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GAS TURBINE BLADE COOLING TECHNOLOGY, ADVANCES, AND CHALLENGES

Harika S. Kahveci [1]
Aerospace Engineering Department, Middle East Technical University (METU)
Ankara, Turkey

ABSTRACT

Flow in a gas turbine engine is exposed to elevated temperatures in the high-pressure turbine that is located immediately downstream of the combustion chamber. If stator and rotor blades are not cooled properly, the temperature limits of blade materials could be exceeded due to hot gas flow, leading to serious damages during engine operation. Continuous advances in cooling technologies have become necessary since the engine thermal efficiency and power output increase significantly with an increase in the turbine inlet temperature. This study explains blade cooling techniques and discusses the related challenges and recent advances in this research field.

INTRODUCTION

A gas turbine is a system based on a gas generator consisting of a compressor, combustor and turbine, which uses the energy released through a combustion process to produce the power or thrust needed by different systems. Today, gas turbines are used for a wide range of applications varying from power generation to aircraft propulsion. The working mechanism of a gas turbine is modeled via the Brayton cycle, which dictates that the thermal efficiency of a gas turbine can be significantly increased if the turbine inlet temperature increases. This has been a driving motivation in today's advanced gas turbine designs, but with the drawback of exceeding material temperature limits.

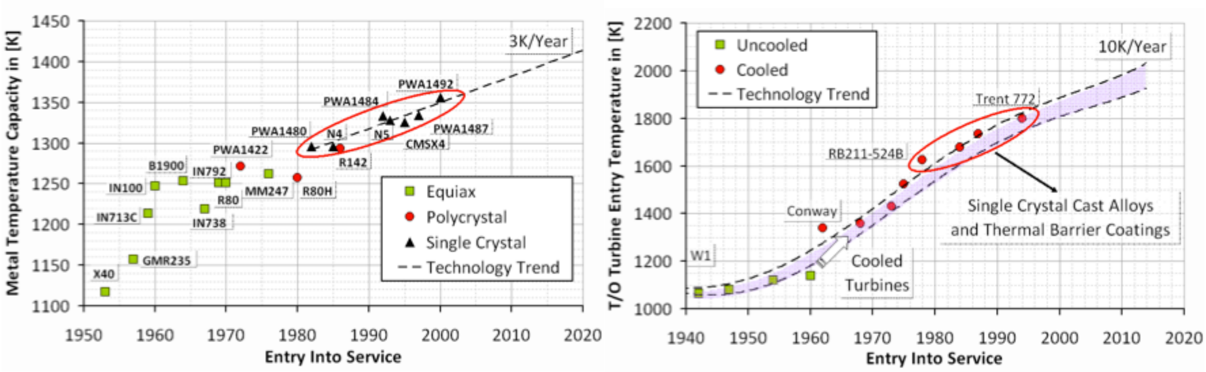

Fig. 1 Increase in temperature limits over years [Kyprianidis, 2011]

Simultaneous advances in materials and directional solidification techniques have enabled the use of high-strength materials and single-crystal alloys, which can drive the material temperature capacity to the levels of 1400 K in the near future. The long-awaited use of ceramic materials has also recently made its way into the engine hot section components.

[1] Assistant Professor in Aerospace Engineering Department, METU, Email: kahveci@metu.edu.tr

Fig. 1 shows the advances in both metal temperature limits and turbine inlet temperatures [Kyprianidis, 2011]. The trends suggest that the turbine inlet temperatures in current designs can reach the level of 2000 K despite the materials limits. This gap between the limits and the needs is fulfilled by the application of cooling techniques and the use of thermal barrier coatings. This means that the improvements in cooling techniques have the significant potential of driving inlet temperatures even further.

In order to cool the components in the hot gas path, the relatively cooler air that is extracted from the aft stages of the compressor is steered towards hot-section components. The combustor and the high-pressure turbine components are the parts that suffer the most from high temperatures due to the combustion process, resulting in an immediate need of sufficient amount of cooling to avoid the risk of a melt-down due to overheating. Of these parts, blades are cooled via several techniques where the cooler air is circulated inside and/or outside of the blades while absorbing heat from their hot metal surfaces.

The goal in blade cooling design is to utilize cooling air in just the sufficient amounts to effectively cool the blades so that the engine performance is not compromised by extracting redundant amounts of air from the main flow path that could be otherwise used for power or thrust generation. Considering that around 20% of the compressed air may be used for cooling purposes, a cooling design that is not performed wisely could clearly cause significant losses in engine efficiency. For this reason, the implementation of these cooling techniques is continuously optimized and supported by novel approaches and designs developed by turbine designers and researchers.

In this paper, the traditional cooling techniques used in gas turbine blade design are reviewed. Just like in any design practice, blade cooling has its own challenges and these challenges have been the motivation behind the execution of novel approaches and the evolution of cooling designs. Hence, this paper also discusses some of the issues encountered during engine operation and some improvements regarding blade cooling design.

BLADE COOLING TECHNIQUES

In order to maintain the engine operation in a high-temperature environment while avoiding blade damage, the turbine blades need to be sufficiently cooled inside out. In addition to cooling, thermal barrier coatings and materials such as nickel and cobalt alloys that are high-temperature and oxidation-resistant are used in blades. Such materials are also implemented in the combustor liner, the turbine exhaust, and at any location that is exposed to high temperature levels. Heat transfer is promoted inside of the blades as it is the cooler air circulated in the passages that absorbs the heat from the hot metal surfaces. On the other hand, the challenge is different on the blade external surfaces since they are exposed to the hot main gas flow instead, resulting in heat transfer from the hot gas to the surfaces that must be avoided. Implementation of any cooling arrangement is dependent on the blade shape and geometric characteristics. The circulating air inside of the blade is later discharged onto the blade external surfaces and is used to form a protective layer here so that the effects of heat transfer can be lessened to the levels where the blade materials can withstand high temperatures. Although the techniques used differ for the internal and external regions of the blade, they are closely related since the local flow properties of the discharged air are determined by the features of the internal design.

