a clarification of the various processes. The turbine blades had a blunt trailing edge; hot spots were detected at the edges of the wake and cold regions were located close to the wake centerline. Vortex shedding frequency increased with Mach number. The highest base pressure losses coincided with the strongest wake energy separation. The analysis indicated that, at subsonic speeds, energy separation and base pressure deficit were caused by vortex shedding. Coincidence was observed between the most active vortex-shedding behavior and the strongest energy separation and base drag. Energy separation and base pressure, and their strong interactions, have been observed in subsonic bluff body flows whenever suitable measurement techniques were deployed.

3.4 Anomalous Vortex Shedding

Awareness of vortex shedding in all flow regimes is essential to minimize the adverse impact of energy separation and base drag. At the sonic condition vortex shedding may still be present but is governed by strong pressure forces across the wake rather than from the blade itself. Both base pressure deficit at the trailing edge and anomalous energy separation in the downstream wake exhibit some different phenomenological characteristics from the subsonic behavior and need to be treated differently.

Similarities between the vortex shedding structures occurring in low speed oscillating cylinder and airfoil flows and transonic cascade flows suggest that the existence of an oscillating body is not a fundamental requirement. The wake instability can be caused by an oscillating flow mechanism and it is argued that the pressure field associated with the trailing edge shocks exerts the fluctuating lateral force which is essential for the vortex shedding process at transonic and supersonic speeds.

Findings, from flow visualization, computational work and a separate hydraulic analogy experiment, have shown the shock - wake interaction structure at the confluence of shear layers to be particularly dynamic. As a result an oscillatory flow is set up causing the observed changes in vortex shedding. It is therefore interesting that the vortex wake shed by an oscillating cylinder reveals a similar behavior. Williamson and Roshko [18] identified several vortex-shedding modes as a function of wavelength and amplitude of oscillation.

It is also clear that the classifications provided by the observations of Williamson and Roshko, and the theory of Ponta and Aref [19], have the potential to be useful not only for the field of vortex-induced vibration but also to classify problems involving both stationary and oscillating airfoils and turbine blades at transonic speed.

Parallels can be found in the behavior of elastically-mounted circular cylinders and the caudal fin oscillation propelling fish. For supersonic flows shock waves from a blade trailing edge may impinge on the adjacent suction surface adversely affecting the downstream boundary layer. The physics of supersonic flows specifically involves shocks and expansions; these flows, and exotic vortex shedding, need particular awareness and treatment. von Kármán vortex shedding may still be present at supersonic speeds but its inception, shape and frequency will differ from the more usual configurations encountered at subsonic speeds.

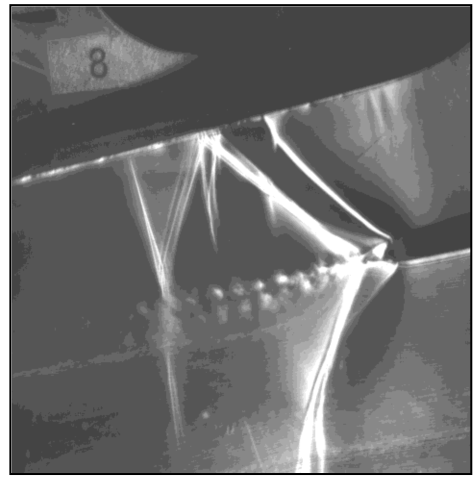

Figure 6 Shedding of Couples at *Ma* = 1.07

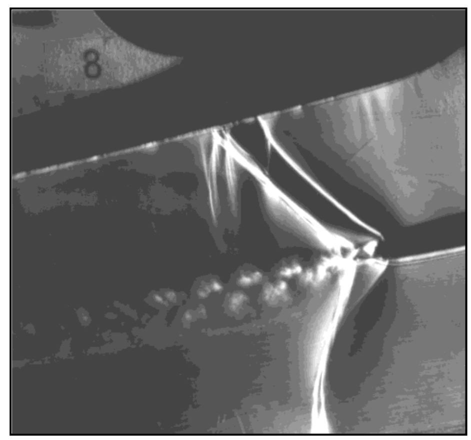

Figure 7 Shedding of Doublets at *Ma* = 1.07

4. DISCUSSION

At subsonic speeds there is reasonable agreement and steady growth. As soon as the discharge flow becomes supersonic there is a very steep drop in temperature difference and loss coefficient.

