A Review Paper on Gas Turbine Blade Cooling Methods

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ABSTRACT

For aircraft propulsion, land-based power generation, and other industrial applications such as trains, marines, automobiles, etc., gas turbines are commonly used. The operating temperature must be raised to increase the thermal performance and output work of the gas turbine engine to accommodate the accelerated production of modern gas turbines. The heat transmitted to the turbine blade, however is greatly increased as the temperature of the turbine inlet is constantly increased. For a long service life and healthy running, it is also very important to cool the turbine blades. Currently available methods for cooling turbine blades include film cooling with impingement cooling for the front edge, turbulent rib cooling with serpentine passages for the middle section of the blade, and pin-fin cooling for the trailing edge of the turbine blade. The cooling system for turbine blades must provide cooling for all potential regions that are subjected to hot gas flow. This paper provides a literature review of blade tip leakage and heat transfer, as well as studies into external and internal cooling technologies.

KEYWORDS: Gas turbine, Turbine inlet temperature, turbine blade cooling, internal convective cooling, Pin fin cooling, and dimples/protrusions

I. INTRODUCTION

A gas turbine is an engine designed to turn a fuel's energy into usable power of some manner, such as shaft power or thrust. Nowadays, gas turbines (GTs) are commonly used in aircraft propulsion, land-based power generation and other industrial applications. For e.g., GTs are used to power commercial aircraft, marines, trains, electrical power generators, cars and gas pipeline compressor drivers.

The reasons for the popular use of gas turbine engines for aircraft propulsion are that they are lightweight, compact and have a high power-to-weight ratio. A gas turbine engine has three primary components: the compressor, the combustor, and the turbine. The compressor is used to compress the incoming air to a particular high pressure, the combustor is used to burn the intake fuel and create the gas at high temperatures, and the turbine extracts and transforms the gas energy into electricity. In the gas turbine system, a variety of components often occurs to boost network performance or thermodynamic quality, e.g., intercooler, recuperator, regenerator, and reheater for combustion. It is important, however to carefully determine the balance of additional capacity, performance, quality, complexity, longevity, compactness, etc.

Adiabatic, reversible, and frictionless are considered the optimal standard cycle. The total thermodynamic efficiency depends on the efficiency of all sections, such as the efficiency of the compressor, the efficiency of the turbine and the efficiency of combustion. Clearly, the performance of the turbine can influence the efficiency of the cycle to some degree. Improving turbine efficiency will also continue to increase a gas turbine engine's overall performance, while losses in turbine efficiency and/or output work will decrease the system's overall performance. The operating temperature of the gas turbine system influences the overall performance in addition to component efficiencies.

It is well understood that one way to improve a gas turbine engine's power output and thermodynamic performance is to increase the temperature of the turbine inlet (TIT). The explanation is that the net work output of a gas turbine increases with increasing turbine blade (also called rotor) inlet temperature at a defined pressure ratio, based on the principles of engineering thermophysics [1, 2]. Latest TIT innovations from 1950 to 2010 are seen in Figure 1. At TIT, modern advanced gas turbine engines run from about 1200-1500°C.
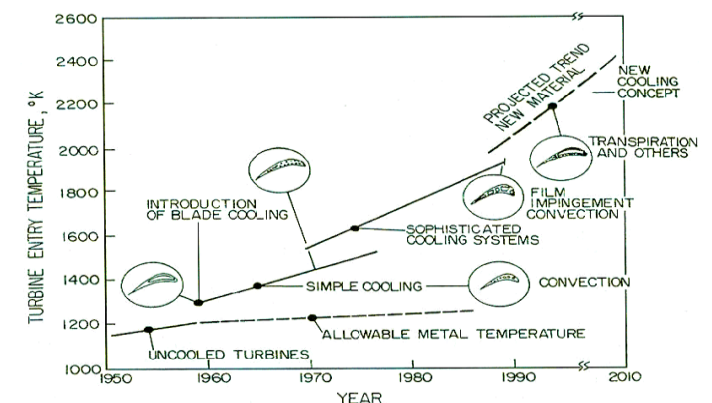

Figure 1. Developments of gas turbine inlet temperature over recent years.

The inlet temperature should be gradually elevated to higher targets to pursue greater control. For instance, to double the aircraft's capacity, the TIT should be increased from 1500 to 2000 °C.However with the rise in blade inlet temperature, the heat applied to the blade increases, and the permissible melting temperature of materials increases at a slower rate. This implies that the inlet temperature of the turbine blade will exceed the melting temperature of the material by more than 500 °C. Thus, cooling turbine blades for a safe and long-lasting operation is important. Only if reliable cooling systems are used will the blades survive. To lower the temperature of the blade content below its melting point, different internal and external cooling techniques are employed.