There are many parameters that must be considered in the design of internal and external cooling structures. Even when the cooling holes are considered alone, several other geometric parameters such as the hole number, location, size, relative spacing, hole arrangement (in-line or staggered), angle, and the interaction of these parameters that will all have pronounced effects on cooling effectiveness must be carefully taken into account. Not only the geometric parameters, but also the cooling conditions such as the mass flow rate, temperature, pressure differentials, and losses must be maintained within reasonable ranges to assure proper component cooling. In addition to these, there are typical main flow characteristics that vary depending on the engine operating conditions such as turbulence, wakes of blades, and turbine inlet temperature profile, which all contribute to the complexity of the flow environment under consideration. In other words, blade cooling design is in fact a complex topic and it continues to pull the attention of researchers due to the promising gains it offers in the overall engine performance.

One can find many studies in literature investigating this topic from both experimental and computational aspects. As a result of almost a half-century of efforts and experience, the developments in the measurement techniques and three-dimensional Navier-Stokes codes have enabled the turbine designers to pursue detailed heat transfer measurements and analyses with high accuracy. When there is a lack of measurements and knowledge, empirical correlations are typically used in design for their ease of use and quick turnaround time, although they provide only approximate calculations. A list of such correlations that were derived from experimental data is provided for use in blade external cooling [Goldstein, 1971].

Gas Turbine Blade External Cooling

The techniques used to cool the external surfaces of the blades are referred to as “film cooling”. Film cooling is the process of discharging air inside the blades through openings such as holes or slots located on the external blade surfaces while ensuring that it forms a protective layer so that the effects of heat transfer from the hot gas path to the surfaces can be reduced. This technique is applied in blade regions where heat transfer is significant, such as the blade leading and trailing edges, endwalls, and the blade tips as shown in Fig. 2. In high-pressure turbine vanes and blades, a combination of such cooling configurations is used simultaneously to provide sufficient protection.

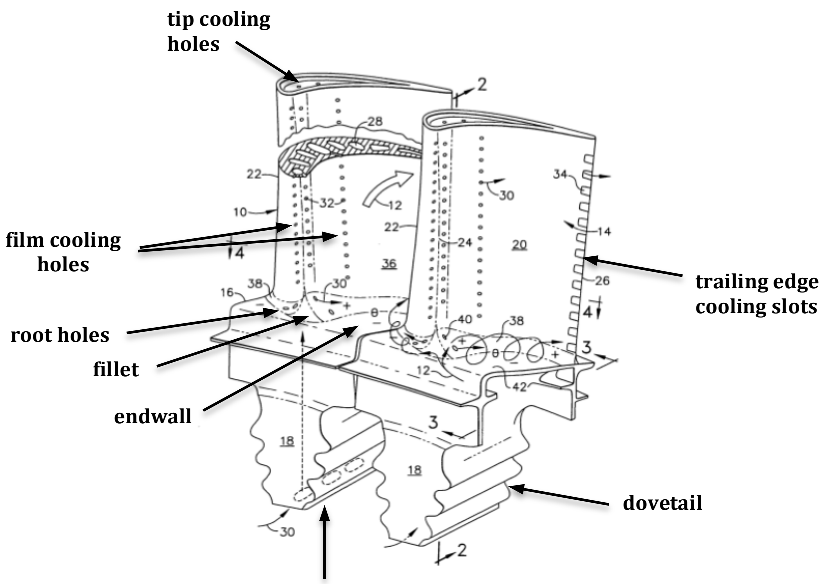

Fig. 2 Film-cooled fillet [Lee, 2014]

Film cooling technique is applied through film cooling holes of varying sizes and shapes all around the blade, except the blade trailing edge. At the trailing edge, film cooling is applied rather through a structure consisting of slots and lands instead of typical film cooling holes. Performance of film cooling is closely related to the cooling geometry and cooling configuration, hence, this has led to considerable amount of research dating back to ‘70s. In majority of the cooling schemes, round holes have been used. As the designs have evolved, however, hole shapes other than round shapes have also been introduced and implemented in designs so that the blade surfaces could be protected more effectively. An example to such holes is the fan diffuser shaped holes. This type is specifically used on the pressure and suction surfaces of the blade as well as on its endwalls, where the round hole drilled through the material is manufactured to also expand at the exit of the hole in the lateral direction, into the surface, or in both directions.

Fig. 3 introduces some hole shapes [Kercher, 2001; Bunker, 2014]. Hole shapes similar to that given in part b have found wide application due to their ease of manufacturing and high cooling performance they offer. Film-cooling effectiveness was shown to increase with the use of such shaped holes, and it was concluded that this was due to the reduction in the momentum of the cooling air caused by widening of the cooling hole at the exit [Goldstein et al., 1974]. With reduced momentum, the cooling air was staying closer to the surface, resulting in higher cooling protection. In manufacturing of the holes, techniques such as lasers and electrical discharge machining (EDM) are used. A detailed review was performed on shaped holes used in gas turbine film cooling [Bunker, 2005].

