Effect of V-shaped Ribs on Internal Cooling of Gas Turbine Blades

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Abstract. Thermal efficiency and power output of gas turbines increase with increasing turbine rotor inlet tem[1perature. The rotor inlet temperatures in most gas turbines are far higher than the melting point of the blade material. Hence the turbine blades need to be cooled. In this work, simulations were carried out with the leading edge of gas turbine blade being internally cooled by coolant passages with V-shaped ribs at angles of 30°, 45° or 60° and at three aspect ratios (1:1, 1:2 and 2:3). The trailing edge of the blade was cooled by cylindrical and triangular pin-fin perforations in staggered and inline arrangements. Numerical analyses were carried out for each configuration of the cooling passages. The best cooling passages for leading edge and trailing edge were deduced by comparing the results of these analyses. It was found that using V-shaped ribs and fins induces a swirling flow, which in turn increases the velocity gradient and hence produces an improvement in heat transfer. The results show that under real time flow conditions, the application of V-shaped ribs and pin-fin perforations is a very promising technique for improving blade life.

Keywords: *internal cooling; leading edge; ribs; trailing edge; turbine blade cooling.*

1 Introduction

Thermodynamic study of gas turbines shows that plant efficiency and energy output can be enhanced with higher turbine inlet temperatures. Modern gas turbines try to approach these high temperatures (1500 °C) to improve performance but are limited by the maximum allowable thermal stresses for the blade material. Many cooling techniques can be used on the exterior of a gas turbine blade to enhance its fatigue life, such as internal convective cooling or film cooling. One of the toughest regions to cool is the trailing edge as it must be thin to reduce aerodynamic losses. As the trailing edge is thin, cooling is a challenging task because not enough coolant can be guided to this region. Additional constraints for internal cooling passage geometry in this thin section also arise due to structural integrity and manufacturing difficulty. One of the cooling techniques frequently used by turbine designers for the trailing edge is

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using twisted tape inserts. Among the different heat transfer techniques, twisted tapes are widely used due to their simple configuration and easy installation. Twisted tapes generate swirls in the tube, which enhances the heat transfer [1-3]. Date and Saha [4,5] used a uniform heat flux tube fitted with regularly spaced twisted tapes and predicted the heat transfer and fluid flow behavior with the help of Navier-Stokes and energy equations. Chang [6] has compared the results of serrated and broken tape inserts with smooth twisted inserts. The results showed that thermal energy transfer could be improved with usage of the serrated twisted tape. It was also shown that the heat transfer coefficient, the Fanning friction factor and the heat assessment factor of the tube were increased in a particular Re range. The numerical and experimental techniques discussed above were used for the present work. Kini, *et al.* [7-14] found that greater thickness of the turbulator geometry improves the cooling effect of the gas turbine blade. A helicoidal shaped duct was analyzed and it was observed that blade cooling was improved in comparison to straight ducted cooling ducts for an HP stage turbine blade. Kini, *et al.* found that CFD analysis of the helicoidal cooling duct, buttress shaped grooved configuration and twisted tapes provided a significant improvement in turbine blade cooling.

In the present work, the combined effect of V-shaped ribs and fins on the cooling of a gas turbine blade is studied. Several investigations have shown that flow separation takes place when V-shaped ribs are used. Due to this phenomenon heat from the surface can be more effectively dissipated and hence the heat transfer coefficient can be increased. In the present analysis, several different pin-fin perforation configurations were used to disturb the flow path and hence affect heat transfer performance.

2 Physical Model and Numerical Method

2.1 Governing Equations

The essential governing equations for flow and heat transfer in a flow passage are the Navier-Stokes, energy and continuity equations along with the equations for modeling the turbulence magnitudes. These set of equations were used to solve the present analysis with ANSYS Workbench.

The mass conservation equation is defined in Eq. (1) as follows:

$$\nabla.(\rho\bar{v}) = 0 \tag{1}$$

Navier-Stokes equations:

Conservation of momentum in an inertial reference frame is described in Eq. (2) as follows:

$$\nabla.\left(\rho\vec{v}\vec{v}\right) = -\nabla p + \nabla.\left(\overline{\overline{\tau}}\right) + \rho\vec{g} \tag{2}$$

where p is the static pressure, $\overline{\overline{\tau}}$ is the stress tensor (described below), and $\rho\vec{g}$ is the gravitational body force.

