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Turbine Endwall Aerodynamics and Heat Transfer

T. W. Simon and J. D. Piggush
University of Minnesota, Minneapolis, Minnesota 55455

This review addresses recent literature on turbine passage aerodynamics and endwall heat transfer; articles that describe the endwall flow and cooling problems are summarized, recent activity on improving endwall aerothermal design is discussed, improved cooling schemes are proposed, and methods for managing secondary flows to allow more effective cooling are suggested. Much attention is given to aerodynamic losses associated with secondary flows developed near the endwalls. The endwall region flowfield is influenced by the stagnation zones established as the endwall approach flow boundary layer meets the airfoil leading edges, by the curvature of the passages, by the steps and gaps on the endwall surface ahead of and within the passage, by the leakage and coolant flows introduced through the endwall surface ahead of and within the passage, by the tip leakage flows between the blades and shroud in the rotor endwall region, and by many more effects. Recent combustor redesigns have flattened the turbine inlet temperature profile and have raised the turbine inlet temperatures. This, coupled with a continued need to improve engine durability and availability, has spurred strong interest in thermal control of the turbine endwall regions. Thus, much of the literature presented herein is focused on endwall cooling and, in particular, the effects of near-endwall secondary flows on endwall cooling.

I. Introduction

THE turbine of a gas-turbine engine presents designers with many challenges. Temperatures can be extremely high, approaching 1600°C, while the gases moving through the engine create large forces on all surfaces, particularly those that turn the flow. To maximize engine performance and cut engine losses, care must be taken to guide the fluid through turbine passages in such a way that secondary flows are kept to a minimum. The need to cool turbine surfaces compounds the problem. Efficiency, durability, and environmental considerations challenge designers to improve engines with techniques that are based on the physics of the complex passage flows. Experimental and theoretical research focuses on general understanding of flowpath phenomena as they relate to flow losses and cooling effectiveness values. One particular area of interest is the study of flow near the passage endwalls and heat transfer on the endwalls. This area is the focus of the present review paper.

II. Endwall Aerodynamics

Early efforts, including those in 1954 by Herzig et al.,[1] identified a dominant passage flow that crosses from the pressure surface to the suction surface in the endwall boundary-layer fluid (see Fig. 1), driven by the pressure difference between the pressure and suction surfaces. The size and strength of this flow, known as the passage secondary flow, are dependent on the amount of turning of the mainstream. A second important study of passage flows considers three-dimensional separation of flow at the junction between a protruding body and a wall. The flow ahead of the junction has a velocity gradient (and therefore a dynamic pressure gradient) normal to the endwall because of the presence of an endwall approach flow boundary layer. When the flow stagnates, the total pressure gradient becomes an endwall-normal pressure gradient. Boundary-layer fluid on the protruding body, driven by this pressure gradient, is forced toward the endwall where it migrates upstream slightly as it is rolled into a vortex upstream of the leading edge (see Fig. 2). This vortex is commonly referred to as the horseshoe vortex. Detailed studies of this flow are available in Pierce and Harsh,[2] Eckerle and Langston,[3] Pierce and Shin,[4] and Goldstein and Karni.[5] The interaction of these two main secondary flows, the passage flow and the horseshoe vortex, along with smaller secondary flows, such as corner vortices, which occur in the corner between adjoining walls, and the vortices induced by the horseshoe vortex make the passage secondary flowfield quite complex.

Many studies that highlight the main features of the passage flowfield have been presented, including those by Langston et al.[6] and Langston[7] (see Fig. 3). They describe the location of a single separation saddle point on the endwall. It is just downstream of the inlet plane and about 20 to 50% of the pitch distance when moving from

Terry Simon has been a faculty member in the Mechanical Engineering Department at University of Minnesota since 1980. His research is on steady and unsteady, turbulent and transitional, single- and two-phase flows and heat transfer. These include boundary layers, channel flows and flows through porous media. Applications include gas turbines, Stirling engines, cooling of electronics and heat transfer in manufacturing. He received his B.S. in mechanical engineering from Washington State University, his M.S. in mechanical engineering from the University of California at Berkeley and his Ph.D. in Mechanical Engineering from Stanford University. His industrial experiences include positions at the General Electric Company Nuclear Energy Division and the Stearns-Roger Architectural Engineering Company (now Praxair Inc.). Professor Simon is a Fellow of the ASME and a member of AIAA. He is also a registered Professional Engineer in the State of Colorado.

Justin Piggush received a Bachelor's (2001) degree in Philosophy from St. John's University of Collegeville, MN and Bachelor's (2004) and Master's (2005) degrees in Mechanical Engineering from the University of Minnesota. While pursuing his Master's degree he studied endwall heat transfer and fluid dynamics in support of his thesis "An Experimental Investigation of Endwall Leakage Flows and Misalignment in a Gas Turbine Nozzle Guide Vane Cascade." He is currently employed at Pratt and Whitney Turbine Module Center as an Aero/Thermal Engineer.

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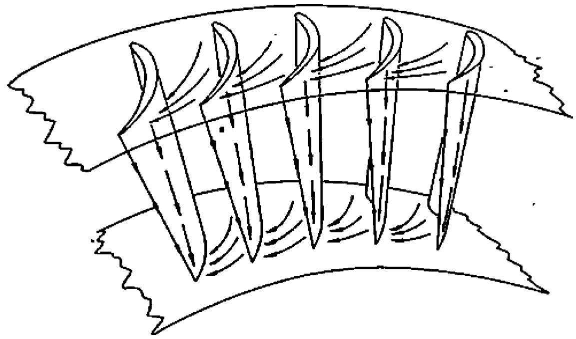

Fig. 1 Endwall secondary flows according to Herzig et al.[1]

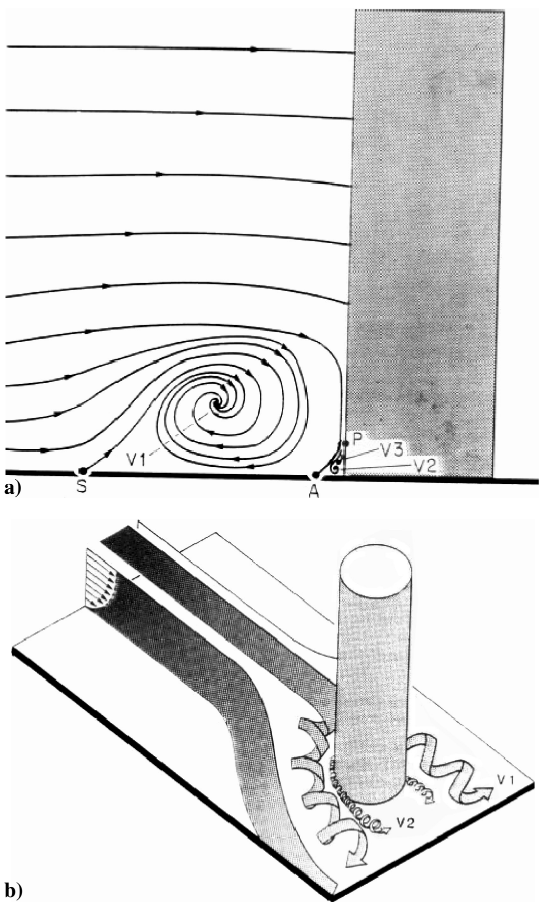

Fig. 2 Secondary flow structure at the junction between a right circular cylinder and an endwall: a) horseshoe vortex at the plane of symmetry (upper figure) and b) incoming boundary layer and trailing vortices. S and P are separation points, A is an attachment point, and V indicates a particular vortex (from Goldstein and Karni[5]).