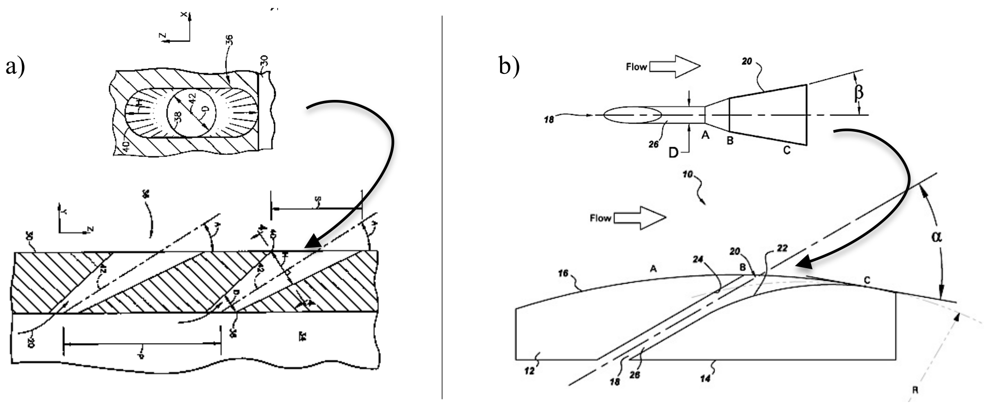

Fig. 3 Film-cooling hole shapes introduced, a) [Kercher, 2001], b) [Bunker, 2014]

Cooling obtained through rows of holes that are densely arranged in an array in the blade leading-edge region is also referred to as showerhead cooling. For this configuration, not only the shapes of the holes but also the local arrangement of the rows of holes with respect to each other is the criteria in the design. There have been numerous studies focusing on showerhead cooling. In one of these studies, the effect of showerhead consisting of six rows of cooling holes on the blade surface heat transfer and cooling performance was investigated [Polanka et al., 2000]. At low blowing ratios, showerhead cooling was found to be causing a decrease in film-cooling effectiveness on the pressure surface; however, at high blowing ratios this trend was reversed due to an increase in turbulence levels. A review was performed for many of such studies concerning the cooling of blade leading edge region [Kercher, 2000].

Trailing edge is a critical region of the blade since there is a fine balance between aero, mechanical, and thermal design criteria to be achieved here. The trailing edge should not be thick so that aerodynamic losses are not aggravated, but it should not be too thin either so that the structural strength of the blade is not compromised while there is still enough room to implement a cooling configuration inside for the thermal protection of the blade. Ribs are used in internal cooling passages as they are known to promote turbulent mixing that helps with cooling of the surfaces. The flow field in the trailing edge internal cooling passage was investigated by performing experiments and a computational analysis on a representative triangular channel containing ribs [Baek et al., 2019]. Comparing the results with those from a channel with no ribs, the mean flow velocity and turbulence intensity were found to have increased at the sharp edges.

Similar types of film cooling holes are also distributed both on pressure and suction surfaces of the vane and blade depending on the cooling need. The pressure surface of the blade may need more cooling coverage than the suction surface due to the radial flow and strong flow mixing occurring here. In a high-pressure turbine vane, the pressure surface is also directly in the line of sight of the hot flow coming from the upstream combustor that necessitates the use of cooling. In the experiments performed using the pressure sensitive paint technique, the effects of blowing ratio, the use of wake rods upstream of the blades, and the hole shape were examined [Gao et al., 2009]. The effectiveness on the pressure surface was found low, but it was observed to be increasing with an increase in blowing ratio on both surfaces. The shaped holes provided higher film-effectiveness compared to the round holes. One other important conclusion was that the film effectiveness was found lower on blade surfaces in the presence of wakes generated by the upstream rods. More recent experimental data were obtained from a fully-cooled high-pressure turbine vane row in a rotating rig, which reflect realistic engine conditions [Kahveci et al., 2013a; 2013b]. The effects of turbine inlet temperature profile and the amount of cooling flow on the heat transfer of cooled vane surfaces were investigated. The vane was cooled via a dense cooling scheme applied on all vane surfaces, covering the leading and trailing edges, pressure and suction surfaces, and the endwalls.

Endwall of the blade is a region where the flow complexity increases due to three-dimensional secondary flows dominating the flow path. The inlet flow rolls into a horseshoe vortex and later turns into a passage vortex with the effect of cross flow induced by pressure gradients. For a cooled endwall, the addition of cooling makes this flow field even more complicated. In the invention shown in Fig. 2, the endwall is connected to the root of the blade through a fillet and changes the contour of the endwall, with the goal of decreasing the adverse effect of the horseshoe vortex on the aerodynamic efficiency [Lee, 2014]. This fillet is also film cooled via the root holes located here. This way, the coolant discharge at this location energizes the boundary layer, thus weakens the vortex structure of the flow. In a large scale, low-speed linear turbine cascade, the ammonia-diazo technique was used to measure the cooling effectiveness in the endwall [Friedrichs et al., 1996]. The ammonia gas in the cooling air was allowed to react with the diazo film coating covering the endwall. The measurements of concentration provided the details of the flow field and also revealed the regions where cooling was not sufficient. Such findings in literature give insight to designers and are critical in improvement of cooling designs.

Leakage flow occurring in the gap between the rotating blade tip and the opposing casing wall not only adversely affects the turbine performance but also causes the wear out of the blade material due to increasing blade tip heat transfer. For this reason, approximately one-third of the failures happening in high-pressure turbines is due to blade tip wear. Therefore, the blade tip region needs to be investigated in detail both from aerodynamics and thermal aspects. When cooling is involved, the flow physics in the gap becomes more complicated. Another review was performed on blade tip heat transfer that summarizes such studies [Bunker, 2001]. During the following almost two decades, there have been more research added to this list. In one study. measurements were performed in a rotating turbine rig where the leakage vortex was observed to be decreasing as the blade tip gap decreased [Rao and Camci, 2004]. When the cooling amount applied into the gap was increased, the vortex was observed to be moving towards the blade tip.

Gas Turbine Blade Internal Cooling

To internally cool the turbine blade, the cooler air extracted from the aft stages of the high-pressure compressor is fed into the interior section of the blade. As this air circulates through the internal passages, it absorbs the heat from the hot metal surfaces. These passages are also referred to as serpentine passages, as they make multiple passes to span the whole internal space for an effective cooling. The front and aft of a blade are typically cooled via different circuits consisting of multiple passes, and each blade design will differ from one another. The goal is to engineer this internal cooling design so that heat transfer is promoted here. For this purpose, geometric features such as ribs and pin fins, and impingement holes, are added into serpentine passages. Considering the overall cooling of the blade, it is the pressure differential that ensures that the cooling is distributed to the critical regions of interest. One criterion in cooling is to maintain a homogeneous temperature distribution across the blade while obeying the material temperature limits so that thermal stress can be kept as low as possible.