The stress tensor is given by the following Eq.(3):

$$\overline{\overline{\tau}} = \mu\left[\left(\nabla\vec{v} + \left(\nabla\vec{v}\right)^{T}\right) - \frac{2}{3}\nabla.\vec{v}I\right] \tag{3}$$

where μ is the molecular viscosity, I is the unit tensor, and the second term on the right hand side is the effect of volume dilation. For incompressible flow $\left(\nabla.\vec{v}I\right)$ becomes zero.

The energy equation can be expressed in Eq. (4) in the following form:

$$\nabla.\left(\vec{v}\left(\rho E + p\right)\right) = \nabla.\left(K_{eff}\nabla T - \sum_{j} h_j \vec{J_j} + \left(\overline{\overline{\tau_{eff}}}.\vec{v}\right)\right) \tag{4}$$

where effective conductivity $K_{eff} = k + k_t$ where k_t is the turbulent thermal conductivity, defined according to the turbulence model being used.

The Reynolds number (Re), Nusselt number (Nu), friction factor (f) and thermal performance factor (f) are defined in Eq. (5) as follows:

$$R_e = \frac{\rho u D}{\mu} \qquad Nu = \frac{hD}{k} \qquad f = \frac{\Delta p}{\left(\rho u^2/2\right)\left(L/D\right)} \qquad \eta = \frac{Nu/Nu_o}{\left(f/f_o\right)^{1/3}} \tag{5}$$

where Nu_0 and f_0 are the Nusselt number and friction factor of the plain tube, respectively.

Conservation equations were solved for the control volume to yield the velocity and temperature fields. The k-ε turbulence model and well-recognized standard wall function were selected for the present work. This k-ε model is based on the Boussinesque approximation of the Reynolds turbulent stresses. The turbulent eddy diffusivity is expressed in terms of turbulence parameters k and ε.

2.2 Physical Model

Schematic diagrams of the gas turbine blade with different rib and fin configurations are shown in Figure 1-6. Modeling of the gas turbine blade was carried out by measuring the coordinates of the gas turbine blade by CMM in CATIA V5 software. The cooling passages were designed using CAD software and then imported into ANSYS Workbench. Figure 1 shows the gas turbine blade model.

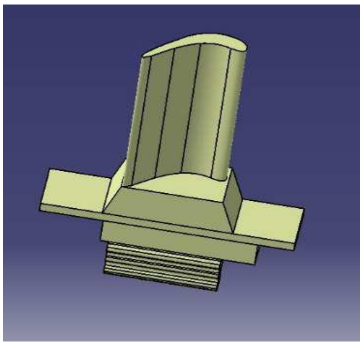
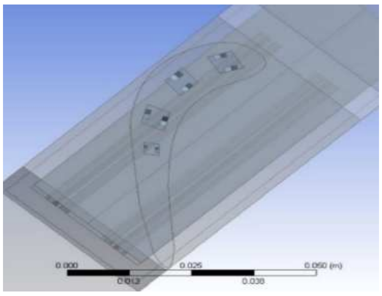
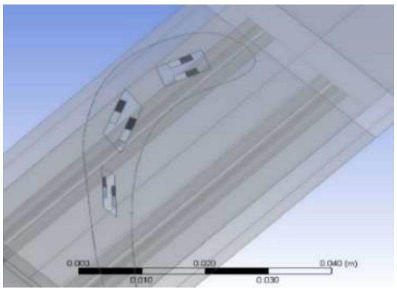


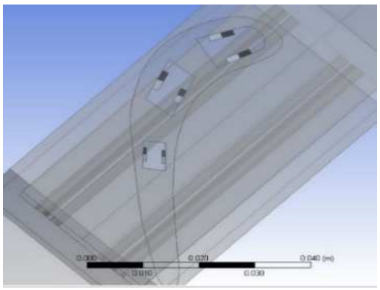
Figure 1 Gas turbine blade model.



