Recent Studies in Internal Cooling of gas turbine blade: a Review

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Abstract
Gas turbines are used extensively for aircraft propulsion, land-based power generation, and industrial applications. Developments in turbine cooling technology play a critical role in increasing the thermal efficiency and power output of advanced gas turbines. Gas turbine blades are cooled by internally & externally. Present paper provides an overview of latest heat transfer augmentation techniques employed for internal cooling of gas turbine blades. From the literature data a very few researchers focus on the combination techniques for internal cooling, such as rib turbulators, pin fins, and dimples/protrusion together. The results of such studies are compared with data obtained from recent studies (from 2018 to 2011) without rotation influences. Some researchers focus on new ribs like wavy rib, criss cross rib pattern, crescent ribs etc. also the result of rotating channels (from 2017 to 2004) presented and compared to literature data. The conclusion from data for stationary passage is that more heat transfer enhancement was observed for combination of ribs- dimples/protrusion pattern compare to single rib pattern. Also a newly developed rib show good performance. For the case of rotating passage heat transfer coefficient is different from those in non rotating passage, rotation can greatly enhance heat transfer on one side and reduce heat transfer on opposite side. From data also concluded that till, w shape, semi circular and multi semi circular shape ribs have limited work for both rotating and non rotating condition.

INTRODUCTION
The gas turbine blades are cooled with extracted air from the compressor of the gas turbine engine. Since this extraction incurs a penalty on the thermal efficiency and power output of the gas turbine engine, it is important to fully understand and optimize the cooling technology for a given turbine blade geometry under engine operating conditions. Gas turbine blades are cooled both internally and externally, Figure (1) shows the common cooling technology with three major internal cooling zones in a turbine blade with strategic film cooling in the leading edge, pressure and suction surfaces, and blade tip region. The leading edge is cooled by jet impingement with film cooling, the middle portion is cooled by serpentine rib-roughened passages with local film cooling, and the trailing edge is cooled by pin fins with trailing edge injection. Internal cooling is achieved by passing the coolant through several enhanced serpentine passages inside the blades and extracting the heat from the outside of the blades. Jet impingement cooling, rib turbulators, dimples and pin-fin cooling are used as a method of internal cooling. External cooling is also called film cooling, in this internal coolant air is ejected out through discrete holes to provide a coolant film to protect the outside surface of the blade from hot combustion gases. The engine cooling system must be designed to ensure that the maximum blade surface temperatures and temperature gradients during operation are compatible with the allowable blade thermal stress for the life of the design.

Figure 1. Gas turbine blade cooling schematic: (a) film cooling, (b) internal cooling [1]
This article is focus on a review of new heat transfer augmentation techniques, as they are employed for internal cooling of turbine components of gas turbine engines. The overall paper is presented in three major parts. First part is a brief review of recent developments in internal cooling passage since 2018 to 2011, considering investigations for stationary case only. In second part focus on latest review considering the combined effect of rotation, channel shape, orientation and aspect ratio on heat transfer with various high performance rib turbulators, protrusions and dimples, Study consider from 2017 to 2004. Final part of the paper then addresses the effect of rotation on heat transfer augmentation technologies for internal cooling followed by conclusion.

Development in heat transfer techniques from 2018 to 2011(stationary case): -

Various experimental and numerical investigations have been conducted to investigate the effects of different parameters such as shape and configuration of ribs as well as shape of cooling passages on fluid flow and heat transfer. Lots of studies focus on the thermal performance in the channel roughened with various shaped ribs. Since the early 1988, heat transfer performance of coolant passages with ribs has been actively investigated [42]. In view of the above, the shape of ribs has an important effect on fluid flow and heat transfer in the channel. Several researchers have carried out experimental & numerical studies on a channel featuring different shapes of ribs [2,3,4]. Few researchers focus on combination effect of rib –dimple or rib-protrusion pattern[5-8]. Researches on the heat transfer of ribs mainly focused on the effect of Reynolds number, rib height, rib spacing, and rib configuration. Prashant Singh et al. [2] used newly developed criss-cross ribbed pattern for investigation of heat and fluid flow in a square duct. A criss-cross pattern formed by 45° angled rib turbulators. They tested Inline and staggered arrangement of criss-cross pattern for Reynolds number ranged from 30,000 to 60,000. Their result showed that the heat transfer enhancement \( (\text{Nu} = \text{Nu}_0) \) varied from 2.7 to 3.1. The enhancement levels for both inline and staggered configurations was similar to each other, the friction factor for the inline configuration was relatively lower than the staggered configuration. Fig. (2) Shows the dimensions of test section & rib pattern.