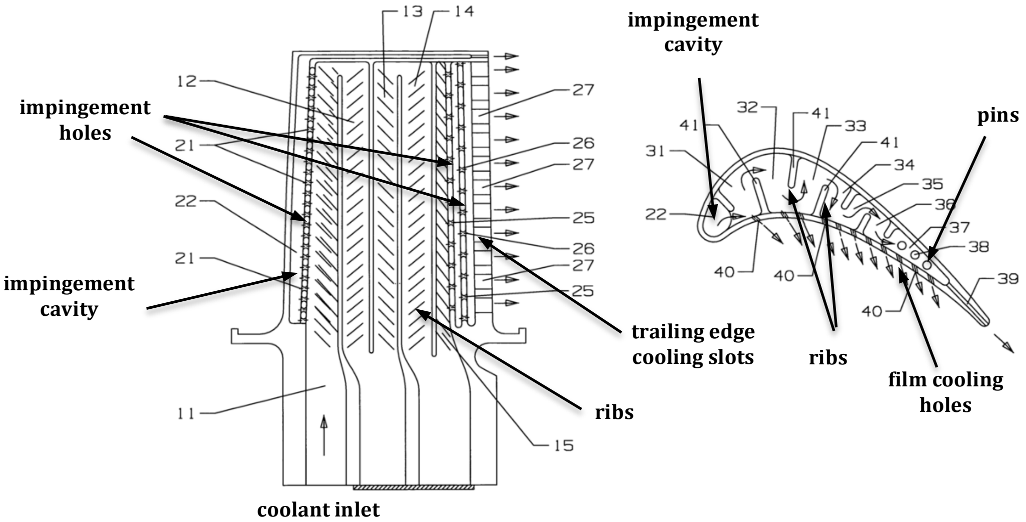

Fig. 4 Dual serpentine cooling [Liang, 2011]

In serpentine passages, the design parameters such as the number of passes, geometry and aspect ratio of the channels, and blade rotation, are known to have a clear impact on heat transfer levels. Coriolis and rotational buoyancy forces that arise due to the blade rotation also have an impact on internal heat transfer. Inside the channels, these effects cause an asymmetric distribution of the air flow in addition to the secondary flows that all complicate the flow field. Fig. 4 shows a blade cooling design invention where there is a serpentine cooling circuit for the airfoil section and another circuit dedicated for the cooling of the blade tip [Liang, 2011]. Some portion of the cooling air impinges through the holes into the impingement cavity at the leading edge, and then is discharged through a showerhead cooling arrangement. Other portion that does not flow through this showerhead arrangement flows into the tip region directly and travels through the other cooling circuit located at the tip. The top view of the blade shows the coolant flow path. There are film-cooling holes on the pressure side of the tip and a row of pins extends from the tip to the hub of the blade in the spanwise direction.

Another example to the serpentine passage arrangements is shown in the invention given in Fig. 5 [Levine et al., 2007]. A U-shaped divider rib extending from the first pass to the second pass is introduced to improve the flow structure inside by guiding the flow, controlling the loss, and eliminating flow separation in some spots. The divider splits the coolant flow into two flow streams in order to accomplish this and provides a more uniform distribution.

The internal surfaces of serpentine passages are intentionally roughened by the use of ribs that come in different configurations with varying spacing, height, and orientation. The ribs separate the flow passing over them and create vortex structures, resulting in enhanced turbulent mixing and increased heat transfer coefficient. This helps the circulating flow to cool the surfaces more effectively since the heat from the surface is dissipated in the flow. In the investigation of internal cooling configuration of the blades, many studies used simplified test sections representing serpentine passages, although these test sections have improved with time and have started replicating more realistic configurations. An earlier study demonstrated the effect of rib orientation on local heat transfer distributions and pressure drop characteristics in square channels [Han et al., 1991]. The test section used was relatively simple: a rectangular duct consisting of heated copper plates. The tested configurations had crossed, parallel and V-shaped ribs with an angle of attack of 45^0, 60^0, and 90^0. The V-shaped ribs were found to give the highest heat transfer augmentation, whereas the crossed ribs produced the lowest pressure drop penalty. Such ribs are also visible in Fig. 5 across the passages.

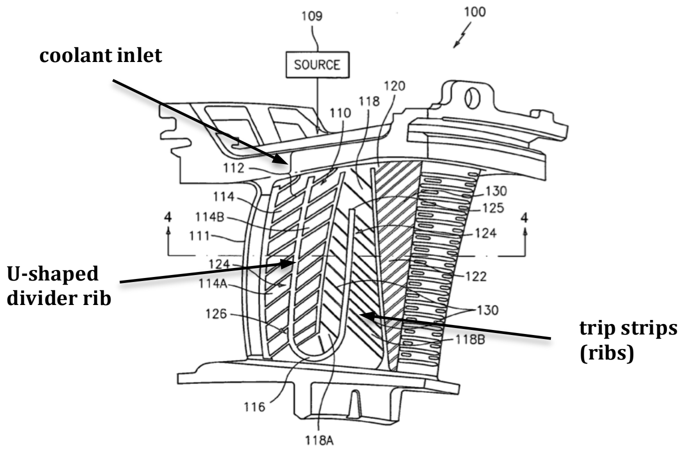

Fig. 5 Serpentine passages with a U-shaped divider rib [Levine et al., 2007]