(a) Ribs with aspect ratio: 1:1



(b) Ribs with aspect ratio: 1:2

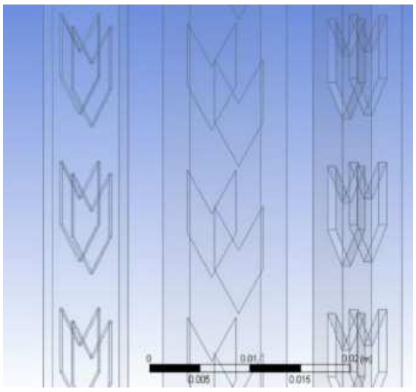


(c) Ribs with aspect ratio 2:3

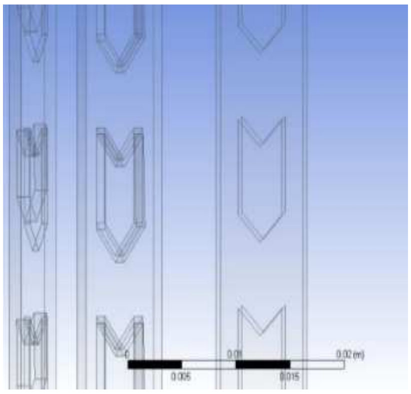
Figure 2 Ribs with three different aspect ratios.

2.3 Leading Edge and V-shaped Ribs

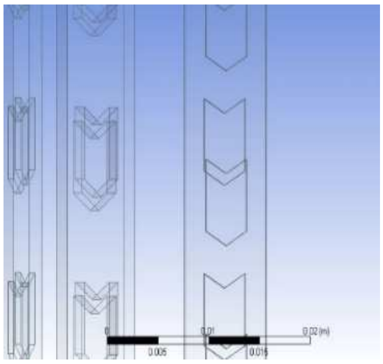
Ribs with aspect ratios (W/H) 1:1, 1:2 and 2:3 were modeled using CAD software and placed on the leading edge of the turbine blade as shown in Figure 2. Similarly, ribs at angles 30°, 45° and 60° were used for the analysis. Figures 3(a), 3(b) and 3(c) show the different rib angles.



(a) 30° rib angle



(b) 45° rib angle

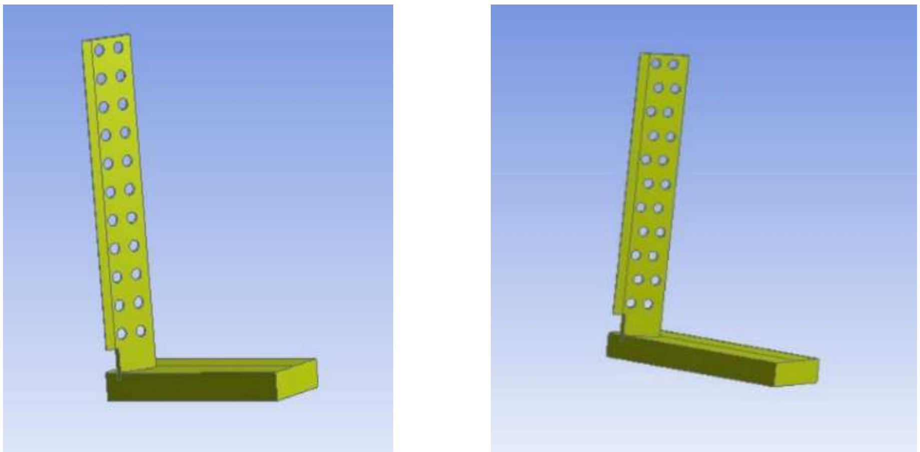


(c) 60° rib angle

Figure 3 Ribs at three different rib angles.

2.4 Trailing Edge with Pin-Fin Perforations

As the trailing edge of the gas turbine blade is thin, ribbed passage cooling is not effective enough. Due to this, circular or triangular pin-fin perforations with different dimensions can be employed to increase the heat transfer rate. The perforation geometry not only increases the surface area but also acts as turbulator and hence increases the overall heat transfer, thus providing adequate blade cooling. In the present work, incline and staggered cylindrical perforations with a diameter of 4 mm were used, as shown in Figure 4. The same work was carried out for staggered and inline cylindrical perforations with a diameter of 2 mm.