Longfei Wang et al. [3] proposed a wavy rib with the simple structure for the internal cooling of U shaped channel in turbine blade. Investigated Reynolds number are 10,000–40,000. The results showed that the rib height, rib round radius and rib angle have great impact on heat transfer and flow of channel, while the influence of rib thickness was relatively small. In comparison with 45° V-shaped ribs, high-performance wavy ribs induce that ribbed wall \( \text{Nu} = \text{Nu}_0 \) and ribbed wall area improved by 7–37% and 28–52%, respectively, without friction loss increased. Also the wavy ribs after optimal shaped design can effectively enhanced the ribbed wall heat transfer by improving heat transfer coefficient and obviously increased heat transfer area in comparison with traditional high-performance 45° V-shaped ribs. Fig. (3) Shows the channel with wavy rib.

Gongnan Xie et al. [4] reported new type of rib called crescent rib for fluid flow and heat transfer characteristics in a cooling channel. Their result showed that the crescent ribbed channel provide a 21–41% higher normalized average Nusselt number relative the straight ribbed channel, while inevitably lead to a 15–80% higher pressure drop. Fig. (4) Shows the crescent ribs.

Prashant Singh et al. [5, 6] tested several unique combinations of ribs and cylindrical dimples for characterization of heat transfer enhancement and frictional losses in a two-pass square channel. Tested four different rib shapes, viz. 45° angled V, W and M with cylindrical dimples. they concluded that 45° angled and V shape compound configurations has highest heat transfer augmentation & thermal hydraulic performance when compared with their corresponding ribs alone and dimples alone configurations. Fig. (5 a, b) shows the globally averaged Nusselt numbers & details of the ribs and dimple for V configurations.

Figure 2. Rib pattern with dimensions [2]

Figure 3. Test section [3]

Figure 4 (b) straight rib (c) crescent rib concave (d) crescent rib convex to the stream-wise direction [4]
Yonghui Xie et al.[7] numerically studied the combination effect of dimples and secondary protrusion. Investigated different parameters such as protrusion print-diameter $D_p$, protrusion-dimple gap $P$, and staggered angle $\alpha$. They concluded that the implication of secondary protrusion considerably increased the heat transfer rates inside dimple cavity & also the additional pressure penalty brought by the protrusion was within 15% resulting in total friction ratio. Fig.(6) shows the channel dimensions with dimple-protrusion.