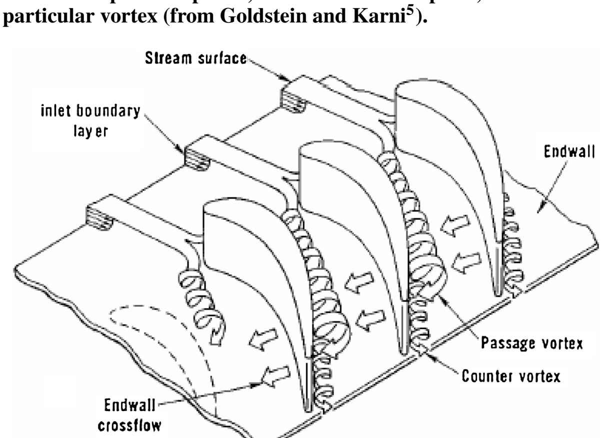

Fig. 3 Passage secondary flows according to Langston.[7]

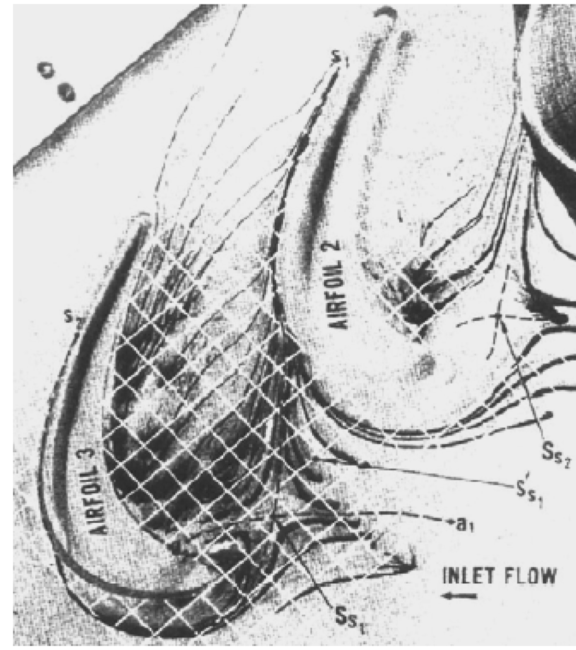

Fig. 4 Endwall secondary flows within a rotor passage. Saddle points are indicated as S_s, separation lines are s_1-S_{s1} and s_2-S_{s1}, and attachment lines are a_1-S_{s1} and a_2-S_{s1} (Langston et al.[6]).

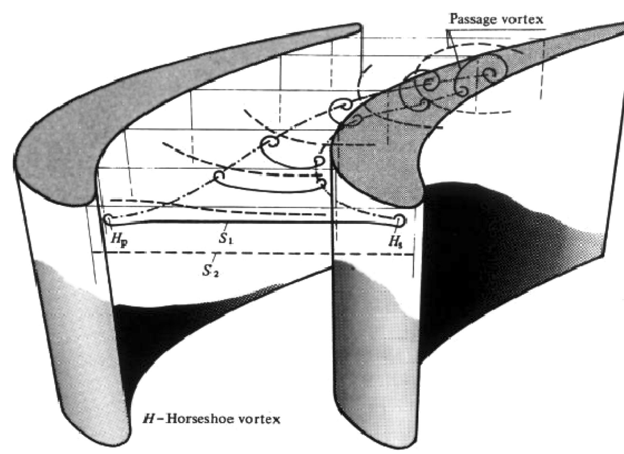

Fig. 5 Secondary flows according to Sieverding and Van den Bosche.[8] The S denotes a stream surface.

the pressure side to the suction side. This can be seen in Fig. 4. Between the saddle point and the junction between the airfoil leading edge and the endwall, a horseshoe vortex similar to those just described is created. One side of the vortex traverses the passage moving toward the suction surface of the neighboring airfoil. Langston's group proposed that the passage flow becomes one with the pressure side leg of the horseshoe vortex, greatly augmenting this leg's strength as it moves through the passage. The detailed passage measurements of Langston et al.[6] also indicate that the inlet boundary layer separates and a new boundary layer forms within the passage downstream of the separation line. The observed boundary layer at the throat of the passage is consequently very thin.

In a low-Reynolds-number study in which colored smoke was used to mark the flow, Sieverding and Van den Bosche[8] observed the secondary flowfield previously measured. In addition to causing augmentation and migration to the suction side of the pressure side leg of the horseshoe vertex, the passage flow causes the whole of the stream surface to rotate (see Fig. 5). This rotation, now referred to as the passage vortex, tends to entrain flow originally outside of the horseshoe vortex system into the horseshoe vortex structure and increases the portion of the passage affected by secondary flows.

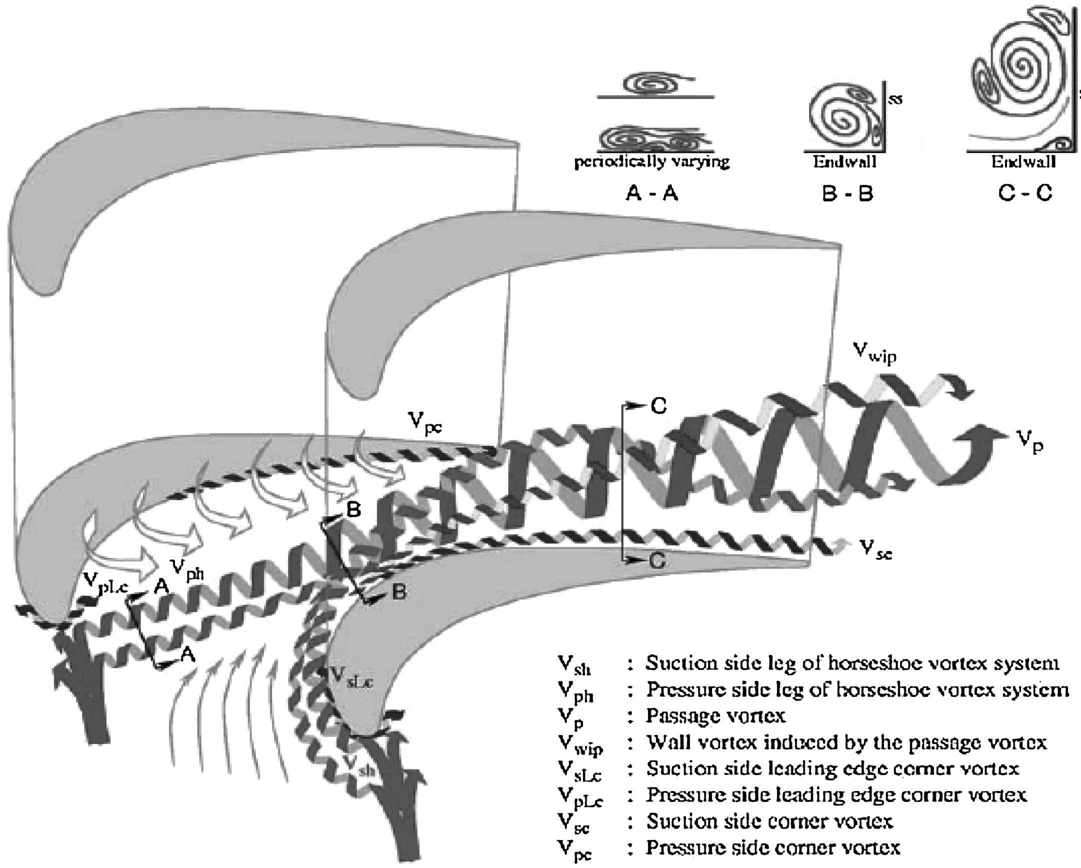

Fig. 6 Turbine passage secondary flows (Wang et al.[11]).

Kawai et al.[9] clarified the passage secondary flow picture using carefully executed endwall oil-film shear-stress direction studies. In addition to identifying all major separation and reattachment lines within the passage, they confirmed many of the observations made by Langston and added new information. First, the single separation saddle point was confirmed. Secondly, the pressure side of the horseshoe vortex was observed to roll up into the passage vortex, an Oseen vortex at its core. The suction side of the horseshoe vortex was shown to have moved up the suction surface and to dissipate as it moves through the passage. Important corner vortices on the pressure side, beginning at the airfoil leading edge, and on the suction side, beginning where the pressure side horseshoe vortex separation line intersects the suction side of the airfoil, were also noted.