(a) Inline cylindrical perforations (b) Staggered cylindrical perforations

Figure 4 Cylindrical pin-fin perforations with a diameter of 4 mm.

2.5 Numerical Model and Boundary Conditions

ANSYS Workbench 14.5 uses the finite volume method accompanied by boundary conditions to solve the abovementioned governing equations. The computational domain was modeled using ANSYS Workbench 14.5 and meshing was done by using the tetrahedral grid with TGrid type. Spacing of 0.7 mm was maintained for the element. Standard-pressure and first-order upwind discretization schemes for the momentum and energy equations were employed in the numerical model. The velocity-pressure coupling was handled through the SIMPLE algorithm (Semi Implicit Method for Pressure Linked Equations) developed by Patankar [15]. In this algorithm, the discretized momentum equation and the pressure correction equation are solved implicitly, while the velocity correction is solved explicitly. In addition, convergence criteria of 10-6 were used for energy, continuity and velocity components.

Simulation needs to be conducted with high pressure and high temperature conditions to understand the physics of cooling of a gas turbine working in a real time operating environment. The parameters simulating the gas turbine operating environment are listed in Tables 1 and 2. The energy equation and k-ε model (second order equation) with enhanced wall treatment were used for modeling the turbulent flow in the analysis. The turbulence model is explained in [16-18] and summarized in Table 2 without further explanation. Boundary conditions and material properties were specified as derived from Kini, *et al.* [7-14]. The through flow of hot gases had a convective heat transfer coefficient of 2028 W/m2K and a free stream temperature of 1561 K. The inlet of the coolant had a pressure of 1.6 MPa and a temperature of 644 K [19-20].

Table 1 Thermo-physical properties of air at 644 K.

Density	0.54 kg/m^3
Specific heat	1.06 kJ/kg K
Thermal conductivity	0.05 W/m K
Kinematic viscosity	31.86 * 10-6 kg/m s

Table 2 Thermal properties of blade material.

Density	8180 kg/m^3
Specific heat	446 J/kg K
Thermal conductivity	11.5 W/m K

2.6 Grid Independence Test

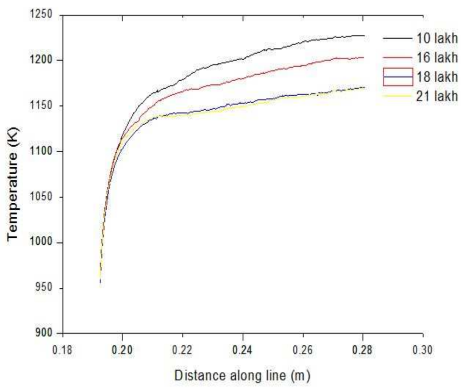


Figure 5 Grid independence test results.

A grid independence test was carried out. Four different grid systems, with 0.35, 0.3, 0.25 and 0.2 spacing, were investigated. The temperature was calculated over the chord length of the blade, as shown in Figure 5, which demonstrates that the difference between the calculated results for 0.25 and 0.2

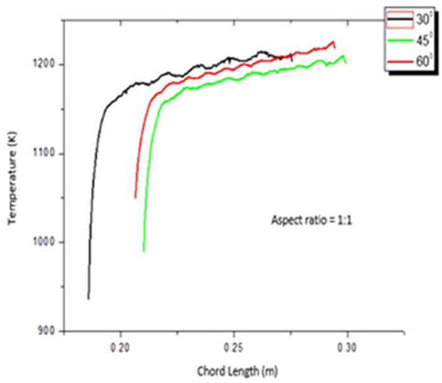
spacing (i.e. 18 lakh and 21 lakh nodes respectively) was very small. Therefore, the gird system with 0.2 spacing was adopted for the simulation.

3 Results and Discussion

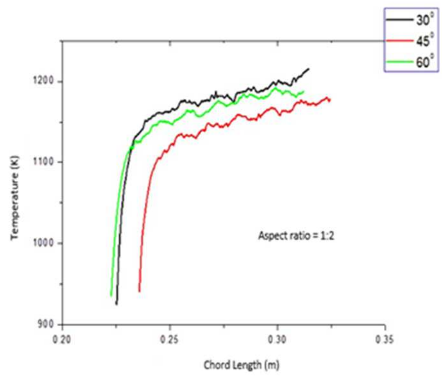
Cooling passages for the leading edge with aspect ratios of 1:1, 1:2 and 2:3, were used for the analysis and the angle between the V in the ribs was varied between 30°, 45° and 60°.