Lu Zheng et al. [8] investigated numerically the combination effect of rib–groove–protrusion on flow and heat transfer characteristics in a channel. There result showed that the high local Nusselt number region was mainly located at the ribs, groove trailing edge, and protrusion leading edge. Also, the rectangle case provides the highest $\frac{Nu}{Nu_0}$. Gongnan Xie et al. [9] used different truncated rib geometries for numerically investigation of turbulent heat transfer. Designed different truncation ratio (truncated-length to passage-width) rib geometries and then the effect of truncation ratio on the pressure drop and heat transfer enhancement was observed under the condition of constant total length. They concluded that the heated face with a rib that was truncated 12% in length in the center has the highest heat transfer coefficient, while the heated face with a rib that was truncated 4% at three locations over its length, in the center and two sides, has a reduced pressure loss compared with passages of other designs and provides the lowest friction factors. Heeyoon Chung et al.[10] studied experimentally the overall heat/mass transfer performance of a rib-roughened channel with an intersecting rib. Tested two types of rib configurations and three different channel aspect ratios. Result showed that the intersecting rib exhibited superior performance with angled ribs. Also, the heat/mass transfer coefficient and thermal efficiency was simultaneously increased by the intersecting rib for all channel aspect ratios and Reynolds numbers. Gongnan Xie et al. [11] numerically studied different arrangements of downstream half-size ribs to determine the most optimal configurations for augmenting heat transfer rates with minimized pressure drop penalties. Six different ribbed channels was evaluated and compared. Result showed that the usage of downstream ribs was a suitable way to decrease the pressure loss and improve the flow structure, while keeps comparable enhancement in heat transfer. Fig.(7) shows simple configuration of rib.
Sebastien Kunstmann et al. (12) conducted investigation to assess the thermal performance of W-shaped, 2W-shaped and 4W-shaped ribs in a rectangular channel. Tested aspect ratios (W/H) were 2:1, 4:1, 8:1 & Reynolds numbers (Re > 90,000) was typical for combustor liner cooling configurations of gas turbines. They concluded that the highest heat transfer enhancement was obtained by rib configurations with a rib section-to-channel height ratio (Wr/H) of 1:1. Also W-shaped ribs achieved the highest heat transfer enhancement levels in channels with an aspect ratio of 2:1, 2W-shaped ribs in channels with an aspect ratio of 4:1 and 4W-shaped ribs in channels with an aspect ratio of 8:1. Furthermore, the pressure loss increased with increased complexity of the rib geometry and blockage ratio. Anil Kumar et al. (13) tested experimentally Multi v-shaped rib for heat transfer and fluid flow characteristics in a rectangular duct. The investigated Reynolds number (Re) range from 2000 to 20,000, relative width ratio (W/w) of 6, their result showed that the maximum enhancement in Nusselt number and friction factor was observed to be 6.32 – 6.12 times of that of the smooth duct, respectively. Akhil P. Rallabandi et al. (14) conducted experiments to find out heat transfer coefficients and friction factors on a 45° parallel rib-roughened square channel, studied range of Reynolds numbers from 30,000 to 400,000, their result showed that greater heat transfer enhancements (compared with a smooth channel) was observed at larger blockage ratios and at smaller rib-rib spacing ratios. These high heat transfer enhancements was accompanied by larger pressure drop penalties (when compared with a smooth channel), resulting in a lower thermal performance. Sourabh Kumar et al. (15) investigated experimentally heat transfer and flow using V and broken V ribs. Four different combinations of 60° V- and broken 60° V-ribs in a channel were considered. The overall performances for broken ribs were higher compared with the continuous ribs in two-pass cooling channels.

Mi-Ae Moon et al. (16) conducted numerical simulations for sixteen rib shapes: square, isoceles triangular, fan-shaped, house-shaped, reverse cut-trapezoidal, cut-trapezoidal, reverse boot-shaped, boot-shaped, reverse right-angle triangular, right-angle triangular, reverse pentagonal, pentagonal, reverse right-angle trapezoidal, right-angle trapezoidal, isoceles trapezoidal, and semicircular ribs. The performance parameters related to the heat transfer and friction factor were found to strongly depend on the cross-sectional rib shapes. The new boot-shaped rib gave the best heat transfer performance with an average friction loss performance, and the reverse pentagonal rib gave the best friction loss performance. Yu Rao et al. (17) investigated experimentally the effects of dimple depth on the pressure loss and heat transfer characteristics in a pin fin-dimple channel. The dimples have three different dimple depth-to-diameter ratios, i.e. d/D = 0.1, 0.2 and 0.3. they showed that the pin fin-dimple channels have further improved convective heat transfer performance by up to 19.0%, and the pin fin-dimple channel with deeper dimples shows relatively higher Nusselt number values. The study still showed the pin fin-dimple channel with shallower dimples shows relatively lower friction factors by up to 17.6% over the studied Reynolds number range. M.J. Sable et al. (40) studied experimentally the effect of dimple surface on horizontal fin array, they concluded that dimple surface enhanced the heat transfer but increased the pressure drop.

Development in heat transfer techniques from 2017 to 2004 (Rotating case):

Over the years, several studies have been carried out to investigate the effects of rotation on heat transfer in rib turbulated channels. One of the latest studies focus on the effects of rotation on heat transfer in U shaped square channel. Prashant Singh et al. (18) studied heat transfer measurements for ribbed (V shape) and smooth two-pass duct (AR = 1:2) by transient liquid crystal thermography under rotating and non-rotating conditions. Tested two rotation numbers 0.036 (400 RPM) and 0.063 (700 RPM) at Reynolds number of 25,000, their result showed that the heat transfer in the first pass was highest on the trialing side followed by stationary and leading side. This trend was similar in the bend region as well. Also the heat transfer in the second pass was highest for the leading side followed by stationary case and trailing side. Numerical predictions show the shifting of large scale vortices towards the wall where the Coriolis force acts relatively stronger, hence leading to increased turbulent transport along that wall. Fig. (8) Shows experimentally obtained regionally averaged Nusselt number for the ribbed two-pass channel under rotating and stationary conditions.

