

Research Article

Gas Turbine Blade Cooling Technology–A Case Study

Pranay Pudake*, A. M. Elgandelwar and Mandar M.Lele

Mechanical Engineering Department, MIT Kothrud Pune, Savitribai Phule Pune University, Maharashtra, India

Accepted 12 March 2017, Available online 16 March 2017, **Special Issue-7 (March 2017)**

Abstract

A gas turbine works on a Brayton cycle. The efficiency of an ideal Brayton cycle depends on the compression ratio and inlet temperature of the gas entering the turbine. If the inlet temperature of gas increases then the efficiency of the Brayton cycle increases. But the inlet gas temperatures has a limit due to the physical properties of the turbine blades. By sophisticated cooling technique and introduction of high temperature withstanding materials, this limitation can be overcome to a great extent. In this paper, various general types of cooling technologies used for cooling the turbine blades are explained. Also new recent types of cooling techniques for gas turbine, different new technology used in gas turbine blade material are explained with case study.

Keywords: Gas turbine engine, Compressor, Turbine, blade, Heat transfer enhancement etc.

1. Introduction

A gas turbine works on a Brayton cycle consisting of 4 processes: 1) isentropic compression 2) expansion, and 3) constant pressure heat addition and rejection as shown in figure 1.

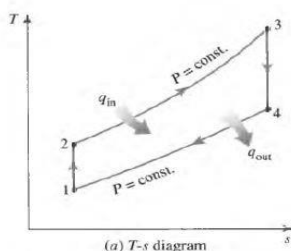


Fig.1 T-s diagram for an ideal Brayton cycle

The efficiency of an ideal Brayton cycle is given by,

$$\eta_{Brayton} = 1 - \frac{1}{(r_p)^{\frac{\gamma}{\gamma-1}}} \quad \text{and} \quad r_p = \frac{P_2}{P_1} = \left(\frac{T_3}{T_4}\right)^{\frac{\gamma}{\gamma-1}}$$

Thus with an increase in the compression ratio which depends on T3, the efficiency of the Brayton cycle increases. The inlet gas temperature has a limit due to the physical properties of the turbine blades. By sophisticated cooling technique and introduction of high temperature withstanding materials, this limitation can be overcome to a great extent. It is a common practice to have multiple cooling passages inside the blade through which coolant fluid is bled in the radial direction. Cooling techniques include jet

impingement, enhanced cooling with rib turbulators, and pin fin method.

Due to the nature of its working, the power generated by a turbine increases with increasing the temperature at which the gas enters, called the turbine inlet temperature. An increased power output results in a higher efficiency. However, the turbine inlet temperature cannot be increased arbitrarily because of the limits imposed due to the temperature at which the blade material melts. Although advances have been made in material science to make new alloys having high melting points that can withstand operation at such high temperatures without failing, these materials are expensive and are difficult to machine (Yugesh Patnaik, 2015).

As the blade material melts at a lower temperature than the operating conditions of the turbine, a cooling method must be incorporated into the blade design to ensure the safe and smooth running of the turbine. It is important, while devising a cooling scheme, to have knowledge about the boundary conditions of the blade during turbine operation, so that large gradients can be avoided. This is because large gradients cause thermal stress cutting the component life short significantly (Yugesh Patnaik, 2015).

2. Types of Cooling

There are two broad categories of cooling used in gas turbine blades:

- 1) Internal Cooling
- 2) External Cooling

*Corresponding author: **Pranay Pudake**

In internal cooling, the cool compressed air flows internally within the passages of the turbine blade and thus heat transfer occurs between the cold air in the passage and the adjacent hot surface of the blade. In external cooling, the cool compressed air is ejected from holes on the surface of the blade or the vane and creates a thin film between the surroundings and the blade surface thus preventing contact between the hot air and the blade surface, enhancing heat transfer (Yugesh Patnaik, 2015).

2.1 Types of Internal Cooling

There are various types of internal cooling which have been developed over the years. No particular type of cooling is suitable for all blades for all applications. Thus the cooling scheme must be selected according to operating conditions and requirements of the application at hand.