This secondary flow picture was confirmed by Chung and Simon[10] and Wang et al.[11] Additionally, a small but strong vortex was observed in the flow beginning at the intersection of the pressure side horseshoe vortex with the suction side of the airfoil. It resides above the passage vortex and rotates in the opposite sense. Also, the time dependency of the horseshoe vortex was noted. At some instances, two vortices that merge into one as they move through the passage are formed. Otherwise, only a single horseshoe vortex is present. From these works, and others, a rather clear picture of the straight (noncontoured) endwall secondary flow structure has emerged (see Fig. 6). Several review articles dealing with cascade secondary flows are available, including those of Langston[12] and Sieverding.[13]

A. Contoured Endwall Aerodynamics

One method used for minimizing secondary flow losses is to accelerate the endwall boundary-layer fluid as it approaches the airfoil leading-edge plane, or as it moves through the passage, or both. The favorable pressure gradient in conjunction with the decreasing passage area tends to thin the endwall boundary layer and reduce secondary flow strength. One can accomplish this thinning by contouring one endwall, or both endwalls. Contouring can be either axisymmetric or nonaxisymmetric. Though the cascades discussed next are mostly linear cascades, the term "axisymmetric" is used with reference to the engine geometry.

Several studies have used axisymmetric endwall contouring. One of the initial studies was that of Deich et al.[14] who investigated stages of very low inlet aspect ratios (0.29–0.54) and large-area contractions. The reduction of loss inspired the work of others on cascades of larger aspect ratios. These include the geometry of Morris and Hoare[15] who found that axisymmetric contouring of one endwall could significantly reduce losses in the vane stage, particularly for passages of low aspect ratio. They found that most of the loss reduction was on the noncontoured (straight) wall. They surmised that loss reduction was the result of a general redistribution of the airfoil pressure profile as a result of endwall contouring. Flow curvature on the contoured endwall might have prevented realizing the large loss reduction observed on the noncontoured endwall. They included cases with nonaxisymmetric profiling that were generally unsuccessful. For those nonaxisymmetric cases, losses near the nonprofiled wall were reduced, and losses on the profiled wall were significantly increased. The endwall curvature of the nonaxisymmetric profile contorted the airfoil wake and created a thick region of high loss near the profiled endwall. This loss distribution is quite different from those observed with the axisymmetric profiling. Their study showed that care must be taken in endwall profiling for the consequences of contouring are difficult to predict. This was a low-Mach-number study: a later study at higher Mach numbers by Kopper et al.[16] confirmed a reduction of secondary losses by contouring. Studies by Boletis[17] and Arts[18] presented measurements and numerical analyses documenting momentum deficits caused mainly by the legs of the horseshoe vortex and the passage flow. Dossena et al.[19] performed a similar study. They noted that the vortex structure on the flat endwall is similar to that for a straight-walled cascade, though the secondary flow strength is reduced near the flat endwall. They stated that "On the profiled endwall, the contraction inhibits the formation of a proper passage vortex and its migration toward midspan; this is the result of intense vortex stretching due to the local acceleration. . . ." The study of Burd and Simon[20] characterizes the flowfield of a cascade with endwall contouring. Streamwise and cross-stream velocities, turbulence and velocity fluctuations, Reynolds shear stresses, total pressure losses, and kinetic energy losses are all presented and discussed.

The complex profiles of nonaxisymmetric contoured endwall geometries are typically designed with the assistance of computational fluid dynamics (CFD). Representative studies in this category include those of Rose,[21] Harvey et al.,[22] Hartland et al.,[23] Yan et al.,[24] Brennan et al.,[25] and Rose et al.[26] The first study, that of Rose,[21] was designed to reduce the pitchwise pressure gradient at the exit of the nozzle guide vanes. Uniform static pressure in this region allows better distribution of rim seal coolant at the junction of the nozzle guide vane and blade section. Rose found that some nonaxisymmetric endwall profiles were successful in reducing static-pressure nonuniformity by as much as 70%. The pair of studies by Harvey et al.[22] and Hartland et al.[23] outlines a computational design method and experimentally checks the results for a nonaxisymmetric profile specifically designed to reduce exit angle nonuniformities. The experimental study confirmed the expected reduction in angle nonuniformities and also produced a 30% reduction in secondary losses at the exit plane, which was not predicted by computation. The studies indicate that properly designed, nonaxisymmetric contoured endwalls lead to decreased secondary losses and reduced variations of flow deviation angles across the passage exit. Schobeiri et al.[27] demonstrated experimentally that a three-dimensional bowed blade design can reduce secondary flow losses.

B. Other Methods of Endwall Modification

Secondary losses can also be reduced through use of a boundary-layer fence.[28–30] The study of Kawai et al.[28] investigated fences of various heights and positions on the endwall. Their conclusion was that appropriately sized and positioned fences can be used to greatly affect the secondary flows within the passage. Flow underturning, secondary kinetic energy, and the thickness of the region of secondary flow vorticity may all be reduced. The studies of Chung et al.[29] and Chung and Simon[30] make use of a fence located on the endwall at midpitch of the passage. The fence was shown to obstruct the migration of the passage flow and turn the pressure side of the horseshoe vortex so that its axis is more in line with the freestream. This removes a mechanism that is responsible for rapid vortex growth, as will be discussed. In unfenced passages, circulation of the pressure leg of the horseshoe vortex is augmented (after it departs from the pressure side of the passage and begins to cross to the suction side) by the skewed endwall boundary-layer flow. The near-endwall portion of the endwall boundary-layer flow is moving toward the suction surface, whereas the flow in the upper reaches of the endwall boundary layer moves in the direction of the main flow within the passage. The pressure side of the horseshoe vortex embedded in this boundary layer is thus intensified by the high shear component normal to the horseshoe vortex axis and acting on the top of the vortex. When the fence lifts the vortex up into the main flow within the passage and turns the axis of the vortex in the direction of the main flow, the mechanism that augments the vortex strength is removed. As a result, the vortex is weaker when it reaches the downstream end of the passage and has been displaced off both the endwall and the suction surface. The magnitude of the passage vortex at the exit plane is greatly reduced by an appropriately positioned fence. The displacement of the vortex off the endwall and the suction surface reduces its augmentation of wall heat transfer and improves the opportunity for film cooling of the surfaces. Other fence designs make use of a small step at approximately the midpassage location (e.g., Kinnear et al.[31]) to produce vortices with rotation counter to the horseshoe vortex. In general, fences show good aerodynamic performance, reduced secondary losses, and decreased strength of the pressure leg of the horseshoe vortex. Unfortunately, the aerodynamic and heat-transfer benefits of having a fence are offset by problems associated with the high local heat-transfer rates on the obstructions (fences) inserted into the engine gas path.

Another method of reducing passage secondary flow, which bears some similarity to the boundary-layer fence studies, makes use of jets located approximately at the midpitch line of the passage. The jets are designed to divert the pressure leg of the horseshoe vortex so that the mainstream flow can carry it downstream. The study of Aunapu et al.[32] indicates some success using this technique. Migration of the pressure side of the horseshoe vortex is retarded, although the vortex is observed to not be significantly weakened. The overall effect is an increase in the passage secondary losses because of the added turbulence generated by the jets.

C. Off-Design and Time-Dependent Aerodynamics

Benner et al.[33] experimentally documented secondary flows under off-design conditions in a turbine cascade. They found that a larger leading-edge diameter gave larger secondary flow losses at off design, contrary to present design rules. They also found that secondary flow losses increased with incidence angle up to 10 deg, but failed to increase further for larger incidence angles, to 20 deg. Dossena et al.[34] measured in a steam turbine linear cascade the effects on secondary flowfields and losses of changing the incidence angle, the pitch-chord ratio, and the downstream Mach number. They noted that the incidence angle and the pitch-chord ratio were the most influential.