3.1 Thermal Performance of V-shaped Ribs at Leading Edge

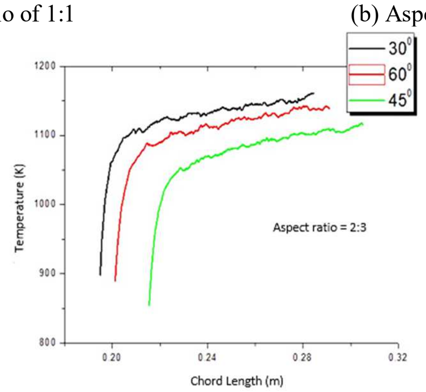
Figure 8 illustrates the temperature distribution plot for the three different angles of the V shaped ribs with aspect ratios of 1:1, 1:2 and 2:3. From the plot (Figure 6) it can be clearly seen that the configuration with 45° had the best cooling effect when compared with other the configurations due to its effective swirling effect.



(a) Aspect ratio of 1:1



(b) Aspect ratio of 1:2



(c) Aspect ratio of 2:3

Figure 6 Temperature distribution plot for V-shaped ribs with different aspect ratios.

From the above results and comparisons it can be concluded that V-shaped ribs with an aspect ratio of 2:3 and a rib angle of 45° offered better cooling when compared to the other rib configurations.

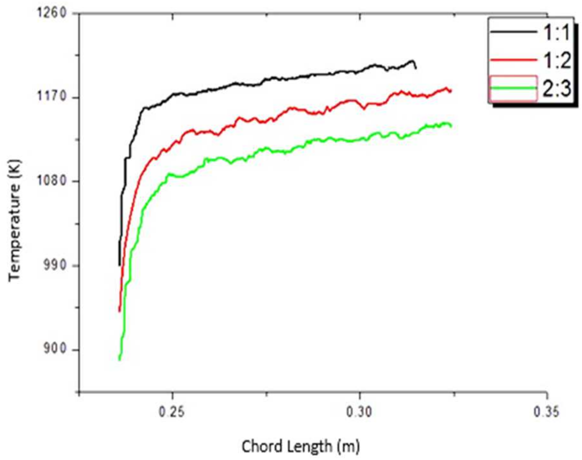


Figure 7 Temperature distribution plot for V-shaped ribs with different aspect ratios and rib angle at 45°.

The results of the three aspect ratios combined with a rib angle of 45° were compared with the other aspect ratios, as shown in Figure 7. From the graph it is clear that the V-shaped rib configuration with an aspect ratio of 2:3 and a rib angle of 45° offered maximum cooling effect when compared to the other configurations. Using V-shaped ribs with an aspect ratio of 2:3 and a rib angle of 45°, the temperature of the blade at the leading edge decreased by 30%, i.e. from 1561 K to 1100 K.

3.2 Thermal Performance of V-shaped Ribs at Trailing Edge

Since the trailing edge is thin, a ribbed passage cannot be applied due to space constraints. For this reason, circular or triangular pin-fin perforations of different dimensions can be employed to increase the heat transfer rate. The perforation geometry not only increases the surface area but also acts as turbulator and hence increases the overall heat transfer, thus providing adequate blade cooling. Simulations were carried out for cylindrical perforations arranged in staggered and inline arrangements. Cylindrical perforations with diameters of 2 mm and 4 mm were used for the first analysis.

Comparing the results of the inline and staggered arrangements of cylindrical perforations with a diameter of 4 mm, as shown in Figure 8, it can be observed that the staggered arrangement showed better cooling than the inline arrangement. Hence the staggered arrangement was selected for further analysis.