The standard cooling technology for internal and external zones is represented in figure 2. With film cooling, the leading edge is cooled by jet impingement, the middle section is cooled by internal serpentine ribbed-turbulators passages, and pin-fins with ejection cool the trailing edge.
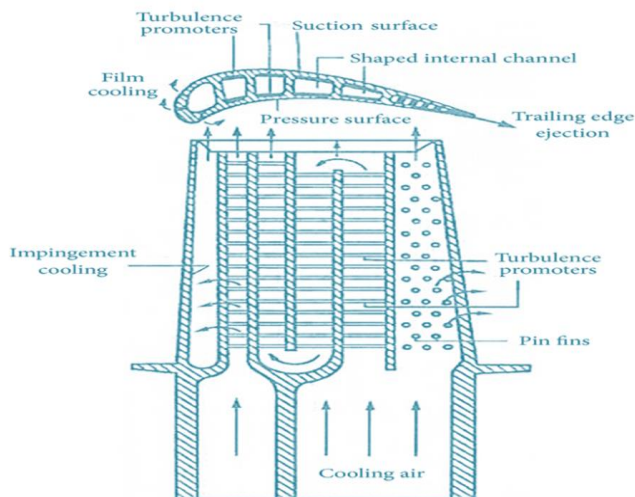
Figure 2. Typical gas turbine cooling structure.

II. METHODS OF COOLING

As applicable to gas turbine components such as high-pressure turbine vanes and blades, cooling technology consists of five main elements that must work in harmony, (1) internal convective cooling, (2) external surface film cooling, (3) choice of materials, (4) thermal-mechanical architecture, and (5) coolant fluid selection and/or pre-treatment.

The comparatively cold air, bypassed/discharged from the compressor, is directed through the hollow coolant passages within the turbine blade during internal cooling. The bypassed air is expelled through certain narrow openings, which are positioned discreetly in the turbine blade, during external cooling. A mixture of internal and film cooling is the widely used cooling system for the high-pressure turbine blade.
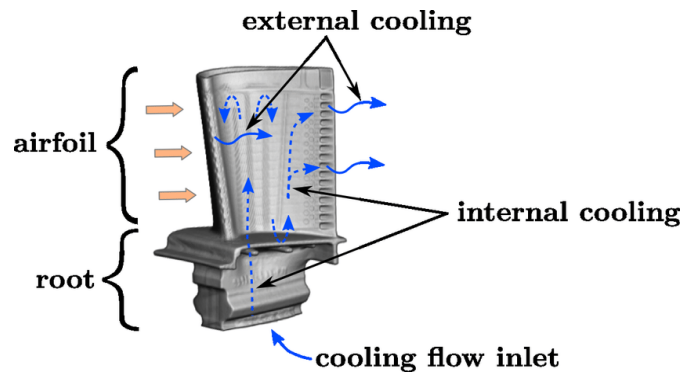
Figure 3. Cooling flow in a turbine blade. Internal serpentine channels are visible by transparency.

High-temperature, high-strength nickel- or cobalt-based super alloys coated with yttria-stabilized zirconia oxide ceramics (thermal barrier coating, TBC) are the components most widely used in cooled sections. Today, protective ceramic coatings are actively used to increase the cooling power of the internal processes of convection (see Thermal Barrier Coatings).

These first three elements must be combined with the **thermal-mechanical design** of the components into a kit that has suitable thermal stresses, coating stresses, oxidation limits, creep-rupture properties, and aero-mechanical reaction.

The last aspect of the cooling design concerns the correct selection of the cooling fluid to execute the role needed with the least effect on the efficiency of the cycle. This is typically accomplished by using compressor air bleed from the compressor's most beneficial level, but it may also be accomplished using off-board cooling sources such as closed-circuit steam or air, as well as intra-cycle and inter-cycle heat exchangers.

III. INTERNAL COOLING

Internal cooling consists mainly in using convective heat transfer in internal channels to extract heat from the blade metallic wall to cool it down. To do so, more or less complex channels are hollowed out of the blade metal. Internal designs may therefore go from simple radial straight smooth channels extending from the hub to the tip, to long serpentine channels with turbulence promoters. A large panel of internal convective cooling systems has been developed since the first smooth channels in the 1960's to improve heat exchanges. A list of the available designs may be the following: surface roughness, rib arrays, jet impingement, dimples, pin fins and swirl chambers.