Schlienger et al.[35] took time-resolved measurements of the flowfield of a rotor and downstream stator passage to document the effects on the stator's secondary flowfield of advection of the rotor's secondary flowfield through the downstream stator's passage. A time-resolved description of the events was given, and it was noted that the redistribution of high loss fluid from the wake and vortices at the rotor hub influences a large portion of the stator's flow area.

D. Studies That Include Endwall Blowing (Film Cooling)

There is a wealth of recent literature available regarding the effects of film cooling and leakage flow on endwall region flow. Effects on the secondary flow of blowing through flat endwalls are first reviewed.

One of the pioneering studies investigating the effects of endwall blowing and the interaction of secondary flows and film cooling flow was by Blair.[36] Passage flows and the passage vortex within the cascade were the flows of primary importance in this study. The endwall boundary layers were removed just upstream of the vane leading edges. The location of transition on the endwall (without a fully developed boundary layer entering the passage, it was possible to trip the flow wherever transition was desired) and the location of film cooling injection through a slot upstream of the vane leading edge had little effect on the passage vortex. Heat-transfer data indicated that coolant flow is swept by the passage flow across from the pressure side to the suction side. The secondary flows within this cascade were not affected by the introduction of coolant flow.

The study of Granser and Schulenberg[37] indicates that coolant injected from a slot tends to reduce secondary flows by reenergizing the boundary layer. Coolant blowing (at a small angle to the endwall surface) adds significant streamwise momentum to the boundary layer to retard its growth downstream of the slot. Thinner endwall boundary layers produce less intense horseshoe vortices and weaker passage flows. Without a well-developed boundary layer, this effect was not seen in Blair's study.

Other studies focus on the complete secondary flowfield within the passage. Goldman and McLallin[38] found that coolant injection could have a significant effect, decreasing both passage loss and flow angle nonuniformity. A later study by Sieverding and Wilputte[39] discusses data taken with two double rows of discrete holes within the passage and a double row upstream of the leading edge. They conclude that the effects of coolant air on secondary flows are more pronounced than the effects documented in the Blair study. Reduction in losses and exit angle nonuniformity along the airfoil axis was confirmed. They suggest that injection of cooling air should be included in an optimal design, noting three important parameters that should be considered: "the coolant to mainstream total pressure ratio, the coolant mass flow ratio and the angles between the coolant flow, main flow and endwall boundary layer."

Work by Bario et al.[40] describes the aerodynamics of jets entering the main flow on the endwall of a turbine cascade. Cooling flow was shown to reduce secondary flow effects. Exit flow angles near the cascade endwalls were reduced with cooling jets. Harasgama and Burton[41] corroborate the findings of Sieverding and Wilputte[39] and Bario et al.[40] They note (as does Blair[36]) that cooling fluid does little for the pressure-side trailing-edge region because much of it is convected toward the suction side of the passage by the passage flow.

Biesinger and Gregory-Smith[42] note the positive effects on loss reduction of a skewed boundary layer at the inlet of an axial-flow compressor and then proceed to study similar effects within turbine rotor blading. Their cascade was designed so that coolant air is injected with momentum in the direction of the pressure surface to simulate the turbine rotor. The results of the study indicate that low blowing rates tend to thicken the boundary layer resulting in greater secondary flows and higher losses. At higher rates of injection, the streamwise vorticity of the coolant counteracts that of the secondary flow, and secondary kinetic energy can be reduced. At very high rates of blowing, the vorticity of the coolant flow persists to the exit and secondary losses increase. The effects of changing the blowing angle were also considered. The study shows that a lower angle of blowing, 20 deg, is more effective than a higher angle, 34 deg (both measured relative to the surface), possibly because cooling fluid does not separate from the wall when the injection angle is small. Also no net gain on aerodynamic performance is achieved when the energy needed to inject the coolant is included in the thermodynamic availability analysis.

Two studies performed by Friedrichs et al.[43,44] give a detailed description of the interaction of cooling flows with secondary flows. Surface flow visualization in the first study, Ref. 43, clearly shows that coolant injection through discrete holes located within and ahead of the passage changes the location of separation lines within the passage. The separation line for the horseshoe vortex appears closer to the leading edge while the separation line of the pressure leg of the horseshoe vortex as it crosses to the suction side appears further downstream. Flow from holes located upstream of the passage and 30% of an axial chord downstream of the leading-edge plane was observed to have the largest effects on secondary flows and was successful in delaying separation, reducing overturning at the passage exit and reducing losses associated with secondary flows. Flow from holes located at 60 and 90% x/C_{ax} downstream of the airfoil leading edges did not reduce secondary flows. Coolant from the holes at 90% x/C_{ax} was observed to thicken the exit boundary layer. The second study, Ref. 44, varied the injection rates from the holes. When injection ratios are high enough that the coolant stagnation pressure was higher than the freestream stagnation pressure, the cooling flow reenergizes the boundary layer, thereby reducing secondary flows and subsequent mixing associated with these flows. The optimum coolant supply pressure gives the coolant a similar streamwise velocity component to that of the freestream.

A study by Songling et al. used discrete holes placed upstream of the leading edge. In contrast to the Biesinger and Gregory-Smith study, they did not attempt to simulate a skewed inlet boundary layer. The results of this experiment generally confirm those of Biesinger and Gregory-Smith[42] with several added conclusions: 1) a decrease of the distance from the injection site to the leading edge or a decrease of the hole inclination angle reduces secondary flows, 2) attachment of the coolant can be improved through the use of a double row of injection holes, and 3) a forced passage vortex with rotation counter to that within the cascade could be created at high blowing ratios.

The geometry used in the study of Roy et al.[45] included three coolant injection ports located ahead of the leading edge of each vane. The coolant thus covered the area directly in front of each vane though not the area between the vanes. The coolant from these ports suppress the formation of the junction corner vortices.

Other important studies include those of Kost and Nicklas[46] and Knost and Thole.[47] Both studies investigate the combined effects of injection from slots and holes. The first notes a strengthening of the horseshoe vortex when fluid is injected from an upstream slot. They suggest that this is because of the unique position of their slot relative to the saddle point of the flow on the endwall of the stator passage. In their study, the slot is placed just upstream of the saddle point. Injection is directly into the vortex and therefore increases the quantity of low momentum fluid that can be entrained by the horseshoe vortex. They also theorize that the wall-normal component of the injected flow increases the circulation of the horseshoe vortex. They suggest that moving the slot closer can actually decrease the vortex circulation. A slight reduction in the vortex strength was achieved at low blowing rates by Georgiou et al.[48] using a slot that wraps around the leading edge of a bluff body. However, this configuration is impractical in an engine. Kost and Nicklas therefore recommend placing the slot farther upstream, ahead of the saddle point, where the streamwise component of the injected flow can reenergize the boundary layer ahead of the vane leading edge. The study also notes that film cooling tends to increase turbulence near the wall, which can enhance heat transfer. Coolant injected from the slot was the major contributor to coolant concentration measured within the passage. Coolant emerging from the holes tended to have a weaker overall effect and only affected the cooling situation near injection holes. Knost and Thole[47] positioned their slot farther upstream and did not note any large increase in secondary flow with this slot configuration. Film-cooling holes were included also on the endwall within the passage. The interaction of slot flow and cooling hole flow was found to affect the secondary flow differently than when there was flow from just the slot or just the holes.

Optimal placement of cooling holes and cooling slots is difficult to determine. Performance is sensitive to passage geometry, passage static-pressure distribution, and secondary flow structure. However, some important progress on the subject has been made. Clearly, secondary flow strength can be affected by leakage flows. Though an additional loss penalty is incurred because of the added turbulence, the cooling benefits can be significant, improving the overall performance of the engine.

Liu et al.,[49] Lapworth et al.,[50] and Oke et al.,[51] experimented with the introduction of film cooling ahead of a nozzle. When film injection is with high momentum, secondary flow strength can be suppressed, providing better thermal protection and reduced aerodynamic losses.