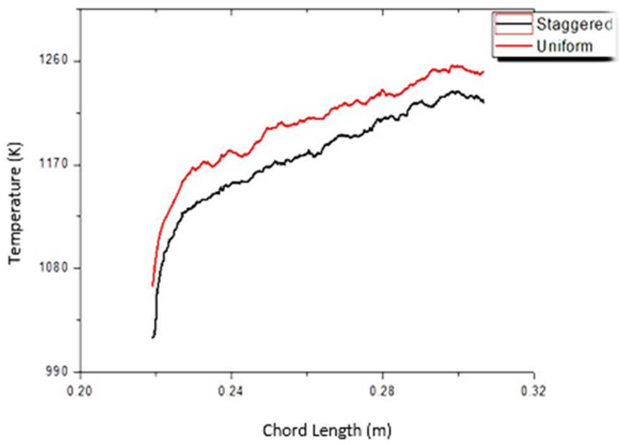


Figure 8 Comparison of staggered and inline arrangement of cylindrical pin-fin perforations with a diameter of 4 mm.

The same analysis was carried out for staggered cylindrical perforations with a diameter of 2 mm. It can be observed from Figure 9 that using staggered perforations with a diameter of 2 mm gave the best cooling effect.

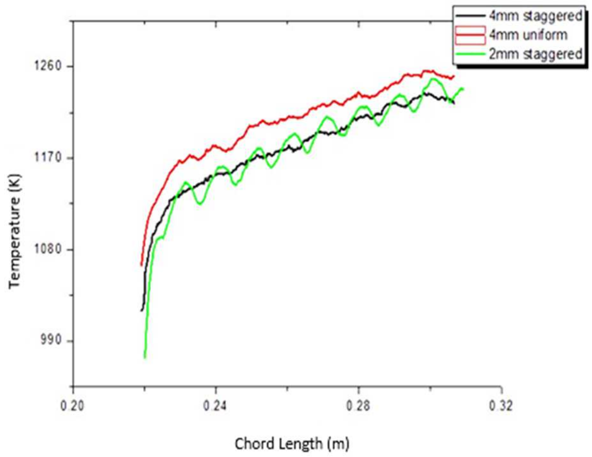


Figure 9 Comparison of staggered and inline arrangements of cylindrical pin-fin perforations with a diameter of 4 mm and staggered cylindrical pin-fin perforations with a diameter of 2 mm.

Simulations were also carried out for triangular perforations and the results were compared with those of the cylindrical perforations, as shown in Figure 10. It is clear that the staggered perforation arrangement of triangular fins with 4-mm sides had the most uniform cooling effect among the other configurations. With application of staggered triangular perforations with 4-mm sides, the temperature at the trailing edge of the blade was decreased by 32%, i.e. from 1561K to 1150 K.

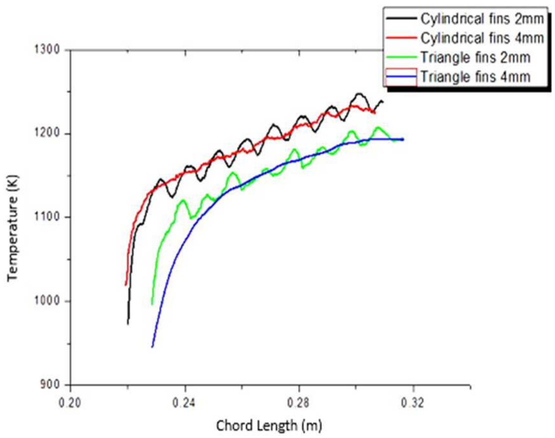


Figure 10 Comparison of triangular and cylindrical pin-fin perforations with a staggered arrangement.

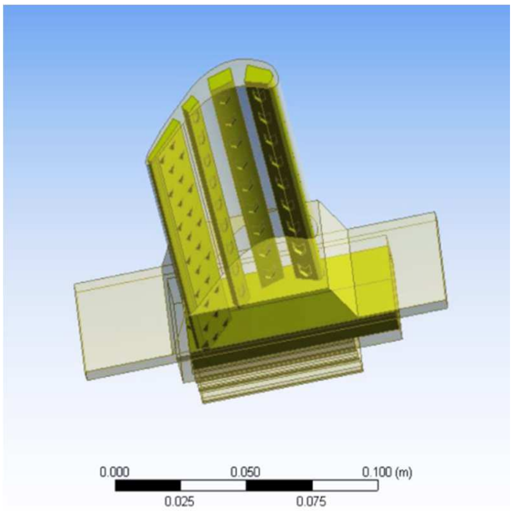


Figure 11 Gas turbine model with ribs and staggered triangular pin-fin perforations.