The main principles on which these systems are based are the augmentation of exchange surface through flow turbulence increase. Many different arrangements are possible and they may be classified following the heat transfer increase in comparison to a similar smooth channel without any cooling enhancement system. To be able to take into account any geometry, this parameter is commonly define as the ratio of the cooling system

Nusselt number Nu to the smooth channel Nusselt number Nu_0. As the main objective of blade cooling, heat transfer maximization while minimizing the pressure drop penalties, the cooling systems may also be classified following ratio comparing modified channel friction factors f to smooth channel friction factors f_0.

3.1. INTERNAL COOLING HEAT TRANSFER AUGMENTATION TECHNIQUES

Rib turbulators, pin fins, dimpled surfaces, surfaces with rows of protrusions, swirl chambers, and surface roughness [1] are the methods used to increase convective heat transfer rates for internal cooling of turbine airfoils of gas turbine engines.

In order to enhance mixing, both of these systems work to enhance secondary flows and turbulence levels, in some cases to form coherent fluid movements in the form of stream wise-oriented vortices. Such vortices and secondary flows work not only to increase secondary heat advection away from surfaces, but also to increase the output of three-dimensional turbulence by increasing shear and generating velocity gradients over large volumes of flow. These then provide higher turbulence transport magnitudes over greater portions of the flow fields. By increasing surface areas for convective heat transfer, all of the devices listed also have some heat transfer augmentation. Optimum thermal safety with limited use of coolant air and coolant mass flow rates as minimum as possible, and limited pressure drop penalties inside coolant passages is the ultimate goal for such internal cooling technologies.

3.1.1. Pin fin arrays

Pin fins or pedestals are typically organized into arrays as used for internal cooling and extend between two opposite walls of an internal cooling passage. Pin fins are typically used in sections of turbine airfoils where higher levels of increase in heat transfer are needed and where high-pressure drops are tolerated and even desired in many situations.

High Reynolds coolant numbers, combined with high coolant pressure ratios, are ideal for heat transfer. The trailing edges of airfoils fall into this group. However, it has always acquired a large amount of heat by the time the coolant reaches the trailing edge, and the task of removing heat from trailing edge components is more complex relative to other sections of the airfoil.

Around the same time, output constraints on the width of the trailing edge slots preclude the coolant from being sufficiently limited, thereby forcing the flow to be determined upstream. Pin fins or pedestals provide sufficient structural protection near the trailing edge and are successful in allowing the pressure to stay high over much of the cooling circuit, while providing the required constraint near the trailing edge to reduce the consumption of coolant to the desired degree.

3.1.2. Dimple Surfaces

Dimples are indentation arrays around the surfaces. These are most commonly circular in form, but a number of other shapes, including triangular and tear-drop, have also been used. Arrays of dimples are a useful internal cooling strategy because they create several vortex pairs that enhance local distributions of Nusselt numbers as they advect downstream. They are remarkable for the penalties they create for low pressure drop, which is because they do not protrude into the flow and produce large levels of shape drag. With this advantage, dimples give advantages for cooling later turbine stages where cooling air is used for lower pressure. They are also advantages because the

pressure drop they create through an airfoil passage is comparatively minimal, allowing desirable pressure margins to be retained in more downstream areas of the airfoil interior.

In comparison to rib turbulators and pin fins, which require additional material and weight, another advantage is that dimple processing eliminates material from internal cooling passage components.

3.1.3. Rib Turbulators

Rib turbulators are frequently positioned around the surface in the shape of rectangular cross-sectional bars that are often bent with respect to the direction of bulk flow. They work to start the flow, combine the flow, and even create vortices and three-dimensional gradients of velocity when they protrude into the flow. In cooled airfoils, rib turbulators or trip strips are general-purpose heat transfer augmentations.

The cooling scheme may be optimised in such a way that the airfoil mid-body is not overcooled by modifying the key geometric parameters, trip strip height, channel blockage, direction, and spacing, while providing the requisite escape temperatures at the leading edge and trailing edge where film cooling may be needed. Ribs are rarely rectangular in cross-section as used inside turbine components due to casting limitations. Instead, owing to manufacturability constraints, they also keep more rounded profiles.

3.1.4. Swirl Chambers

Swirl chambers are internal flow passages arranged with either spinning vanes, internal inserts, or inlets and outlets designed to induce large-scale flow swirling (relative to the dimensions of the chamber) usually around the main chamber axis. This large-scale swirling and the pairs of Görtler vortex that are generated increase the transport rates of surface heat.

IV. LITERATURE REVIEW

Typically speaking, in order to increase the thermal performance of the aero-engine[1, 2], the blades and hubs of a gas turbine generally have to bear an rising temperature. Owing to the constraint of the sustainable temperature of the metal components, the turbine 's cooling techniques are becoming increasingly necessary and emphasised.