Lampart et al.[52] computed the effects of tip leakage flow at a rotor stage on the endwall boundary-layer secondary flows in a downstream vane row passage. Effects of leakage flow extraction from the passage to the gap and leakage flow injection into the passage from the gap were considered. The leakage flow intensifies secondary flows at the tip endwall of the downstream stator.

A combined measurement and computational study by Paniagua et al.[53] in a high-pressure, transonic turbine documents the effects of leakage through the hub between the stator and rotor stages. They noted a large blockage of the vane exit flow caused by leakage. They also noted an unsteadiness of ingestion/ejection of this leakage flow driven by the relative position of the rotor blade to the stator vane. The effect of leakage of cold flow on the rotor is an enhancement of migration of secondary flow from the pressure surface to the suction surface and up the suction surface toward the midspan.

III. Heat Transfer

Heat-transfer rates on the endwall are directly related to the structure of endwall secondary flows. Large local variation in heat-transfer coefficients often result from vortices of varying intensities scouring the walls of the passage. Many studies have documented the distribution of heat-transfer coefficients using various methods. Early work includes the studies of Blair,[36] who used an array of thermocouples and small heaters (monitoring the power required to maintain each heater at a given temperature), Graziani et al.,[54] who used a similar method but with higher resolution, York et al.,[55] who monitored heat flux through a nickel wall using thermocouples placed on either side of the nickel, and Gaugler and Russell.[56] Blair's study indicates that increased heat transfer can be found near the leading edges of the vanes, the result of the roll up of the horseshoe vortex. Though the study notes several other trends in endwall heat transfer, the resolution is not sufficient to capture the finer points. Graziani et al.[54] improved resolution to allow a much more complete picture of endwall heat transfer (see Fig. 7). Upstream of

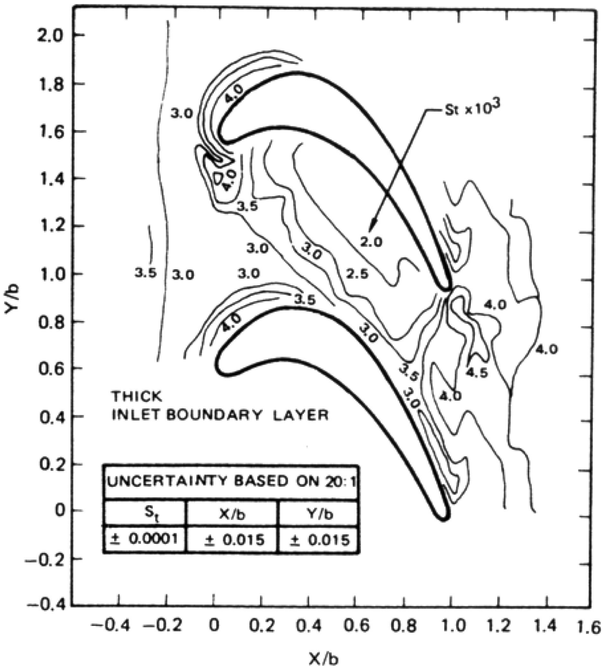

Fig. 7 Endwall Stanton numbers according to Graziani et al.[54]

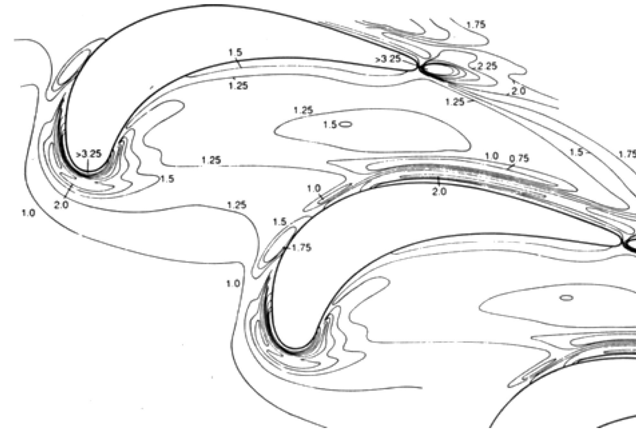

Fig. 8 Mass-transfer increase over flat-plate values for a turbine rotor cascade (Goldstein and Spores[58]).

the cascade, the boundary layer is essentially two-dimensional, and Stanton-number contours are parallel to the leading-edge plane. The leading-edge region experiences high heat-transfer rates because of the horseshoe vortex, as noted in Blair. The leading-edge region shows a distinct wedge-shaped area approximately defined by the leading-edge plane, the suction-side leading-edge separation line, and the separation line of the pressure-side leg of the horseshoe vortex. The heat-transfer rates in this area remain approximately equal to those of the incoming boundary layer. Just downstream of the separation line of the pressure side leg of the horseshoe vortex, a sharp decrease in the heat-transfer rate is apparent, and a region of low heat transfer extending all of the way to the trailing edge is formed. Because the inlet boundary layer has been swept up into the horseshoe vortex, a new boundary layer, driven by the cross passage pressure gradient, must be formed. Heat transfer and secondary flow phenomena in the throat region are very complex and apparently dependent on inlet boundary-layer thickness. A spot of high heat-transfer rates exists in the wake region behind the trailing-edge plane, and that Stanton numbers remain essentially uniform downstream of the cascade.

Subsequent studies by York et al.[55] and Gaugler and Russell[56] corroborate the work of Blair and Graziani et al. Gaugler and Russell suggest that a flow of fluid toward the endwall exists in the vane wake, explaining the region of high heat-transfer rates downstream of the vane trailing edge. Kumar et al.[57] presented correlations to determine average heat-transfer rates within a passage. They were segmented into five separate regions.

Goldstein and Spores[58] displayed excellent spatial resolution using mass-transfer sublimation measurements. Their study clearly shows the effects on the endwall of the secondary flows (see Fig. 8). Many of the regions of interest identified in Graziani et al. were visualized by mass (heat)-transfer data in this study. However, the wedged-shaped region identified by Graziani et al. did not extend as far into the passage as suggested by Graziani. The effects of corner vortices were seen clearly in the Goldstein and Spores study, and a region of enhanced mass (heat) transfer near the leading-edge plane was identified. The improved resolution indicates that the region of high mass (heat) transfer in the airfoil wake zone was composed of two peaks. The larger of the two peaks is the result of strong recirculating wakes. The lesser peak, which always resides nearer the suction surface, might be the product of the strong suction-side corner vortex continuing past the trailing edge and interacting with the wake to produce a region of strong vorticity.

A. Effect of Turbulence on Heat Transfer

It is important to note the effects of turbulence on endwall heat transfer in cascade passages. Engine combustors typically produce high turbulence intensity values and large turbulence length scales. Efforts to understand the effects of turbulence structure on endwall flows continue. In general, higher freestream turbulence can be expected to promote an earlier transition to turbulence of the endwall boundary layer, which will cause an increase in endwall heat transfer. However, large turbulence length scales exhibit a reduced amount of heat transfer when compared to smaller length scales of turbulence at similar turbulence intensity values.[59] A study by Thole et al.[60] indicates that for high freestream turbulence levels the horseshoe vortex moves closer to the leading edge of the vane. This is because of the turbulence flattening the inlet boundary-layer profile, creating higher velocities near the wall. Overall, higher turbulence levels act to increase heat transfer throughout the passage with less of an effect seen near the trailing edge region. Lee et al.[61] report similar results. Their study indicates that separation lines move further downstream with higher turbulence levels. Turbulence raises heat-transfer levels throughout the passage but with less of an effect near the leading edge and the trailing edge. Thus, the heat load on the endwall is more uniform. The overall increase in heat transfer was 27%, which compares well with the 25% increase reported by Thole et al.[60] Ames et al.[62] indicate that high freestream turbulence causes a weaker augmentation of heat-transfer coefficients at higher Reynolds numbers.