It is clear from the previous results that by using ribs with an aspect ratio of 2:3 and a 45° rib angle in the leading edge and staggered triangular pin-fin perforations with 4-mm sides in the trailing edge, cooling of the gas turbine blade can be enhanced. Hence, ribs with an aspect ratio of 2:3 combined with a 45° rib angle and staggered triangular pin-fin perforations with 4-mm sides were used for simulation of cooling at the leading and trailing edge respectively, as shown in Figure 11.

The results show that by using V-shaped ribs with an aspect ratio of 2:3 combined with a 45° rib angle and staggered triangular pin-fin perforations with 4-mm sides, the blade temperature decreased by 47%, i.e. from 1561 K to 825 K. Hence it is clear that as the fluid flows along the gas turbine blade the temperature of the blade keeps decreasing. This is mainly because the ribs and pin-fin perforation configurations create disturbance to the fluid flow and hence a swirling action takes place inside the gas turbine blade. This leads to an enhancement of the cooling effect.

4 Conclusions

It was found that the application of V-shaped ribs and pin-fin perforations is a promising technique for heat transfer enhancement inside gas turbine blades. CFD analysis was carried out for ribs with different aspect ratios and rib angles at the leading edge of the gas turbine blade. The results showed that ribs with a 2:3 aspect ratio combined with a 45° rib angle provided the best cooling at the leading edge. The temperature at the leading edge of the blade was decreased by approximately 30%, i.e. from 1561 K to 1100 K.

Simulations were carried out for pin-fin perforations at the trailing edge of the gas turbine blade with different configurations. With application of staggered triangular perforations with 4-mm sides, the temperature at the trailing edge of the blade was decreased by about 32%, i.e. from 1561K to 1150 K. The results showed that with the application of ribs with an aspect ratio of 2:3 combined with a 45° rib angle at the leading edge and staggered triangular perforations with 4-mm sides at the trailing edge, the cooling of the blade can be more effective. With the use of these configurations, the blade temperature decreased by 47%, i.e. from 1561 K to 825 K. Hence, it can be concluded that cooling of gas turbine blades can be enhanced with suitable rib and pin-fin perforation configurations.

Nomenclature

E	=	Energy
H	=	Height of rib (mm)
h	=	Heat transfer coefficient ($W/m^2 K$)

k	=	Thermal conductivity of fluid (W/m K)
Nu	=	Nusselt number
R_e	=	Reynolds number
u	=	Flow velocity (m/s)
$\vec{v}$	=	Volume
W	=	Width of rib (mm)
W/H	=	Aspect ratio
Δp	=	Pressure drop between entry and exit (Pa)
δ	=	Thickness of rib (mm)
μ	=	Fluid dynamic viscosity (Kg/m s)
ρ	=	Density (kg/ m^3)

References

[1] Manglik, R.M. & Bergles, A.E., *Heat Transfer and Pressure Drop Correlations for Twisted Tape Inserts in Isothermal Tubes*: *Part I – Laminar Flows*, ASME J. Heat Transfer, **115**(4), pp. 881-889, 1993.

[2] Manglik, R.M. & Bergles, A.E., *Heat Transfer and Pressure Drop Correlations for twisted Tape Inserts in Isothermal Tubes: Part II – Transition and Turbulent Flows*, ASME J. Heat Transfer **115**(4), pp. 890-896, 1993.

[3] Martemianov, S. & Okulov, V.L., *On Heat Transfer Enhancement in Swirl Pipe Flows*, Int. J. Heat Mass Transfer, **47**(10-11), pp. 2379-2393, 2004.

[4] Date, A.W., *Prediction of Fully Developed Flow in a Tube Containing a Twisted Tape*, International Journal of Heat and Mass Transfer, **17**(8), pp. 845-859, 1974.

[5] Date, A.W. & Saha, S.K., *Numerical Prediction of Laminar Flow and Heat Transfer Characteristics in a Tube Fitted with Regularly Spaced Twisted-Tape Elements*, International Journal of Heat and Fluid Flow, **11**(4), pp. 346-354, 1990.