Another blade cooling technique is the impingement cooling, where the cooling air that is discharged from the serpentine pass directly impinges on the internal surface of the leading edge, increasing the local heat transfer coefficient significantly. The configuration given in Fig. 4 also houses the impingement-cooling technique as is mentioned above. This technique is traditionally used in the leading-edge region where the cross-section is thick enough so that the structural integrity is not compromised and the thermal gradients are significantly high. In stationary blade designs where the applied stresses are in lesser amounts, the impingement channels can also be cast into the airfoil wall around the pressure and suction surfaces. An impingement configuration consists of an insert containing pressurized air that is ejected through cooling holes located on this insert and a target surface such as the inside of the leading edge surface that is aimed to be cooled. The impingement process is considered to be fundamentally split into two parts: the cooling air acts as a free jet in the pressurized compartment but acts as a wall jet and creates a cross flow once it impinges on the target surface. The heat transfer data obtained from many experiments so far investigating the effects of parameters, such as jet-to-target plate spacing, jet-to-jet spacing, hole diameter and hole arrangement, are typically used to develop correlations in order to predict heat transfer in similar configurations. One of the earlier studies that has been of guidance to the turbine designers involves circular jet arrays that were arranged in in-inline and staggered patterns [Florschuetz et al., 1981]. Using the results of an experimental matrix based on the variation of geometric parameters, correlations for the calculation of jet and cross flow velocities and Nusselt numbers were presented. In another study, the aim was to improve the impingement cooling technique by introducing shaped holes into the channel geometry [Chambers et al., 2009]. Computations were performed to determine the optimum jet aspect ratio, and then experiments were performed with the improved design for varying amounts of cross flow, indicating that the use of shaped holes noticeably increases heat transfer.

Pin fins are typically used close to the trailing edge of the blade. They are the extensions built in a surface with the aim of increasing the surface area so that heat transfer from the cooler air to the surfaces can be increased. This increase in surface area increases flow turbulence since each of these pins causes disturbance in the flow field, resulting in augmented heat transfer. For this reasons, pin-fins are typically used inside of the blades as a means of internal cooling.

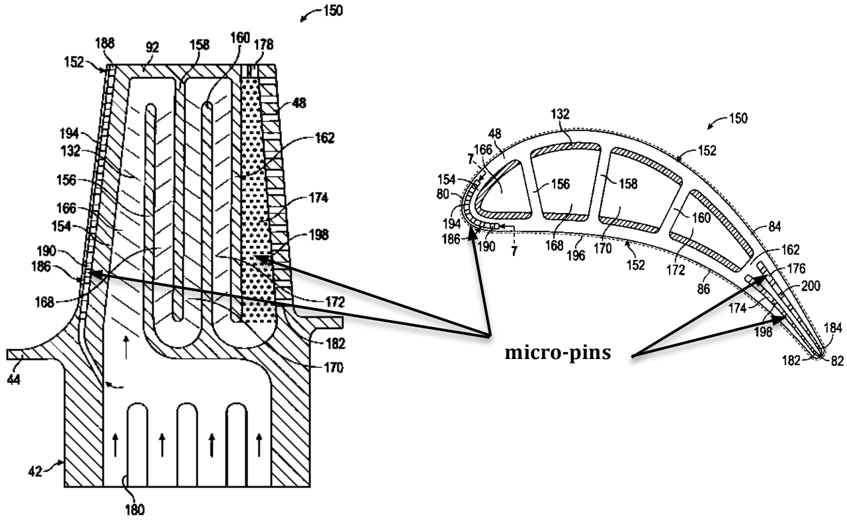

Fig. 6 Near wall micro-circuit edge cooling [Liang, 2015]

An array of pin fins located along the trailing edge region as shown in Fig. 6 can be considered as an example to both internal and external heat transfer cases: air flows internally between the pressure and suction surfaces of the blade near the trailing edge, while it flows externally around the pin fins. They are typically used inside of the narrow trailing-edge region since other types of cooling configurations such as the impingement inserts would not fit into this section. Just like in the arrangement of cooling holes, pin fins can be applied in in-line or staggered arrangements. In their design, pin height-to-diameter ratio, spacing, shape, and arrangement are some of the geometric parameters that are studied. Specific to the invention shown in Fig. 6, the pins at the trailing edge region are micro-pins that form a micro-circuit cooling channel [Liang, 2015]. Another micro-circuit cooling channel is implemented at the leading edge of the blade that also includes an array of micro-pins that extends around the leading edge and across the blade span. Both pin arrays are in staggered form and provide double wall cooling.

Researchers have established extensive databases over the years focusing on different combinations of these parameters and proposed several correlations to be used in pin-fin design. Metzger and his coworkers have extensively studied the arrays of pin fins and introduced correlations applicable for a range of parameters. One of these studies presented an experimental data set for an array of staggered pin fins in constant and converging cross-sectional areas for different pin spacing and Reynolds numbers [Metzger et al., 1986]. The arrays of pin fins have evolved into a combination of different surface shapes with time. In a computational study where an array with dimples located between the pin fins was considered, the flow Reynolds number and dimple depths were varied, and the Nusselt number was found to be increasing with the Reynolds number and the dimple depth [Rao et al., 2012]. It was concluded that the convective heat transfer in the channel was enhanced with the use of dimples due to the vortices generated by the increased levels of turbulent mixing.

ADVANCES AND CHALLENGES IN BLADE COOLING

Cooling techniques play a critical role in the design of hot-gas-path components that consist of the combustor, stationary and rotating blades of the turbine, and the blade shrouds. Although the discussion presented in this study has been limited to blade cooling, there are already several techniques for blade alone that need to be implemented in different combinations for proper cooling coverage. Application of each of these techniques has their own challenges. In this section, some of the recent developments and main challenges faced by turbine blade cooling designers are discussed.

Blade cooling designers go through an iterative design process during the optimization of a cooling configuration that requires the use of correlations based on experimental data and computational studies for a detailed analysis. Designers must adhere to the additional design constraints provided by the aero, mechanical, and system designers, and also be aware of the limitations of the manufacturing capabilities so that they can implement necessary modifications into the design. Since the use of computational tools and experimental data and manufacturing of parts are some of the crucial elements of design process, it is obvious that blade cooling technology will benefit from any improvement achieved in these areas. On the other hand, since this technology involves a cooling process, thermal gradients will be formed in hot surfaces due to the distinct temperature difference that cause threat to component life. As the basic constituent of film cooling, the cooling holes are susceptible to blockage that downgrades their film-cooling performance. Flow conditions at the exit of holes or slots are also known to be affecting the downstream cooling coverage, hence the cooling arrangements would need to be designed considering the effects on flow conditions such as the sources of unsteadiness in the flow path. The uncertainties associated with the computational approaches and experimental techniques used in the design process are yet other challenges that need to be taken into account for accurate measurements and predictions.