Additional studies that characterize the near-endwall flowfield include the work of Kang et al.,[63] Kang and Thole,[64] and Radomsky and Thole.[65] Sveningsson and Davidson[66] computed secondary flows and heat transfer in a stator vane passage to find that the $\overline{v^2} - f$ turbulence closure model yields better comparisons with experimental results than predictions computed using the realizable k–ε turbulence closure model.

B. Mach-Number Influence

Many of the studies reviewed in this paper were collected on low-speed turbine vane or rotor cascades. Engine representative Mach numbers have not been reproduced in these studies. The study of Bassi and Perdichizzi[67] indicates that Mach number has an appreciable effect on the secondary flow structure in that the passage vortex is shifted towards the endwall. However, the overall loss is not significantly affected by Mach-number changes. The work of Hermanson and Thole[68] indicates that the subsonic flowfield is similar to the flowfield under transonic flow conditions upstream of the shock location. A study by Giel et al.[69] investigates the difference between sonic and transonic flow on heat-transfer coefficients on the endwall. They note that increased Mach numbers tend to decrease heat-transfer rates.

C. Surface Roughness Effects

Surface roughness will change endwall heat-transfer rates. Studies by Blair[70] and Guo et al.[71] address the subject. Blair found that a rough wall increases heat-transfer rates over the whole endwall region. Roughness was credited with causing early transition to turbulent flow of the endwall boundary layer. A corresponding increase in heat-transfer rates is observed. Guo et al. observed increased heat-transfer rates caused by the roughness but noted that the heat-transfer coefficient patterns remained unaffected by an increase in roughness.

D. Heat Transfer in Blown Cascades

The introduction of coolant fluid along vane surfaces has been standard practice in the turbine industry. The use of injected flow through vane endwalls for cooling purposes is of relatively new interest. It became an area of stronger interest when recent turbine inlet temperature profiles from the combustor became more flat and active endwall cooling became necessary. Several important studies on the subject are reviewed next.

One of the first studies to include film cooling on the endwall was that of Blair.[36] Blair's study made use of a large-scale test section with coolant injection through a single slot running the full pitch of the passage. The test section included an endwall boundary-layer bleed slot just ahead of the coolant injection slot. Therefore the coolant was not injected into a mature boundary layer. Results of the study showed that film-cooling effectiveness is not uniform over the full pitch. Effectiveness near the suction side is high, whereas that near the pressure side is low. The maldistribution of coolant effectiveness is caused by the passage flow sweeping the coolant fluid along with the endwall boundary-layer fluid from the pressure side to the suction side. Heat-transfer measurements performed in the cascade show a slight decrease in heat-transfer coefficients with the added coolant injection. This was attributed to thickening of the boundary layer by the addition of low-streamwise-momentum coolant flow.

A study by Takeishi et al.[72] added to the understanding of endwall heat transfer with film cooling. This study made use of a single row of holes located at the inlet plane, a double row of holes approximately midway between the leading edge and the passage throat, and a double row of holes at the passage throat. They noted that passage cross flows move coolant toward the suction side of the passage reducing film-cooling effectiveness on the pressure side of the endwall. This confirms the observations of Blair.[36] A second zone of low film-cooling effectiveness is on the suction side near the leading edge. Here, strong roll up of the endwall boundary layer into a horseshoe vortex removes coolant fluid from the endwall. The authors conclude that passage secondary flows have a strong effect on heat transfer and film cooling within the passage.

Granser and Schulenberg's study[37] identifies the importance of the momentum flux ratio between the injected flow and the main flow in determining both the film-cooling effectiveness and the amount of reduction of secondary flow achievable. For momentum flux ratios less then one, coolant does not penetrate the mainstream, and the film-cooling effectiveness increases as the heat capacity of the injected fluid increases. At higher ratios, the film-cooling effectiveness varies with both the momentum flux ratio and the blowing rate. The study indicates no gain in additional film-cooling effectiveness at momentum flux ratios higher than 2.5. The studies of Harasgama and Burton[41,73] and Jabbari et al.[74] confirm the results found in the previous studies.

Effectiveness values for film cooling from individual holes were investigated by Freidrichs et al.[44] The holes are just upstream of the leading edge and at 30, 60, and 90% of the axial chord in the passage. Flow from the coolant hole just upstream of the leading edge tends to produce greater effectiveness values near the suction side of the passage and reduced effectiveness values near the pressure side between the liftoff line of the horseshoe vortex and vane leading edge. Similarly, flow from the holes at 30% of an axial chord downstream of the leading-edge plane produces good film-cooling effectiveness values near the suction surface. Flow from a single hole near the pressure surface also performs well while flow from a hole located under the liftoff at the pressure side of the horseshoe vortex performs poorly. This creates an uncooled region between the rows of holes. Cooling by flow from holes at 60% of an axial chord downstream from the leading-edge plane shows a similar trend, although flow from holes near the pressure side was effective and poor performance was confined to a small region located near the suction side of the vane. Flow from the last row of holes, downstream of where the horseshoe vortex impinges on the suction surface of the vane, provides a uniformly good effectiveness distribution. Flow from a film-cooling hole located near the vane trailing edge produced a large area of elevated effectiveness that could be used to protect the endwall from the high heat-transfer rates produced by the trailing-edge vortex.

A particularly well-developed study on a blown cascade is that of Nicklas.[75] The study confirms much of the phenomena previously documented but paid careful attention to the influence of local increases in turbulence on the observed heat transfer rates.

The study of Roy et al.[45] used injection ports upstream of the leading edge. The coolant from these ports was shown to increase heat-transfer rates in the area downstream of the ports and ahead of the leading edge. This might be because of increased turbulence produced by the injected flow. However, the small region of high heat transfer typically observed at the vane leading edge to endwall junction was greatly reduced. Coolant injection was credited with weakening the junction corner vortex. The cooling flow also produced high film-cooling effectiveness values downstream of the slots and upstream of the vane leading edge.

Knost and Thole[47] investigated two hole array configurations. The holes were positioned along the passage isovelocity lines and along lines that would be parallel to the engine axis. Interaction of flow from the cooling holes and slot cooling flow was noted, and it was concluded that slot cooling alone was not sufficient to provide cooling to the whole endwall. Film cooling from holes within the passage was necessary. Still, the region around the slashface (or gutter), between individual vane units, was poorly protected. Knost and Thole[76] measured film-cooling effectiveness with injection through a slot ahead of the leading-edge plane and through discrete holes between the slot and the leading-edge plane. They found that the coolant from the slot must be considered in an analysis of the coolant coverage. They found also that difficult to cool regions near the leading edge and at the pressure surface-endwall junction could be cooled more effectively if the momentum of the discrete jet flows ahead of the pressure surface were increased to allow the coolant to penetrate the leading-edge vortex, impinge upon the pressure surface and be washed to down that surface and onto the endwall. Even higher discrete jet coolant rates led to stronger jet separation and less flow to the pressure surface.

A study by Zhang and Jaiswal[77] showed the combined effects, in a turbine vane passage, of upstream slot cooling and downstream film cooling through holes. The upstream slots provided nonuniform cooling along the vane endwall. A region near the pressure side was not covered. Related studies are Zhang et al.[78] and Zhang and Pudupatty.[79,80]

Haselbach and Schiffer[81] note research activity underway in which cooling flow is introduced through a slot ahead of a vane row with various pitch and swirl angles and with various blowing rates. They documented the effects of injection on endwall aerodynamics and heat transfer.

E. Heat Transfer in Contoured, Blown Cascades

Clearly, flow phenomena influencing heat transfer within vane cascades are driven by a complex interdependence between endwall and vane geometries, main flow features, cooling flow characteristics and locations, and angles of coolant injection. As suggested, it is difficult to isolate the effects of any one of these or to predict their cumulative effects. Next, cases with endwall contouring and blowing through the endwall are discussed. Though general design rules are difficult to draw from the following specific cases, they do illustrate combined effects of contouring and endwall blowing on aerodynamics and heat transfer.