In recent years, in the tip region of the turbine blade, multiple augmentation devices such as fins, ribs, pins, and dimples / protrusions have gained a lot of attention to enhance heat transfer. Many computational simulations have been conducted in the meantime. Recently, a variety of experiments have been presented on inner cooling heat transfer augmentation techniques. A brief overview of the relevant literature is listed in this chapter to highlight the amount of work already published in the open literature on the development of augmentation techniques for internal cooling heat transfer.

4.1. PREVIOUS WORK

Ligrani et al. (2003) By comparing the flow structure, heat transfer, and friction factor of all these systems, some standard cooling strategies, including pin fin arrays, dimple, and rib turbulator, were summarised. The convective heat transfer can be distinctively enhanced by the pin fin arrays.

In addition, pin fin arrays will increase the reliability of the structure of the hollow trailing edge area of the blade [3].

Several experiments have been carried out on the heat transfer effects of the pin fin arrays. The heat transfer efficiency and friction factor of pin fin arrays with distinct height-to-diameter ratio and array orientations were analysed by **Metzger et al. (1982).** The findings showed that both of the above factors were significant in influencing the convective heat transfer of the channel with pin fins[4, 5].

In order to calculate the heat transfer coefficient and resistance, **Chen et al. (1997)** used the naphthalene sublimation technique. The study showed that for channels with drop-shaped pin fins, the heat transfer improvement was higher than for channels with circular pin fins [6].

Choi et al. (2007) a series of studies were performed to research the results of pin fin arrays with various angles of inclination and concluded that the inclination of the pin fin arrays caused the rise in heat transfer to deteriorate [7].

Chyu et al. (2007) a liquid crystal imaging technique was used to test the output of pin fins with circular, cubic, and diamond shape heat transfer. The findings revealed that the transfer of heat from the arrays of cubic pin fin and diamond pin fin arrays is greater than that of the arrays of circular shaped pin fin arrays [8].

Furthermore, **Zhou and Catton (2011)** In a plate-pin fin heat sink with different pin cross section (square, circular, elliptical, NACA profile, and drop-from) the flow and heat transfer was measured by a numerical approach and concluded that the square cross section pin-fin had the best heat transfer increase of all the pin fins investigated[9].

Later, **Siw et al. (2012)** via a comprehensive experiment, the heat transfer efficiency of triangular, semicircular, and circular shaped pin fins was investigated. The findings calculated by hybrid liquid crystal imaging showed that the largest heat transfer increase was provided by the triangular shaped pin fin array but also followed by the highest friction factor [10].

With the elevated turbine inlet temperature, the need for cooling alone can not be fulfilled by pin fin arrays. Thus, to be blended with the pin fin arrays, several other methods are added. With minor lack of pressure, dimples and protrusions are fine options. Dimples and protrusions are produced on a smooth surface to indent or protrude in order to produce high kinetic energy turbulence (TKE) flow and facilitate heat transfer. Many research, including dimple forms, dimple depth, and so on, have been carried out to figure out the impact of the dimple geometrical factor on the heat transfer and flow structure.

Ligrani et al. (2001) Experiments to visualise the flow pattern of the airflow in the vicinity of the dimple were performed and the heat transfer enhancement process was clarified. Periodic appearance and shedding of the vortex pair will, according to his theory, boost the speed of the turbulence and thus greatly increase the heat transfer [11].

Burgess and Ligrani (2005) lot of experimental studies have been carried out to examine how the width of the dimple impacts the amount and friction factor of the Nusselt tube. Experimental findings found that vortices and related secondary flow with higher turbulence strength were caused by a deeper dimple. For a stronger heat transfer boost, higher turbulence mixing is responsible. The channel pressure penalty [12] could also be raised by deeper dimples, though.

Park and Ligrani (2005) heat transfer and friction factor of surfaces assigned to dimples in various cross sections have been investigated. Cylindrical types were regarded as circular, triangular, and titled. The local distribution of heat transfer revealed that the spherical shaped dimple had the highest value for heat transfer [13].

Rao et al. (2015) to explore dimples of various forms, that is, circular, teardrop-shaped, elliptical, and inclined elliptical, experimental and computational tests were conducted. The teardrop-shaped dimple has the highest value for heat transfer augmentation based on its findings [14].

Other scholars have also published experimental and computer experiments on the shape of dimples, the depth of dimples, and the configuration of dimples[15-19].

Luo et al. (2016, and 2018) to research the effects of dimple configurations, dimple depth, and converging angle in a pin fin channel / duct on the heat transfer and flow structure, computational methods were used. The dimple-pin fin channel results showed a tremendous output of heat transfer increase [20-23].