2.1.1. Impingement Cooling

Impingement cooling is commonly used near the leading edge of the airfoils, where the heat loads are the greatest. With the cooling jets striking (impinging) the blade wall, the leading edge is well suited for impingement cooling because of the relatively thick blade wall in this area. Impingement can also be used near the mid-chord of the vane. Fig. 2 shows jet impingement located throughout the cross-section of an inlet guide vane. Several aspects must be considered when developing efficient cooling designs. The effect of jet-hole size and distribution, cooling channel cross-section, and target surface shape all have significant effects on the heat transfer coefficient distribution. Jet impingement near the mid-chord of the blade is very similar to impingement on a flat plate; however, the sharp curvature at the leading edge of the vane must be considered when utilizing impingement in this region (Je-Chin Han, Lesley M. Wright, 2009).

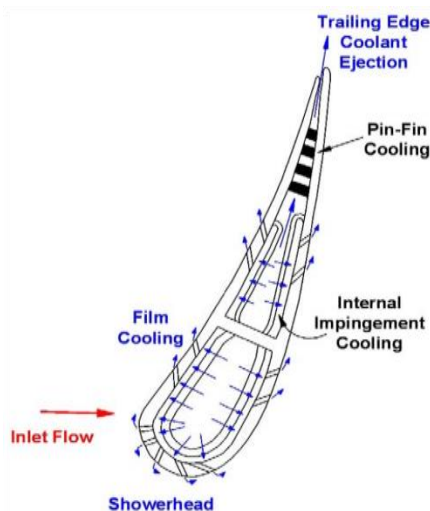


Fig.2 Schematic of a Turbine Vane Cross-Section with Impingement and Trailing Edge Pin-Fin Cooling

2.1.2 Pin Fin Cooling

Due to manufacturing constraints in the very narrow trailing edge of the blade, pin-fin cooling is typically used to enhance the heat transfer from the blade wall in this region. The pins typically have a height-to-diameter ratio between 1/2 and 4. In a pin-fin array heat is transferred from both the smooth channel end wall and the numerous pins. Many factors must be considered when investigating pin-fin cooling. The type of pin-fin array and the spacing of the pins in the array effect the heat transfer distribution in the channel. The pin size and shape also have a profound impact on the heat transfer in the cooling passage (Je-Chin Han, Lesley M. Wright, 2009).

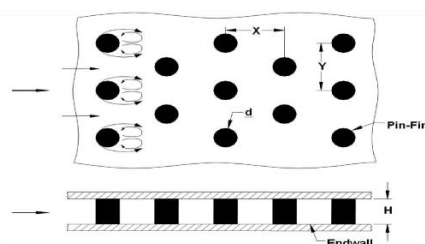


Fig.3 Pin Fin Cooling at Trailing edge of Turbine Blade

2.1.3 Dimple Cooling

In recent years, dimples have been considered as an alternative to pin-fin cooling. Dimpled cooling is a very desirable alternative due to the relatively low pressure loss penalty (compared with pins) and moderate heat transfer enhancement. A typical test section for dimple cooling studies is shown in figure 4; this figure also shows the dimple induced secondary flow. These concave dimples induce flow separation and reattachment with pairs of vortices. The areas of high heat transfer include the areas of flow reattachment on the flat surface immediately downstream of the dimple. The heat transfer in the dimpled channel is typically 2 to 2.5 times greater than the heat transfer in a smooth channel with a pressure loss penalty of 2 to 4 times that of a smooth channel (Je-Chin Han, Lesley M. Wright, 2009).

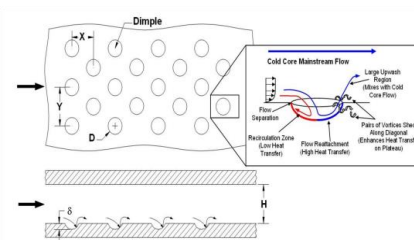


Fig. 4 Dimple Cooling

2.1.4 Rib Turbulated Cooling

Rib turbulators are the most frequently used method to enhance the heat transfer in the internal serpentine cooling passages. The rib turbulence promoters are

typically cast on two opposite walls of the cooling passage. Heat that conducts from the pressure and suction surfaces through the blade walls is transferred to the coolant passing internally through the blade. The heat transfer performance of the ribbed channel depends on the channel aspect ratio, the rib configurations, and the Reynolds number of the coolant flow (Yugesh Patnaik, 2015).