One of the original studies that simulated many of these complex interactions was that of Burd et al.[82] The study was performed in a two-passage cascade with bleed flow entering through a single, nearly continuous slot located ahead of the vane leading edge plane. The endwall was contoured within the passage beginning at $x/C_{\mathrm{ax}} = 0.5$ and ending at the trailing-edge plane. Data include leakage cooling effectiveness values at three planes within the passage for several different blowing flow rates. The study shows that coolant entering the passage at low flow rates (under 2.0% of the passage mass flow rate) does not fully cover the endwall, leaving the downstream portion of the pressure surface near the endwall with no cooling protection. Coolant accumulates in the corner between the suction surface and the endwall, having been carried by the passage flow. Higher blowing flow rates, 3.2–4.5%, provide the coolant flow with enough momentum to overcome the cross-stream secondary flow and remain near the pressure side of the passage. This provides better thermal protection as a result of both better coverage and a larger mass of coolant flow. At flow rates higher than 3.2%, the coolant is observed to collect near the pressure-side wall, covering as much as 25% of the pressure surface span. The suction surface is not similarly well covered. Effectiveness values in the suction side, endwall corner are reduced from those seen at lower blowing rates. The study offers two possible explanations for this behavior. The first explanation notes that high blowing is seen to shift the location of the passage vortex, moving it down the suction side of the vane toward the endwall with increased blowing (data shown in Burd and Simon[83]). The effective mixing of the passage vortex is responsible for the low effectiveness values in the corner. According to the second theory, the acceleration imposed by the contoured endwall thins the endwall boundary layer, weakens the passage flow, and reduces its influence on carrying coolant toward the suction surface.

A similar study by Oke et al.[84] produced corroborating results in a slightly different cascade configuration. For this study, endwall contouring began ahead of the airfoil leading-edge plane and continued through the passage to the airfoil trailing-edge plane. They observed coolant accumulation similar to that described by Burd and offered a variation on Burd's coolant flow model. It was speculated that the component of coolant flow momentum normal to the endwall might be sufficient to carry this flow over the top of the horseshoe vortex. It then impinges upon the vane pressure surface and is carried with the passage secondary flow down the pressure surface toward the endwall. They offered a second hypothesis that (as noted in Granser and Schulenberg[37]) the emerging coolant energizes the boundary layer ahead of the leading-edge plane, thereby reducing the strength of the vortex that forms at the leading edge of the vane endwall junction. This weakens secondary flows ahead of and within the passage and allows less mixing of the coolant with the main flow near the pressure wall. The net effect is more efficient cooling of the airfoil pressure surface near the endwall when blowing rates are sufficiently high, as already noted above.

Oke et al.[87] noted that acceleration caused by endwall contouring can help keep the coolant near the endwall, whereas the higher momentum associated with single-slot injection (as opposed to a double-slot injection with the same mass flow rate) tended to increase the uniformity of cooling flow injection and of endwall cooling effectiveness near the leading-edge plane and throughout the passage. Increasing the injection mass flow rate further, with either single- or double-slot injection, tends to increase the overall effectiveness. However, little improvement on uniformity of effectiveness was noted. This latter result is somewhat consistent with the results of Songling et al. taken in a noncontoured passage. They found that injection through a double row of holes (and therefore double the flow rate) was more effective than with single-row injection. Oke et al. determined that moving the slot nearer to the vane leading edge produced higher effectiveness values, but reduced the uniformity of pressure side coverage. However, it should be noted that this claim was based on data taken at a single measurement plane near the leading edge and that a more complete study might be needed to support it.

Numerical studies by Lin et al.[85] and Shih et al.[86] investigated the contoured endwall geometry of Oke et al.[84] and another geometry where contouring was complete ahead of the leading-edge plane. These studies included blowing on the contoured and flat endwalls of the cascade through slots ahead of the vane leading edges. The contouring in the Oke et al. studies tends to produce adiabatic effectiveness coverage over much of the first half of the passage. The study with contouring completed ahead of the leading-edge plane had high adiabatic effectiveness values just downstream of the slot, but poor coverage within the passage. Adiabatic effectiveness value distributions on the flat endwall were similar to those on the contoured endwall for both configurations.

A later study performed by Oke and Simon[87] investigated the effects of different geometries of the film-cooling injection slots made by partially blocking the slots. This increased the momentum for the lower blowing flow rate cases. Modification of the slot geometry was shown to allow placement of coolant where it was most needed and to control secondary flow within the passage. One problem noted in this study is that a partial slot leads to partial blockage of the mainstream approach flow. This, in turn, causes a streamwise-oriented vortex at the edge of that blockage, which is effective in mixing the coolant with the mainstream and negating the benefits derived by the controlled placement of the coolant.

The study by Pasinato et al.[88] considered another contoured endwall geometry. In this study, the injection ports were located only in the pitchwise vicinity of the vane leading edge (similar to the geometry of Roy et al.[45]). The ports were embedded in backward-facing steps. The endwall axial contouring was credited with causing a roll up of the horseshoe vortex ahead of the leading edge, limiting the degree to which the vortex mixed hot passage fluid with the endwall boundary-layer fluid. The study showed that the lowest heat-transfer rates were upstream of the passage throat. An increase in heat transfer was observed as the flow was accelerated through the throat and the boundary layers were thinned.

Pasinato et al.[89] made comparisons between measurements and computed heat transfer, pressure loss, and film-cooling effectiveness. They also extended the investigation of Ref. 88.

IV. Areas Requiring Further Study

Heat transfer and secondary flows within cascades of several specific geometries were documented thoroughly in the studies just discussed. Because both secondary flows and heat transfer in engines are so highly geometry dependent, general design guidelines are difficult to construct. We often use CFD to bridge from one geometry to the next. To verify the CFD codes experimental studies of high accuracy and resolution made within simulations of representative engine geometries that include important aspect of leakage and film-cooling flow injection are needed. Particularly important would be accurate heat-transfer measurements on contoured endwalls with blowing.

An area deserving attention is misalignment of components along the gas path. One location requiring attention is the gap at the combustor interface with the stator section endwall. This gap is designed to accommodate manufacturing variations and differential thermal expansion. Though many studies investigating the effects of backward- or forward-facing steps on heat transfer are available, relatively few exist for cascade geometries with the steps just ahead of the airfoil row, particularly when leakage fluid is introduced through the gap. One study of this ilk, but without downstream airfoils, is by Chyu et al.[90] The test section includes a gap with blowing and misalignment. As one might expect, the study indicates a large difference between the heat-transfer rates downstream of a forward-facing step and heat transfer downstream of a backward-facing step. The forward-facing step produces a slight reduction of heat-transfer rates ahead of the gap leading edge and then an increase downstream of the gap. The backward-facing gap produces a large area of decreased heat-transfer rates downstream of the step in the recirculation zone. Blowing through the gap, which has a forestep or backstep, does not change these trends, although heat-transfer rates downstream of the gap tend to increase. Yu and Chyu[91] studied the influence of leakage downstream of injection cooling holes. Moderate film cooling upstream of the slot provides better protection than without it; increased leakage flow led to decreased cooling protection. Zhang and Moon[92] investigated the effects of a backward-facing step with blowing in a cascade. The step is shown to create an unstable boundary layer that reduces the effectiveness of film cooling. They later showed that the effect of the backstep could be reduced, and acceptable film-cooling effectiveness could be attained by proper choice of the injection velocity.[93] Colban et al.[94,95] also investigated the effects of steps and leakage flow on endwall aerodynamics and cooling. Their work shows sensitivities to various parameters and indicates the importance of fully characterizing the inlet flow.