Zhongyang Shen et al. (19) studied numerically a compound heat transfer enhancement technique in a U-shaped square channel. Tested the combination of ribs, dimples or protrusions, for rotational number 0, 0.4 and 0.6. Their conclusion that rib-protrusion structure seems to be the most effective structure while rib-dimple structure has only slight advantage than ribbed channel, also the heat transfer rates in second pass was obviously higher than those in the first pass. The rotation effect on the Nusselt distribution for rib-protrusion channel was more intense than the rib-dimple channel. For the friction penalty, the rib-protrusion channel own the highest friction ratio among the four channels followed with the rib-dimple channel and ribbed channel.

Figure 8. Regionally averaged Nusselt number for rotation and stationary cases (ribbed) (18)
Shyy Woei Chang et al. [20] studied experimentally the pressure drop coefficients ($f$) and the full-field end wall Nusselt number ($Nu$) distributions of a channel, tested with inclined rectangular slender pin-fins by skewed ribs with radially outward flow at Reynolds number ($Re$) from 5000 to 15,000 & rotation number ($Ro$) from 0 to 0.4. They concluded that the relaxation of pressure gradients by rotation moderates the pressure drop penalties from the non-rotating references, leading to further elevations of thermal performance factors (TPF). Also, as $Ro$ increased, the trailing end wall $Nu$ consistently increased; whereas the leading end wall $Nu$ was initially reduced from the static $Nu_0$ references. Jiang Lei et al. [21] studied experimentally the effect of rib spacing on heat transfer in a two-pass rectangular channel at high rotation numbers. Their result showed that for $Ro$ from 0.1 to 2.0, the $Nu/Nu_0$ ratios along the leading and trailing centerlines consistently decreased with increased aspect ratio ($AR$) due to the combined $Ro–Bu$ impacts. Again rotation number ($Ro$) increased the heat transfer levels along the trailing edge was consistently improved from the zero-rotation references whereas the leading-edge heat transfer levels was initially reduced from the zero-rotation references but recovered as $Ro$ exceeded the critical values. Shyy Woei Chang et al. [24] investigated the effect of coriolis & rotation on heat transfer distributions. Their result showed that the two unstable ribbed walls in the inlet and outlet legs show the higher $Nu$ over the opposite stable ribbed walls as a result of the coriolis-force effect on the flow structures. Also, with rotation number ($Ro$) = 0.3, the vortices tripped at the roots of the ribs was respectively intensified and suppressed over the unstable and stable walls so that the high $Nu$ imprints between two ribs over the unstable and stable ribbed walls was accordingly augmented and moderated. Michael Huh et al. [25] reported the effect of rib height on heat transfer in a two-pass rectangular channel ($AR = 1:4$) with a sharp entrance. They concluded that the effect of rotation in the first pass (downstream from the entrance), served to increased the heat transfer on the trailing surface significantly ($Nu/Nus = 2.0$), and decreased the heat transfer on the leading surface significantly to values of ($Nu/Nus = 0.5$). A critical rotation number exists ($Ro = 0.3$) after which an increased in heat transfer occurs on the leading surface. They also found that the effect of rotation in the second pass (downstream of the turn) decreased. Only slight increase in the heat transfer on both surfaces was observed. 