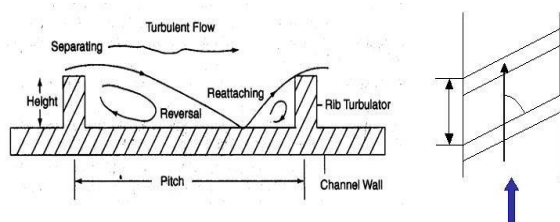


Fig. 5 Rib Turbulated Cooling

2.2 Types of External Cooling

2.2.1 Film Cooling

Film cooling is one of the major technologies allowing today's gas turbines to obtain extremely high turbine firing temperatures, subsequent high efficiencies, and longer life parts. In turbine blade film cooling, relatively cool air is injected from the inside of the blade to the outside surface, which forms a protective layer between the blade surface and hot mainstream. These film-hole patterns (i.e., film-hole location, distribution, angle, and shape) affect film-cooling performance. The art and science of film cooling concerns the bleeding of internal component cooling air through the external walls to form a protective layer of cooling between the hot gases and the component external surfaces. The application of effective film cooling techniques provides the first and best line of defense for hot gas path surfaces against the onslaught of extreme heat fluxes, serving to directly reduce the incident convective heat flux on the surface (Je-Chin Han, Lesley M. Wright, 2009).



Fig. 6 Film Cooling

3. Recent Cooling Techniques for Gas Turbine

3.1 Internal Cooling Passages with a Compound Surface Features

Because of the advancement in manufacturing techniques, innovative approaches of producing

compound surface roughness become the frontier of heat transfer enhancement in gas turbine airfoil cooling. The approach of having two or more surface features involving rib-turbulators, pin-fins, and dimple has received much attention from various groups of research in the past several years. Instead of achieving significant wetted surface area for effective heat transfer area, the combination of two or more surface enhancement features allows turbine designers to have various design solutions for heat transfer and pressure loss objectives. However, this practice is usually penalized by the pressure loss in the system (Minking K. Chyu, Sin Chien Siw, 2013).

General Electric, filed a patent in 2007 for introducing the innovative cooling technique of combined dimples, pin-fins and rib-turbulators. Figure shows an exemplary model of dimples combined with either Chevron rib-turbulators or pin-fins.

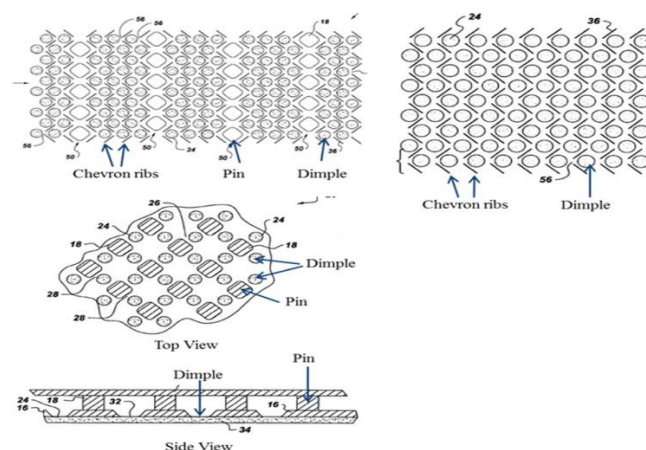


Fig. 7 Innovative cooling configurations with dimple and mesh

Murata *et al.* performed experimental and numerical studies on combined dimples, short pin-fins and rib-turbulators, the region around the dimple showed moderate HT enhancement compared to the pin-fin and rib turbulator (Minking K. Chyu, Sin Chien Siw, 2013).

A study by Lan *et al.* explored several configurations, which involved a combination of rib-turbulators, dimples, and hemispherical shaped protrusions, numerically using ANSYS Fluent revealed similar conclusions with Murata *et al.* The simulation results concluded that the highest heat transfer enhancement is obtained using the protrusions combined with rib-turbulators. These results concluded that lower heat transfer is observed on the dimples where the recirculation occurs and higher heat transfer is observed using protrusions where the flow reattaches. The presence of hemispherical shaped protrusions has further enhanced the heat transfer by approximately 10%.