Many experiments have been carried out progressively, based on the effects of protrusion on the flow system and heat transfer.

Kithcart and Klett (1996) On flat plates with hemispherical dimples, hemispherical protrusions, and rectangular protrusions, skin friction and heat transfer were measured. The results showed that the heat transfer with lower pressure drop penalty was greatly improved by hemispherical dimples [24].

Hwang et al. (2008) the coefficients of heat transfer on dimple or protrusion walls were tested. The findings obtained by the transient liquid crystal thermochromics showed that the double protrusion-wall provided the best value for heat transfer but was also correlated with the largest decrease in pressure [25].

Kim et al. (2012) in a cooling passage with a protrusion-in-dimple wall, a numerical analysis was carried out and the heights of the protrusions were the geometry parameters for their study. They indicated that when the dimensionless height of the protrusion was 0.05, the pressure drop and heat transfer were increased [26].

Xie et al. (2013) conducted more studies on the role of the internal protrusion in a dimple. The key design parameters were the positions of the protrusion installed in the dimple cavity along the stream-wise direction. This research culminated in a significant improvement in the fluid flow area in the region of the inner-protruded dimples. Cases with internal protrusion installed in the dimple's rightmost central location yielded the highest improvement in heat transfer [27].

Besides, **Xie et al. (2015)** Using a numerical approach, they explored a rectangular channel with teardrop dimples or protrusions. The study claimed that the teardrop dimple / protrusion displayed improved heat transfer efficiency at a lower Reynolds number relative to a hemispherical dimple / protrusion [28].

Hwang et al. (2010) Local heat transfer and thermal output were investigated with transient TLC (thermochromics liquid crystal) technique on periodically dimple-protrusion plates. The findings showed that the thermal efficiency at a given Reynolds number for all the plates tested was similar [29].

Lan et al. (2011) In the Reynolds number range of 10,000 to 60,000, mixed ribs, dimples, and protrusions and five cases of separate combinations were studied. The findings showed that in a rectangular tube, the combination of rib and protrusion techniques had the ability to provide low-pressure drop penalty heat transfer enhancement [30].

Luo et al. (2017, 2018) To analyse the flow structure and heat transfer properties of a channel / duct with dimples / protrusions, a numerical approach was used. According to their results, converging angle channels demonstrated a stronger improvement in heat transfer but was also followed by a greater loss of pressure. In comparison, the protrusion cases provided improved heat transfer and greater loss of friction compared to the dimple cases [31, 32].

Wang et al. (2019) The heat transfer properties of a dimpled / protusioned pin fin wedge duct with multiple converging angles for turbine blades have been investigated. According to their data, the larger converging angle pin fin-dimple wedge duct achieves higher heat transfer enhancement due to flow acceleration, impingement area rise, and flow recirculation region shrinkage, but it is also followed by a much larger friction factor. A wider converging angle pin fin-protrusion wedge duct induces greater heat transfer increase due to flow acceleration and more extreme impingement on the protrusion, but it is often associated with a greater pressure penalty [33].

V. CONCLUSIONS

The development of internal cooling configurations for gas turbine engines is subject to several major restrictions. In addition to heat transfer and thermal concerns, meeting these restrictions includes simultaneous consideration of multidisciplinary problems, such as output, airfoil surface cooling requirements, aerodynamic losses, supply of coolant, second law losses, required volume capacity, airfoil shape, and pressure drop penalties. As a result, current and future trends for advanced turbine part cooling architecture include parallel production of internal cooling technology of external thermal safety systems, such as film cooling, including consideration of adjacent conjugate conduction differences in adjacent solid components, as well as related penalty problems with aerodynamic pressure loss.

Designers, designers and researchers must build internal cooling systems with combinations of various devices together within one coolant passage to satisfy these specifications. Optimal thermal safety and minimum pressure loss penalties are the resulting targets.

The cooling efficiency of the blade inner tip area should be further investigated based on analysis, especially when organised with a heat transfer enhancement structure. In recent years, in the tip region of the turbine blade, multiple augmentation devices such as fins, ribs, pins, and dimples / protrusions have gained a lot of attention to enhance heat transfer. With increasing inlet temperature of the turbine, pin fin arrays cannot satisfy the need of the cooling alone. To be paired with the pin fin arrays, several more methods are also added. With slight loss of pressure, dimples and protrusions are fine options. In order to produce high turbulence kinetic power (TKE) flow and facilitate the heat transfer, dimples and protrusions are created to indent or protrude on a smooth surface.

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