**Figure 9.** TP for all channels under different rotational condition [19]

**Figure 10.** Conceptual flow patterns around ribs and turn [21]

**Figure 11.** Effect of rib on (a) mainstream flow separation and reattachment and (b) Angled secondary flow. [25]
Fuguo Zhou et al. [26, 27] reported experimentally heat transfer measurement in 4:1 coolant passage with 45° skewed ribs. Parameters studied Reynolds number (Re) in the range of 10,000–70,000, rotation number (Ro) in the range of 0–0.6, and density ratios (DR) between 0.1 and 0.2. Their results showed that rotation effects enhanced the heat transfer on the destabilized surfaces of the 4:1 AR channel. This enhancement was stronger on the inlet-trailing wall than on the outlet-leading wall. Also, rotation effects degrade heat transfer on the stabilized walls, and cause a decreased in $Nu/Nu_0$ on the inlet-leading and outlet-trailing walls. They also showed that higher density ratio enhanced heat transfer on all of the four walls in the inlet and in the outlet of the 4:1 AR. However, the density ratio effect was considerably weaker compared to that observed for the 1:1 Aspect Ratio (AR) channel. Figure (12) shows the stream wise $Nu/Nu_0$ distribution at Re=40,000 for Ro values up to 0.2.

K. Arun and S. V. Prabhu [28] had conducted the experiment to investigate the effect of Reynolds number, rotation number, orientation angle, Aspect Ratio, Rib Pitch-to-Height Ratio, and Number of ribbed walls on Pressure Drop Characteristics in a Channel with Detached Ribs. Reynolds number ranging from 10000–17000 with rotation numbers varying from 0–0.38. Their results showed that friction factor ratio in detached ribs was higher compared to the attached rib configuration, and the difference in the friction factor between the detached ribs & attached ribs increased with the increase in Reynolds number. They also said that friction factor ratio in single wall attached ribbed channel increased with the increase in the orientation angle from 0° to 90° and decreased with the increase of orientation angle from 90° to 180° for a given Reynolds number & rotation number. Tong-Miin Liou et al. [29] studied the detached & attached ribs, the ribs were square in cross-section and their detached-distance/height ratio was 0.38. Duct Reynolds number was fixed at $1 \times 10^4$ and rotating number ranged from 0 to 0.2. Their results showed that the attached – detached ribs attained heat transfer enhancement about 1.03 to 1.39 times that of attached ribs. They also showed that attached – detached configuration of ribs generate friction loss approximately 2.8 - 3.7/2.8-3.7 and 3.3-4.3/3.1-4.4 times that of smooth walled case. Fig. (13) Shows the configuration of test section.

Figure 12. Rotation effects for DR=0.1 at Re=40,000. L-leading wall, T-trailing wall [27]

Figure 13. Sketch of configuration, coordinate system, and dimension of test section [29]
Wen-Lung Fu et al. [30,31] studied the effects of the buoyancy force and channel aspect ratio (W:H) on heat transfer in two-pass rotating rectangular channels with smooth walls and 45° ribbed walls, studied five different channel ratio & four Reynolds numbers. They concluded that the 1:4 channel incurred the lowest pressure penalty; therefore, the thermal performance of the 1:4 channel was superior to 1:2, 1:1, and 2:1 channels, respectively. Again for the chosen angled rib geometry, the first pass, leading surface was adversely affected by the interaction of the rotation and rib induced vortices. They also found that the 45° channel orientation created less heat transfer difference between the leading and trailing walls than the 90° channel orientation for both aspect ratio(AR:1:2,1:4) ducts. Fig.(14) shows aspect ratio effect on heat transfer.

Mayank Tyagi et al.[32] studied Large eddy simulations with normal rib turbulators , results showed that large scale vortices play a major role in the mixing between the core fluid and the near-wall heated fluid. The temperature field was driven by the large-scale mixing, was inherently unsteady, and contains low frequency mode with long time periods. Lesley M. Wright et al. [33] conducted experimental study to measure the heat transfer distributions and frictional losses in ribbed channels with an aspect ratio of 4:1, investigated various ribs such as, discrete angle, V-shape, discrete V-shape ribs and newly proposed W-shape and discrete W-shape ribs. Their result showed that the discrete V-shaped and discrete W-shaped ribs had the best thermal performance in both rotating and non rotating channels. These configurations was followed closely by the W-shape rib configuration, they also found that for narrow rotating rectangular channels (AR=4:1) with various rib configurations, the heat transfer enhancement on both the leading and trailing surfaces increased with rotation. Fig (15) shows the various rib configurations.