Use of Additive Manufacturing

One of the recent revolutionary advancements having an impact in almost any engineering field is the additive manufacturing. This is a technology where material is added in successive layers to produce three-dimensional objects in contrast to the traditional techniques. A variety of materials such as metal powder, ceramics, and composites can be used in production, which are also some of the materials used in gas turbine parts. With additive manufacturing, lighter designs with precise geometries can be fabricated in shorter time.

Manufacturing capabilities have been one of the main constraints on the improvement of blade cooling technology so far. The limitations and the allowable tolerances of manufacturing methods have been an obstacle to achieving the desired cooling performance with the cooling design. The use of additive manufacturing in turbine blade cooling is promising in the way that it enables the production of many different complex and intricate cooling designs that were not previously practical to manufacture.

With this recent progress in manufacturing, the use of additive materials has pulled attention in the most recent investigations. A numerical optimization of wavy micro-channel configurations was performed to minimize pressure loss and maximize heat transfer [Kirsch and Thole, 2018]. Later, these optimized channels were manufactured using Direct Metal Laser Sintering (DMLS) technique and measurements were performed. It was observed that pressure loss was actually not minimized due to the large roughness features of the manufacturing technique used, while the heat transfer was found to have increased as planned. This indicates that proper surface finishing is still needed for a part after it is printed, just like in the case for a raw part manufactured using traditional techniques. Hence, there is currently an accompanying progress in surface finishing techniques, as the traditional manual and machine-based surface finish treatments have limitations in the process of additive manufacturing. The additive manufactured parts are typically rough and porous consisting of fused powders. For the surface finish of these parts, digitized and automated chemical treatment processes have been considered.

Improvement in Computational Capabilities

The complexity of the turbine operating environment involving unsteady and three-dimensional flow features is further exacerbated with cooling air-mainstream interactions. This level of complexity requires an accurate computation of both the flow field and the heat transfer phenomenon. In the extensive review of heat transfer and aerodynamics in axial flow turbines, it was stated that the state-of-the-art in heat transfer predictive capability has evolved from the use of two-dimensional boundary layer codes to the use of three-dimensional and unsteady versions [Dunn, 2001]. Since this review, some significant effort has been put forth regarding the modeling of turbulence effects both in commercial software and in in-house tools. The Reynolds-Averaged Navier-Stokes (RANS) solvers have been used with different turbulence models to investigate the computational accuracies in resolving vortical structures in the flow field, whereas the unsteady version of the solvers (URANS) have been used for the transient problems.

The aim of resolving turbulence in gas turbine flows have led to the use of the Large Eddy Simulation (LES). LES brings more accuracy as it only models the smaller scale of the three-dimensional random motions in the turbulent flow called eddies, and directly calculates the large-scale ones. This approach increases the prediction accuracy and provides instantaneous solutions as well. LES was originally proposed in the ‘60s, but it pulled the attention of blade cooling designers in the early 2000’s and has been widely used as a research tool since then. Within this same period following the progress in LES, the Detached Eddy Simulation (DES) was introduced which is a hybrid modeling approach that uses RANS for shear layers and LES for separated flow regions, bringing in considerable computational savings. Another approach that is currently of interest in the computational arena is the Direct Numerical Simulation (DNS). DNS is the direct solution of the full Navier-Stokes equations so that all scales of eddies can be resolved, but in return it requires significant amount of computational resources and time, which is currently not practical.

In blade cooling research, the steady and unsteady RANS and LES approaches and their hybrids have been employed for flow and heat transfer predictions in the analysis of film-cooling and internal cooling configurations. Furthermore, the complexity of engineering and scientific problems has led to parallel processing techniques regarding the use of computational resources and the advances in high-performance computing have enabled more efficient and time-saving solutions for detailed analyses. Such advances have considerably increased the predictive capabilities. There is a continuous effort in this area towards increasing the computational accuracy even further while achieving a reduction in computational expenses so that the blade cooling design process can benefit from. In one of such recent studies, measurements were conducted with Particle Image Velocimetry (PIV) and Temperature-Sensitive Paint (TSP) to investigate the flow and heat transfer, respectively, over a test section representing an impingement channel [Hossain et al., 2018]. The channel consisted of an orifice plate with cooling holes and a target plate, mimicking the impingement configurations similar to those used in turbine blade cooling. Computations with RANS and LES were also performed, and the predictive capabilities of the two approaches were analyzed by comparing the predictions with measurements. The results showed the superiority of LES over RANS in predicting the flow field and heat transfer phenomena in an impingement configuration. In another investigation, the film cooling performance of a showerhead arrangement at the leading edge of a first-stage nozzle guide vane was examined [Ravelli and Barigozzi, 2017]. Adiabatic film-cooling effectiveness was measured using the Thermochromic Liquid Crystals (TLC) technique. Numerical simulations were performed using RANS and DES, where the latter was observed to predict enhancement in the mixing between adjacent cooling jets compared to the former.

Thermal and Mechanical Stresses

Proper cooling is not only a heat transfer related concern but also requires the attention of aerodynamics and mechanical designers, since the thermal gradients in blade surfaces cause stresses and are detrimental to blade life. The improvement in cooling techniques has brought solutions to some existing challenges, but it has also generated new ones as the material temperature limits can be exceeded with today's technology by a considerable amount as shown in Fig. 1, resulting in higher heat loads. There is obviously a need for a detailed three-dimensional thermal-mechanical understanding in achieving operational durability. In an investigation, the relationship between the geometrical features of the cooling configuration and the resulting metal temperatures was studied based on differing configurations that are typically found in power generation and aircraft engines [Cunha et al., 2005]. It is obvious that a wise selection of cooling design parameters helps to achieve improved metal temperature distributions across the trailing edge, which determines the thermal-mechanical behavior of the design.