A study by Rao *et al.* concluded that dimples with pin-fins exhibit superior heat transfer performance compared to pin-fin arrays alone while producing

lower pressure losses. The presence of dimples in the pin-fin array has induced turbulence and mixing in the flow near the wall by producing multiple vortex pairs periodically, which enhanced the turbulent flow heat transfer from the end wall and the pin fins. As dimples tend to reduce the hydrodynamic resistance in the flow domain, the pressure loss in the pin-fin and dimple arrays is ultimately dominated by the blockage and frictional drag induced by the pin-fins. Overall, the pressure loss of the pin-fin and dimple arrays is approximately 10–25% lower than that of pin-fin array

Recently, Siw *et al.* performed a detailed experimental study on the combination of detached pin-fin and rib-turbulator arrays using the transient liquid crystal technique. Figure 8 illustrates the top view of the test section in their study which consists of two newly proposed ribs, named as broken rib and full rib. The results of the local heat transfer coefficient distribution, show the heat transfer along the rib-turbulators and the region immediately behind the ribs is enhanced substantially, which contributed to greater convective heat transfer on the end wall. Depending on the geometry and length of the rib-turbulators, evidently, the presence of rib-turbulators has a great impact towards the flow field on the end wall. In the full-rib case, the horseshoe vortices are largely altered as the ribs are extended up to the base of the pin-fin whereas in the baseline (without ribs) and broken rib cases, the horseshoe vortices are preserved. Detailed comparison revealed that the local heat transfer coefficient on the endwall is enhanced substantially, by approximately 20% to 50% compared to the neighboring pin-fin, while induced insignificant pressure loss to the entire domain (Minking K. Chyu, Sin Chien Siw, 2013).

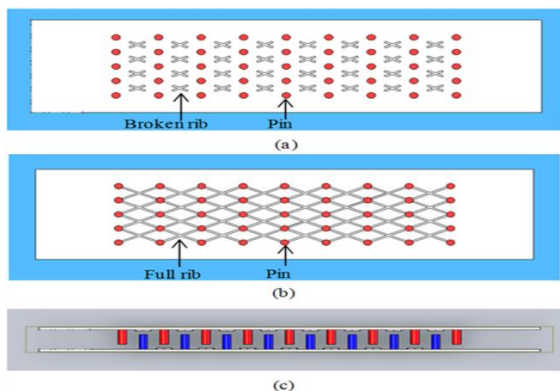


Fig. 8 Schematic layout of detached pin-fin with broken rib and full rib

3.2 Latticework (Vortex) Cooling

Latticework cooling, also known as vortex cooling or bounded vertical duct cooling, in its application to high temperature gas turbine components originated within the former Soviet design bureau engineering system 25 years ago. Latticework cooling can most simply be described in the radial cooling channel format shown in Fig. 9.

The very name is descriptive of the geometry which forms the basic sub-element of the design, “latticework cooling” by means of coplanar crossing channels. The two portions of sub-channels are oriented so as to oppose each other, or cross as in a latticework design. When cooling flow enters the main network, such as at a blade root section, essentially half proceeds in the upper sub-channels, and half in the lower sub-channels, with little or no mixing between upper and lower sub-channels. The main action within this cooling design comes at the edges of the lattice network where the sub-channels encounter seemingly “dead ends” or “bounding” walls, these would be the interior rib or the external wall of an airfoil design. The main advantages of this technology include (1) a robust architecture for investment casting with ceramic cores, (2) overall heat transfer coefficient enhancement levels comparable to those of turbulated serpentines, (3) similar overall pressure losses to turbulated serpentines, and (4) a potentially higher blade strength (R.S. Bunker, 2008).

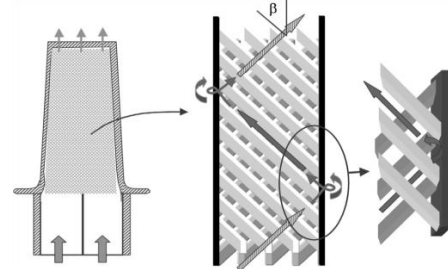


Fig. 9 Schematic of latticework cooling

3.3 Swirl (Cyclone) Cooling

In the broadest sense, the concavity surface flows are one of a larger category known as “vortex” technologies, which include various means of the formation of organized vertical or swirling flows in turbines. Another emerging vortex technology is the use of discrete wall jets injected into concave cooling passages, or along concave internal wall sections, to induce a bulk swirl motion. This cooling technique is generally known as swirl cooling, and also cyclone cooling. Figure 10 shows two sketches of swirl cooling chambers implemented inside a blade leading edge, one without film extraction and the other with film extraction. Swirl cooling can provide equivalent overall heat transfer to that of direct impingement (R.S. Bunker, 2008).