The paper has concentrated on providing an indication of progress on base pressure and energy separation rather than any attempt to produce universal correlations. The focus has been on providing detailed information and physical explanations and to demonstrate the energy separation phenomenon.

The question posed at the beginning was whether there is a connection between the two phenomena of base pressure and energy separation. At subsonic speeds the link between the two is von Kármán vortex shedding.

In addition to the observations on turbine blading time-resolved pressure distributions gave information on the location and strength of surface pressure fluctuations on a circular cylinder. The presence of areas of reduced and increased total pressure and total temperature have been measured in the wake of a circular cylinder in cross flow at a high subsonic Mach Number. Results from the circular cylinder tests were in excellent qualitative agreement with those from the turbine blading. This all took place at a significantly lower cylinder Mach Number than that from the blading. By itself this provides the first time-resolved experimental proof of the existence of energy separation in the wake of circular cylinders in compressible cross flow.

At supersonic speeds in turbine blading the von Kármán vortex street was found to be but one of a number of transient shedding patterns. In addition to the classical von Kármán shedding, patterns designated as “couples” and “doublets” were found (Figures 6 and 7). Although these modes are similar to others observed in the wake of oscillating cylinders and plunging airfoils none of these additional transonic modes are explained by conventional stability theory.

In addition the wake behavior downstream of the trailing edge at supersonic speeds is entirely dependent on the confluence region of couplets and doublets in addition to the conventional vortex shedding and any others that may appear makes the wake behavior title “exotic” quite appropriate. Likewise the wake behavior at supersonic speeds also displays energy separation. When dealing with these phenomena the experimental modeling approach is still the most appropriate.

5. CONCLUSIONS

Intrinsic to many axial flow turbomachines, compressibility effects need to be considered. Both subsonic and supersonic speed ranges were considered. The subsonic flow past a turbomachine blade with a thick trailing edge is still not well predicted. Subsonic surface base pressures, and energy separation in the wake, are principal manifestations of the same phenomenon. Both are a direct result of periodic von Kármán vortex shedding. Vortex shedding is the principal cause of both wake energy separation and the related subsonic base static pressure deficit.

Subsonic surface base pressures, and wake energy separation are principal manifestations of the same phenomenon and are a direct result of periodic von Kármán vortex shedding. This is the principal cause of both wake energy separation and the related subsonic base static pressure deficit.

Testing was undertaken over a wide range of subsonic speeds; the wake flow was supposedly isothermal. Instead a 17°C temperature difference between the wake outer edge and its center line was observed. Time-averaged temperature separation was a manifestation of the energy separation (Eckert-Weise) effect. The thermo-acoustic energy separation process was at its strongest under these conditions.

At supersonic speeds the trailing edge base pressure, and the energy separation in the downstream wake, will exhibit different characteristics from the subsonic behavior and should be treated differently. There is not the strong coupling between energy separation and base pressure behavior that developed for subsonic speeds. Supersonic flows usually involve the impingement of shock and expansion waves and this can be a steady flow affecting the downstream boundary layer. Shock waves from a blade trailing edge may impinge adversely. Vortex shedding may occur from the confluence region of the wake.

This is not the only form of shedding; at times anomalous (or “exotic”) vortex shedding was observed and other wake modes are possible. Nevertheless the periodic unsteadiness that was important for wake behavior in subsonic flows cannot be ignored.

NOMENCLATURE

C_p : specific heat at constant pressure
Ma : isentropic exit Mach number
R : gas constant
p : pressure
s : entropy
t : time
T : temperature
y : transverse distance
Subscripts:
s : static
0 : stagnation value

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