The use of pin fins, ribs, and some other coolant path features increases heat transfer area and also turbulence levels, which enhance internal heat transfer as desired. However, this process also gives rise to thermal gradients in blade material. Additionally, the use of film cooling holes produces local thermal stresses due to the local temperature differences in the vicinity of each cooling hole. Hence, one of the challenges is to reduce these thermal gradients, and one way to accomplish that is to ensure cooling to be as uniform as possible.

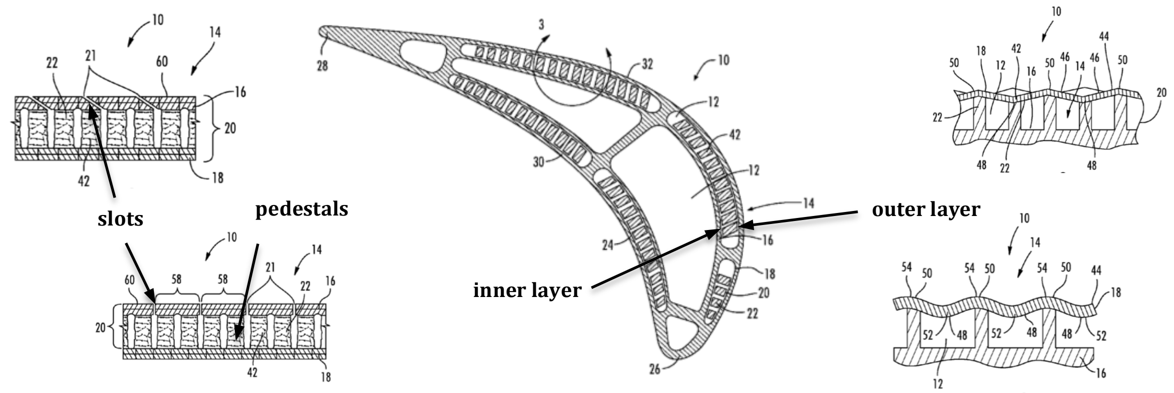

Fig. 7 Dual wall configuration [Campbell and Morrison, 2012]

Another way of reducing thermal gradients is to implement a double wall structure to separate the outer layer from the inner layer so that thermal expansion between the two layers is enabled, while reducing stresses. Multiple pedestal structures can be used for support between these layers. Additional slots may be used to limit the buildup of stress. This structure is introduced by the invention shown in Fig. 7 [Campbell and Morrison, 2012]. Here, the outer wall is the surface of the airfoil that is exposed to the hot gas path. This surface expands at a different rate than the inner wall as these two walls are separated. Fig. 7 also shows alternative double wall designs that implement pedestals, slots, and planar or non-planar outer layers.

Another challenge is that as cooling configuration becomes more complex with the use of alternative hole shapes, number, and arrangements, the structural strength of the blade weakens. The use of high-strength materials has been considered as another remedy to this problem. The thermal barrier coatings are also used to reduce blade tip oxidation and corrosion that is likely to occur in the harsh engine environment. This shows that the advances in materials are closely linked to the turbine blade durability.

Material Deposition and Blockage of Cooling Holes

As the turbine inlet temperature approaches the levels of 2000 K with the advances in cooling technology, the rotating turbine blades in this harsh operating environment have become more vulnerable to oxidation followed by material corrosion. As the blade rotates, the blade tip has the potential risk of wearing and erosion if it rubs against the opposite shroud causing material losses. Application of protective coatings on blade surfaces and particle ingestion into the flow path, on the other hand, result in material deposition. All these are the reasons for surface deterioration that eventually leads to alteration and blockage of cooling holes reducing cooling performance.

Particle ingestion can occur due to engine operations in dusty lands or over volcanoes. As these particles flow through hot gas path, not only do they damage blade surfaces by erosion, but also they are ingested into cooling holes and block the cooling passages. If not due to external flight conditions, the combustion products typically consist of different contaminants depending on the fuel type used, which again possess similar risks. Due to high operating temperatures, these particles also melt on the surfaces causing deposition and rougher surfaces. This results in a change in the hole exit geometry, a decrease in the cooling hole area, and typically leads to a reduction in cooling protection.

The effect of deposition of volcanic ash was examined by performing measurements on test pieces representative of an internal cooling passage with rows of holes [Wylie et al., 2017]. Samples from two volcano eruptions were used and the change in the flow parameter was calculated as the ash concentration, particle size, metal temperature, passage Reynolds number and the hole angle were changed. This study shows that there are several key parameters contributing to blockage amount in cooling holes that could be detrimental to engine operation. In another study, the effects of deposition of combustion products near cooling holes and the blockage of cooling holes, as well as the effect of spallation of thermal barrier coating were investigated [Sundaram and Thole, 2007]. Although an improvement in cooling effectiveness was observed up to a certain deposit height, with further increase in the deposit height the cooling effectiveness was found to decrease. Partially-blocked holes and thermal barrier coating spallation produced considerable amounts of degradation in film-cooling effectiveness. On the other hand, the effect of near-hole deposition on effectiveness was found to be rather dependent on the deposition height and location.