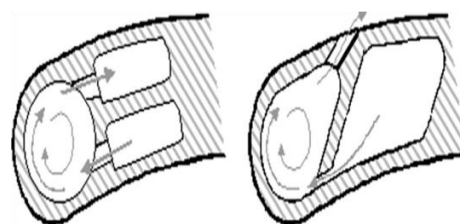


Fig.10 Swirl (cyclone) cooling passages

4. New Technology Used In Gas Turbine Blade Materials

The gas turbines used in aircraft engine are crucial for its applications in aeronautics and industrial processes. At the beginning materials used in designing compressor and turbine blades, could not survive more than a few hundred hours at then relatively modest temperatures and low power settings. These led to accidents, causing damages to both men and machines. Those who achieve excellence in product design and simultaneously speed the development cycle, provide high quality products that exceed customer expectations, become the leaders of aircraft technology. Development of materials for aircraft design is diverse (Carlos A Estrada, 2007).

4.1 Materials Used In Gas Turbine Blades

Modern gas turbines have the most advanced and sophisticated technology in all aspects; construction materials are not the exception due to their extreme operating conditions. As mentioned before, the most difficult and challenging point is the one located at the turbine inlet, because, there are several difficulties associated to it; like, extreme temperature (1400°C – 1500°C), high pressure, high rotational speed, vibration, small circulation area, and so on .

In order to overcome those barriers, gas turbine blades are made using advanced materials and modern alloys (super alloys) that contains up to ten significant alloying elements, but its microstructure is very simple; consisted of rectangular blocks of stone stacked in a regular array with narrow bands of cement to hold them together. This material (cement) has been changed because in the past, inter metallic form of titanium was used in it, but nowadays, it has been replaced by tantalum. This change gave improved high temperature strength, and also improved oxidation resistance. However, the biggest change has occurred in the nickel, where high levels of tungsten and rhenium are present. These elements are very effective in solution strengthening (Carlos A Estrada, 2007).

4.2 Latest Developments

4.2.1 Creation of Thermal Barrier Coatings

It is also important that the ceramic coating be homogeneously applied to the surface of the turbine blade. This is achieved by either Electron Beam Physical Vapour Deposition (EB-PVD) or the Arc Plasma Sprayable (APS) powder method. EB-PVD is the process currently recommended for high quality coatings. In this technique, a cylindrical ingot of the coating material is vapourized with an electron beam, and the vapour uniformly condenses on the surface on the turbine blade. One of the most important advantages of the EB-PVD process is the strain-tolerant coating that is produced (Carlos A Estrada, 2007).

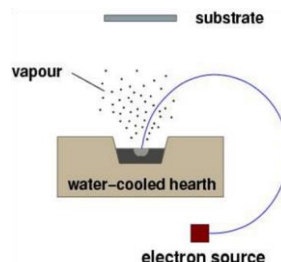


Fig. 11 Schematic EB-PVD process, the whole assembly would be under vacuum. Rotation of the electron beam is obtained by a magnetic field perpendicular to the drawing

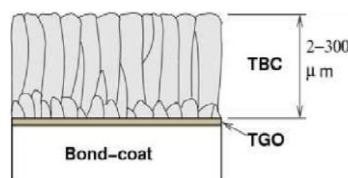


Fig. 12 Schematic microstructure of a thermal barrier coating (TBC) obtained by electron beam physical vapour deposition (EB-PVD). The columnar microstructure considerably enhances the strain resistance and therefore thermal cycling life

In the Air Plasma Spray powder application method, the ceramic material is in the form of a flowable powder that is fed into a plasma torch and sprayed molten onto the surface of the metallic substrate. Droplets of molten material form “splats” on the metallic substrate. Sprayed coatings have half the thermal conductivity of the EB-PVD coatings and are therefore better isolators.

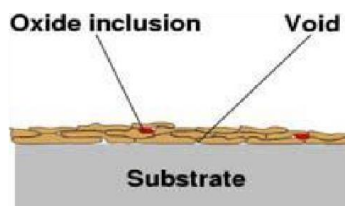


Fig.13 Schematic microstructure of thermal spray coating, showing only a few layers of particles

The “splats” form a lamellar structure consisting of fissures with a non-uniform density and pore size (Carlos A Estrada, 2007).