A series of papers by Wu et al.[96–98] investigate the effects of a step on the endwall similar to the misalignment, which might be present in an industrial gas turbine. Two of the studies, Wu et al.[96] and Wu and Lin,[97] include a forward-facing step. The first uses the transient liquid crystal method to show the heat-transfer coefficients on the vane endwall. With an entrance step height of 4% of chord length, separation and reattachment of the boundary layer over the step causes an area of higher heat transfer just downstream of the leading edge. The step is also credited with weakening the horseshoe vortex. Wu and Lin[97] investigated endwall film-cooling effectiveness with a similar forward-facing step ahead of the leading-edge plane and ahead of the injection holes. They found that the step caused a very significant reduction in the film-cooling effectiveness, particularly in the forward part of the passage. The latest study[97] investigates a backward-facing step. A region of high heat transfer corresponding to the reattachment of the flow was noted downstream of the step.

Another geometry that deserves particular attention is the slashface gap (gutter) on the endwall between individual vanes. Again, manufacturing variations and differential thermal growth can cause steps. Studies are underway to document the effects of slashface gaps, steps, and blowing in conjunction with similar features at the combustor-to-turbine transition section. One by Piggush and Simon[99] provides measurements of aerodynamic losses where steps, gaps, and leakage flows are added at the transition section and at the slashface. In that study, n-factorial experimental design is used to learn that leakage through the slashface gap is more important than the other effects documented: however, the effects of having a step at the transition section are also significant. The study of Yamao et al.[100] simulates the vane slashface gap in a flat wall cascade. The study indicate that there is little effect on the passage loss for the slashface flow and heat there is little effect on the passage adiabatic effectiveness values between a case with blowing and one with no blowing. The discrepancy in measured effect of slashface blowing between the Yamao et al. study and the Piggush and Simon study might be caused by the difference in the no-blowing base cases. The Yamao et al. base case is an open-slot, no-blowing case, whereas the Piggush and Simon base case is a smooth-slot (covered) no-blowing case. Also, the Yamao et al. study had blowing through the transition section gap as well as through the slashface gap, whereas the Piggush and Simon study isolated the slashface gap effect. Finally, the Piggush and simon study is with a contoured endwall so that the comparison case is one of particularly low losses. Adiabatic film-cooling effectiveness values were measured by Ranson et al.[101] in a rotor cascade constructed with straight endwalls having a slot ahead of the airfoils, three slot segments on the endwall, and a slot downstream of the airfoils. Some benefit in adiabatic effectiveness in the upstream portions of the endwall attributable to flow through the upstream slot was recorded. Increased flow did not lead to increased effectiveness. The endwall slot showed little benefit in cooling effectiveness and no improvement with increased blowing. Computed results showed higher effectiveness values on the endwall than measured.

The study of Aunapu et al.[32] (discussed earlier) in which there was blowing within the passage has some features akin to slashface gap step disturbances, although it was performed in a straight-walled cascade and heat-transfer measurements were not made.

Modification of the wing-fuselage junction has been employed in the aircraft industry to reduce the overall drag experienced by the aircraft.[102–104] Modifications typically include a large fillet or similar geometry to fair out the right angle of the junction. As discussed frequently, the junction of a bluff body with a wall creates a horseshoe vortex. This is because of the lower momentum of the boundary layer near the wall. As the fluid stagnates against the body, a gradient in static-pressure gradient is established with drives fluid down the front of the bluff body and upstream as a roll-up vortex (Fig. 2). A separation point ahead of the leading edge of the body is created on the endwall. Modifications of the wing-fuselage junction, such as fillets, are effective because the fluid approaching the leading edge of the bluff body accelerates locally as it moves up the fillet. The effects of the total pressure deficit created by the endwall is reduced by this imposed acceleration.

The use of a vane-endwall modification in gas turbines (similar to the wing-fuselage modification) has recently received increasing attention. In the turbine, the flow is more complicated than flows found on the aircraft body. Although most experiments have shown a reduction of loss caused by fillets, the exact mechanism responsible for the reduction is poorly understood. The work of Sauer et al.[105] in low-pressure turbine applications has shown loss reductions of up to 50%. Similar modifications in compressor cascades have shown similar loss reductions.[106] Sauer makes use of a leading-edge bulb, where the leading-edge radius is increased locally near the endwall. This strengthens the horseshoe vortex, in particular the suction side of the horseshoe vortex. Sauer et al. theorize that the enlarged suction-side vortex displaces the pressure side of the horseshoe vortex off the suction surface of the vane. (The sense of rotation of the suction-side vortex is opposite to the pressure side, and therefore the vortices will not combine.) This prevents interaction of the passage flow with the pressure-side vortex. Though the horseshoe vortex is strengthened, preventing interaction between the passage flow and the pressure side of the horseshoe vortex creates a loss reduction of a much greater magnitude, and the net effect is a loss reduction.

Zess and Thole[107] investigated the effects of a leading-edge fillet endwall modification. Shih and Lin[108] computationally investigated the performance of particular designs of leading edge fillets and documented the effects of changing the degree of inlet swirl. They noted that introduction of a fillet or inlet swirl can reduce both the aerodynamic losses and endwall heat transfer. However, they also noted that when there is swirl, leading edge fillets become less effective. This shows the importance of optimizing the fillet design with swirl in mind. They suggested that a description of the mechanisms responsible for aerodynamic losses and surface heat transfer changes may require more than simply considering changes in intensity of secondary flows. The results indicate that the characteristic horseshoe vortex was not formed at the leading edge. This is because of local acceleration. Also, unsteadiness in that region, usually associated with the horseshoe vortex, was not observed. Turbulent kinetic energy in the passage was reduced by 80%. They theorized that these changes might be responsible for loss reductions observed with the use of fillets. The fillet appears to have a sharp leading edge. Because the magnitude of the horseshoe vortex scales on the leading-edge radius, the vortex might simply not have been formed because of the shape, rather than because of local acceleration. This sharpening would increase off-design incidence losses.

Work by Becz et al.,[109,110] investigating a leading-edge bulb of a geometry similar to that of Sauer et al.,[105] did not show the same magnitude of loss reduction as reported by Sauer. Becz et al. suggest that strengthening the horseshoe vortex might result in increased loss. Their studies indicate that more research is needed to identify the optimum geometry for loss reduction and to identify the actual mechanisms of loss reduction.

A study on endwall fillet heat transfer by Lethander et al.[111] reports a slight improvement on passage cooling with a fillet for three reasons: the reduction in passage surface area when the fillet, endwall, and vane surfaces are considered, the reduction in secondary flow from acceleration at the leading edge preventing the formation of the horseshoe vortex, and leading-edge acceleration, which prevents hot fluid from being driven to the endwall at the vane leading edge.

V. Conclusions

Papers in the literature that describe endwall flow and heat transfer have been reviewed. As a result of the activities mentioned, the complex flow patterns in the endwall regions of turbine passages are becoming well understood. With this new understanding, researchers are finding methods for improving aerodynamic performance of turbines and are finding methods to manage the high thermal loads that must be accommodated in modern engines. The results are increased aerodynamic efficiencies, improved cooling performance with reduced cooling flows, and greater engine durability. Success has been demonstrated with such methods as endwall contouring, leading-edge modification, strategic application of film cooling, and optimum use of leakage flows for sealing and film cooling. As more is learned, real effects such as leakage flow interactions, endwall steps and gaps as created in assembly or as a result of thermal growth, and advected flow features like embedded vorticity and turbulence from upstream are being integrated into the analysis and design. It seems that more knowledge is needed on Mach-number effects, the effects of rotation, and on the benefits that can come from airfoil to endwall junction modification, and three-dimensional airfoil and passage geometries. Though the experimental work has been and will continue to be valuable in documenting the flow and heat transfer and in evaluating new methods for improving the endwall regions, CFD has had a major impact on this topic. The flowfields are complex, but can be computed rather accurately. Thus, CFD has given great insight into this complex problem and has given a means for testing proposed aerothermal improvement schemes. This is a complex flow with separation, stagnation, transition, embedded vorticity, and strong pressure gradients. Thus, improvements in CFD modeling are still needed. As with many engineering flows, more is to be learned about turbulence modeling and transition to turbulence.

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