Free-Stream Effects

The combustion process introduces high levels of free-stream turbulence of up to 20% in the hot gas path. This value gradually decreases as the flow propagates through downstream blade rows. Additionally, the relative motion of the rotating blades with respect to the stationary ones gives rise to unsteadiness in the flow field. The rotating blades are periodically exposed to the wakes of the upstream stationary blades where periodic variations in static pressure, temperature, and velocity field as well as the turbulence intensity can be observed. Besides, if the turbine is operating in transonic regime, there will be also shock waves contributing to the unsteadiness in the flow field, likely to cause early boundary layer transition. On a rotating blade, the cooling flow that is in the vicinity of the hole exit is both affected by these fluctuations and the turbulence of the free-stream. Depending on the level of turbulence or unsteadiness in the flow, the hole geometry, and the blowing ratio, the cooling performance might improve or deteriorate. This clearly shows that detailed measurements of these flow parameters are critical for quantification of the changes in blade cooling performance under different circumstances.

In one of the studies focusing on free-stream effects, the effects of both an unsteady wake and the vane trailing edge cooling on the downstream turbine blade film cooling were analyzed [Li et al., 2012]. A spoked wheel-type wake generator having rods with cooling holes was used to generate the free-stream conditions. Measurements were performed with the Pressure Sensitive Paint (PSP) technique to obtain detailed film-cooling effectiveness distributions on the downstream blade surfaces. The results revealed that the overall film-cooling effectiveness was reduced due to unsteady wakes, but when combined with trailing edge coolant ejection, this trend was reversed. In another study, the free-stream turbulence effects on heat transfer over a leading-edge geometry was investigated using the LES technique [Kanani et al., 2018]. Calculations for different turbulence levels were performed and heat transfer coefficient and film-cooling effectiveness trends were compared over the surface. It was observed that increasing turbulence level increased heat transfer coefficient while decreasing cooling effectiveness.

Uncertainty in Predictions and Measurements

A thorough understanding of the complex turbine operating environment requires high-fidelity computations and measurements of flow field and heat transfer. However, this is bounded by the capabilities and limitations of the computational tools and the measurement techniques that are involved in the design work. Hence, quantification of uncertainty is necessary in order to build confidence in the tools and the techniques used.

Although the modeling of multi-physics and multi-scale engineering problems can be done with improved accuracy today with the advances in numerical algorithms, there is a continuous effort in this research area to reduce the turnaround time while increasing the reliability of predictions. Regarding the blade cooling design process, the wake-blade interaction between the blade rows that contributes to the unsteadiness in the flow field, or the rotation of internal cooling passages at high rotational numbers that significantly affects flow and heat transfer, are only some of the many complex problems that are of interest to the designers. For quantification of uncertainty in computations, validation of predictions with experimental data is an essential step. Therefore, obtaining high-quality data is also critical for reliable predictions. A detailed uncertainty analysis was performed where the statistical model of the measurements obtained from a 1-1/2 stage high-pressure turbine in a rotating rig was used to quantify uncertainty in the heat transfer predictions [Kahveci and Kirtley, 2014]. The vane row in the stage was fully cooled with hundreds of holes located at various parts of the airfoils. The blade did not have cooling holes on it, but it received the upstream cooling from the vane row and the additional coolant provided through the purge cavity between the vane and the blade rows. In the study, the inlet temperature profile, location of the gauges on the blade surface that were used for measurements, and surface roughness were varied to observe the effects on the blade heat transfer predictions. The results revealed that the profile variation was the most significant contributor to the overall uncertainty among the parameters studied.

Parallel to the efforts in the computational field, the experimentalists have been working on improving the existing experimental techniques and developing new facilities. Many of the blade cooling research found in literature is based on data obtained from stationary cascades. However, the effect of rotation and sources of unsteadiness that have significant impact on the main flow path cannot be fully generated in such facilities. Including rotating rods in a cascade setup upstream of the blade of interest helps to simulate the wake generated by an upstream vane that exists in the actual engine to some extent. Although used much less in number due to the complexity of their operation and the related costs, rotating rigs have been another type of facility used in turbine heat transfer experiments. The development of high-temperature and high-frequency response measurement devices has enabled unsteady measurements from turbine stages in rotating rigs operating under corrected engine conditions. In rotating rigs, the corrected engine conditions are matched, which is considered to be more closely simulating the actual engine environment. Nonintrusive optical techniques have also been used extensively in cooling experiments for flow and thermal field measurements. To obtain high-quality data sets to be used for validation of predictions, the uncertainties associated with steady and unsteady measurements must be understood and approaches to reduce these uncertainties must be developed. This has resulted in an ongoing effort in the improvement of calibration techniques, data acquisition, instrumentation, and accuracy of measurement devices. One example is the study where the uncertainty levels in the measurements of adiabatic film-cooling effectiveness obtained using the PSP measuring technique were investigated [Johnson and Hu, 2016]. The measurements were conducted in a low-speed wind tunnel using a flat plate with an array of cooling holes for a range of blowing ratios. It was observed that the PSP technique produced varying amounts of uncertainty depending on the location. Highest levels of uncertainty were observed to be at the near field behind the cooling holes.

As a rule of thumb, for blades limited by creep, a 10 K increase in blade metal temperature may decrease blade life nearly by half. For this reason, obtaining accurate predictions and measurements are crucial in the design of any blade cooling arrangement that is responsible for providing adequate amount of cooling to the critical spots on blade surfaces that have the risk of overheating.

CONCLUSIONS

Blade cooling is a technology in the heart of gas turbine hot gas path design. In gas turbines, an increase in the turbine inlet temperature results in higher thermal efficiency and higher power output. For this reason, today's modern gas turbine designs are driven towards even higher-temperature operations, which requires further advances in materials and the use of higher amount of cooling. Proper cooling of a turbine blade can be achieved by implementing a combination of various techniques in different parts of the blade both internally and externally. Design features used in each of these techniques are continuously improved by the help of experimental findings and computational studies. Since a successful design relies on the use of high-quality experimental data and accurate predictions as well as on the manufacturing capabilities, the limitations in all of these areas need to be overcome by practical and cost-effective solutions. These challenges have been the motivations behind the evolution in blade cooling technology. This paper provides a background in blade cooling techniques, points to some of the complexities in the cooled turbine blade environment, and discusses some of the recent advances and challenges in the area of blade cooling design.

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