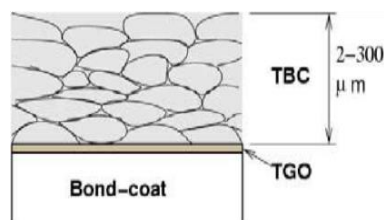


Fig.14 Schematic microstructure of a thermal barrier coating (TBC) obtained by air plasma spray (APS)

5. Case study

Internal Cooling Passages at the Trailing Edge by using Zig-Zag Channel with Rib Turbulators

The trailing edge region, which is known to be the thinnest section of the airfoil, imposes the greatest challenges to turbine designers in ensuring the reliability and durability of the entire airfoil through advance cooling techniques. In order to maintain the structural integrity of both the suction and pressure side at the trailing edge region, dense pin-fin arrays have become a viable solution in achieving this objective. Other than the typical circular pin-fin element, diamond or cubic shaped pin-fin elements with better heat transfer performance also proved to be an ideal candidate to be considered for cooling designs in the trailing edge section. Generally, the pin-fin arrays are arranged in a dense configuration in the trailing edge region to maintain the structural integrity at this rather thin section, while providing a much larger wetted area for more effective convection cooling. As the diamond shaped pin-fin arrays are arranged in a dense configuration, the internal flow domain appears to resemble a somewhat zig-zagshape.

An innovative zig-zag channel configuration was examined by Siw *et al.* experimentally. The results of the smooth zigzag channel revealed that the presence of each turn enhances the heat transfer enhancement in the channel. Overall, the heat transfer enhancement of the zig-zag channel is greater as compared to the smooth channel counterpart. The other advantage of such a design is that the wetted area is increased substantially compared to those typical straight channels. The research efforts are later extended by exploring the effects of rib-turbulators and tapering endwall on zig-zag channel based on the configurations presented in Fig.15. Figure 16 illustrates the total heat transfer enhancement of the zig-zag channels normalized by fully developed smooth channel based on the Dittus-Boelter correlation. Overall, the result revealed that the zig-zag channels (ZZ_Rib1, ZZ_Rib2, and ZZ_Rib3) have comparable heat transfer performance with longer pin-fin arrays, ranging from approximately 2.5–3.5 times. Note that, by using larger rib-turbulators (ZZ_Rib4), the heat transfer is further enhanced up to 4.5 times higher than that of smooth channel. The pressure loss of the smooth zig-zag channel is relatively constant and insensitive as Reynolds number increases within this tested Reynolds number. However, the pressure loss in all other test cases with surface features increases with Reynolds number. The pressure loss in ZZ_Rib1 ranged from approximately 8–11, is 30–80% higher than that of smooth zigzag channel. By having larger rib-turbulators with the height of twice than that of ZZ_Rib1, which imposed the largest restriction, the ZZ_Rib4 has the highest pressure loss among all tested cases. The pressure loss in ZZ_Rib4 case is approximately 35–60% higher than that of ZZ_Rib1

case. Both ZZ_Rib2 and ZZ_Rib3 have similar pressure loss characteristics which is lower than that of ZZ_Rib1 as shown in figure 17 (Sin Chien Siw, Mary Anne Alvin, 2013).