**Figure 14.** Aspect ratio effect on heat transfer. (β= 90 deg)[31]

**Figure 15.** Top view of the six rib configurations [33]
Tong-Miin Liou et al. [34] studied the local velocity and wall static-pressure distributions with ribs placed on the leading and trailing walls at an angle of 45 deg to the main stream, their result showed that the 45° ribs was found to reduce the friction loss to 60% compared to 90° ribs. They also showed that the difference of Cp between the two walls first increased with distance from the mid-turn and then maintained the same in the second passage. Peeyush Agarwal et al.[35] studied experimental study of heat/mass transfer coefficient in aspect ratio (AR) 1:4 rectangular channel with smooth or ribbed walls, for Reynolds number in the range of 5000–40,000 and rotation numbers in the range of 0–0.12. Their result showed that for the smooth duct, the Sherwood numbers was relatively insensitive to Re. For the ribbed duct, the Sherwood number ratios show a weak Re number dependence under stationary and rotating conditions. They also showed that at Reynolds number (Re) 30,000, as rotation number (Ro) increased from 0 to 0.045, the 1:4 cross-section smooth ducts showed roughly a 10–12% change in the inlet duct relative to the stationary case. Akira Murata et al. [36] had studied centrifugal buoyancy effect by using the large eddy simulation their result showed that the pressure loss coefficient of the sharp turn was decreased by the buoyancy and that of the straight pass was increased and decreased in the first & second straight passes resp.also the heat transfer efficiency index was slightly increased by the buoyancy due to the decreased friction factor. Luai Al-Hadhrami et al.[37] investigated the effect of various 45° angled rib turbulators. They positioned five different arrangements of rib turbulators on the leading & trailing surfaces. Their result showed that the Nusselt number ratios in the first pass trailing and second pass leading surfaces increased with an increase in rotation number. They also concluded that the Nusselt number differences between the leading and trailing surfaces due to rotation was reduced as the channel orientation changes from $\beta = 90°$ to $\beta = 135°$.

**Rotation effect:-**

Fluid flows within rotating channels are different from those in stationary channels because rotation induces coriolis and centrifugal forces that produce cross-stream secondary flow in the rotating coolant passages as a result, local surface heat transfer and friction factor augmentation levels are often altered because of the presence of rotation compare to non rotating frames. One important finding from literature survey is that rotation can greatly enhance heat transfer on one side of the cooling channel and reduce heat transfer on the opposite side of the cooling channel due to rotating-induced secondary flow, depending on the radial outflow or inflow of the cooling passages. Without considering rotational effect, the coolant passage would be over-cooled on one side while over-heated on the opposite side. Recent studies focus on the combined effects of rotation, channel shape, orientation, and aspect ratio on rotor coolant passage heat transfer with various high performance rib turbulators. Results showed that the channel shape, orientation, rib shape and aspect ratio significantly change local heat transfer coefficient distributions in rotor coolant passages with rib turbulators. Also results show that rotation creates a negative impact on rotor coolant passages with impinging jets. In general, rotation reduces the impingement cooling effect due to jet deflection away from the impinged surface. Fig. No.(16) shows the conceptual view of the secondary flow due to rotation and ribs.

**CONCLUSIONS**

To provide an overview of the current state of the art of heat transfer augmentation techniques employed for internal cooling of gas turbine blades, results from an extensive literature review are presented for rotation and non rotation passages. According to this survey, new rib pattern concepts are developed by researchers such as criss-cross rib, continuous wavy rib, and crescent rib patterns. These rib pattern show more enhancement in heat transfer compared to regular ribs such as V & angled ribs. This rib pattern has scope in rotating cases for gas turbine blade cooling. Also from literature data, a very few researchers was focus on combination of rib-dimple pattern, such as, rib turbulators and dimples together , a combination of dimples - protrusions and Groove–Protrusions with Ribs .The results of such studies shows increased heat transfer enhancement to single rib or dimple/protrusions pattern. For rotation cases rib-
protrusion structure seems to be the most effective structure while rib-dimple structure has only slight advantage than ribbed channel. In addition, further studies are needed to explore the rotating effects in internal cooling passages other than conducting detailed experiments; this can be achieved by using software packages such as CFD. Numerical results provide detailed insights of the flow characteristics in the test domain, which cannot possible from experimentation. Finally from this study it observed that there is scope to use different combination of rib-dimple patterns such as W shape, semi circular, S shape ribs with different shape dimples for internal cooling of gas turbine blade.

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