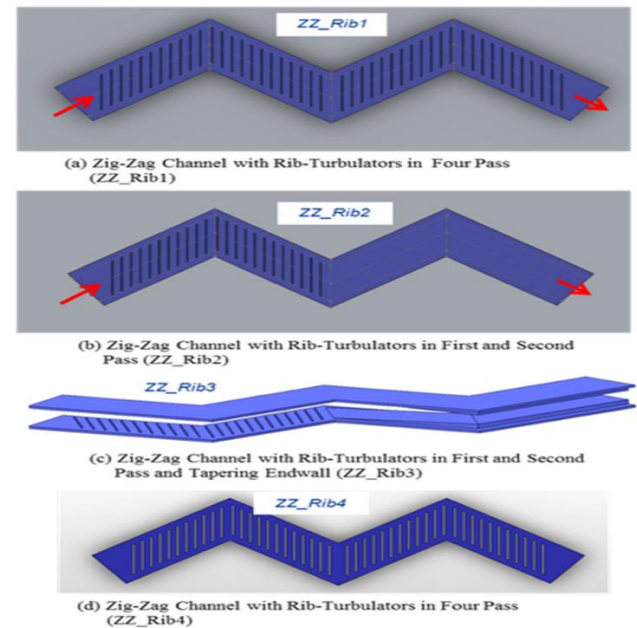


Fig.15 Zig-zag channel with different surface configuration

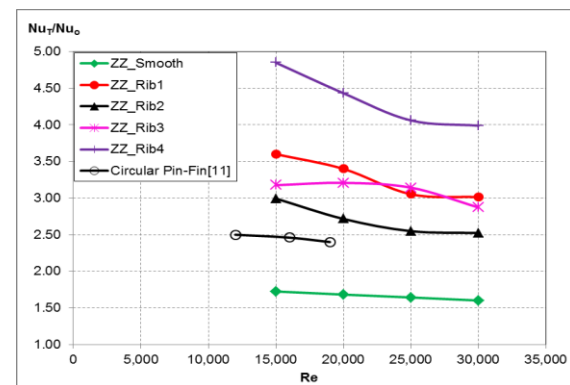


Fig.16 Total heat transfer enhancement versus Re (zig-zag channel)

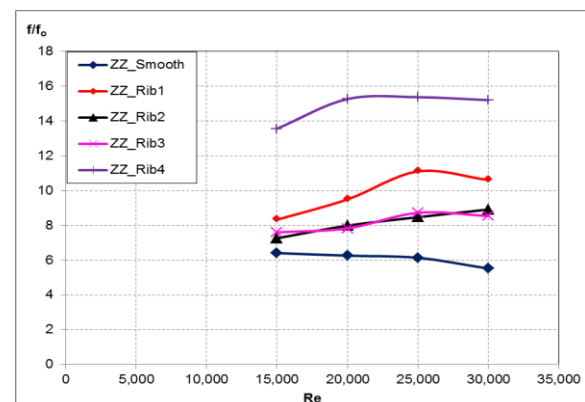


Fig.17 Pressure loss Vs Re (zig-zag channel)

Conclusions

The advancement of gas turbine technologies which continue to seek for higher turbine inlet temperature in meeting the efficiency demand present great challenges to turbine designers. Highly accurate and highly local detailed heat transfer data are required in each turbine airfoil section to prevent the airfoil from failure due to local hot spots. More research efforts shall be focused on the thin and narrow region, such as the tip and trailing edge sections of the turbine airfoil. In addition, more studies are needed to explore the rotating effects in those internal cooling passages. Other than conducting detailed experiments, this can be achieved by using advanced computational fluid dynamics software packages that have become not only more accurate, but time and cost effective. Such numerical results provide further detailed insights of the flow characteristics in the test domain, which are crucial in explaining some of the heat transfer phenomena that can be quite challenging to be explored experimentally, especially at realistic gas turbine conditions.

Nowadays, with the continuous advancement in computational fluid dynamics field, this design and analysis tools not only lead to reduction of design cycle time and product development costs, but also improved test models.

References

- Yugesh Patnaik, (2015), CFD Analysis of Rib Turbulated Cooling in Gas Turbine Blades, B-Tech Thesis.
- Minking K. Chyu, Sin Chien Siw, (2013), Recent Advances of Internal Cooling Techniques for Gas Turbine Airfoils, vol.5, pp.021008-1 To 021008-12.
- Sin Chien Siw, Mary Anne Alvin, (2013), Heat Transfer and Pressure Loss Characteristics of Zig-Zag Channel With Rib-Turbulators.
- Jibing Lan, Yonghui Xie, Di Zhang, (2011), Heat Transfer Enhancement in a Rectangular Channel with the Combination Of Ribs, Dimples And Protrusions.
- Je-Chin Han, Lesley M. Wright, (2009), Enhanced Internal Cooling of Turbine Blades and Vanes, vol.22, pp. 321-352.
- R.S. Bunker, (2008), Innovative Gas Turbine Cooling Techniques, vol.42, pp.199-229.
- Carlos A Estrada, (2007), New Technology Used in Gas Turbine Blade Materials, vol.36, pp. 297-301.