[6] Chang, S.W., Jan, Y.J. & Liou, J.S., *Turbulent Heat Transfer and Pressure Drop in Tube Fitted with Serrated Twisted Tape*, Int. J. Therm. Sci., **46**(5), pp. 506-518, 2007.

[7] Kini, C.R., Shenoy, B.S. & Sharma, N.Y., *A Computational Conjugate Thermal Analysis of HP Stage Turbine Blade Cooling with Innovative Cooling Passage Geometries*, Journal of Lecture Notes in Engineering and Computer Science, **2192**(1), pp. 2168-2173, 2011.

[8] Kini, C.R., Shenoy B.S. & Sharma, N.Y., *Computational Conjugate Heat Transfer Analysis of HP Stage Turbine Blade Cooling: Effect of Turbulator Geometry in Helicoidal Cooling Duct*, Proceedings of World Academy of Science Engineering and Technology Special Journal Issue, 0070, pp. 645-652, 2012.

[9] Kini, C.R., Shenoy B.S. & Sharma, N.Y., *Numerical Analysis of Gas Turbine HP Stage Blade Cooling with New Cooling Duct Geometries*, International Journal of Earth Sciences and Engineering, **5**(4(2)), pp. 1057-1062, 2012.

[10] Kini, C.R., Yalamarty, S.S., Mendonca, R.Y., Sharma, N.Y. & Shenoy, B.S., *CHT Analysis of Trailing Edge Region Cooling In HP Stage Turbine Blade*, Indian Journal of Science and Technology, **9**(6), pp. 1-6, 2016.

[11] Kini, C.R., Shenoy, B.S. & Sharma, N.Y., *Thermo-Structural Analysis of HP Stage Gas Turbine Blades Having Helicoidal Cooling Ducts*, International Journal of Advancements in Mechanical and Aeronautical Engineering, **1**(2), pp. 57-60, 2014.

[12] Kini, C.R., Sharma, N.Y. & Shenoy, B.S., *Thermo-Structural Investigation of Gas Turbine Blade Provided with Helicoidal Passages*, Indian Journal of Science and Technology, **9**(20), pp. 1-6, 2016.

[13] Kini, C.R., Kamat, H. & Shenoy, B.S., *Numerical Simulation of Internal Cooling Effect of Gas Turbine Blades using Twisted Tape Inserts*, Indian Journal of Science and Technology, **9**(31), pp.1-6, 2016.

[14] Kini, C.R., Kamat, H. & Shenoy, B.S., *Effect of Twisted Tape Inserts and Stacks on Internal Cooling of Gas Turbine Blades*, Indian Journal of Science and Technology, **9**(31), 6 pp., 2016.

[15] Patankar, S.V. & Spalding, D.B., *A Calculation Procedure for Heat, Mass and Momentum Transfer in Three-dimensional Parabolic Flows*, International Journal of Heat Mass Transfer, **15**(10), pp. 1787-1806, 1972.

[16] Li, X. & Wang, T., *Two Phase Flow Simulation of Mist Film Cooling on Turbine Blades with Conjugate Internal Cooling*, Journal of Heat Transfer, **130**(10), 102901, 8 pp., 2008.

[17] Guo, J., Fan, A., Zhang, X. & Liu, W., *A Numerical Study on Heat Transfer and Friction Factor Characteristics of Laminar Flow in a Circular Tube Fitted with Centre-cleared Twisted Tape*, Int. J. of Thermal Sciences **50**(7), pp. 1263-1270, 2011.

[18] Choi, J., Mhetras, S., Han, J., Lau, S.C. & Rudolph, R., *Film Cooling and Heat Transfer on Two Cutback Trailing Edge Models with Internal Perforated Blockages*, Journal of heat transfer by ASME, **130**(1), 012201, 13 pp., 2008.

[19] Kim, K.M., Park, J.S., Lee, D.H., Lee, T.W. & Cho, H.H., *Analysis of Conjugated Heat Transfer, Stress and Failure in a Gas Turbine Blade with Circular Cooling Passages*, J. Engineering Failure Analysis, **18**(4), pp. 1212-22, 2011.

[20] Albeirutty, M.H., Alghamdi, A.S. & Najjar, Y.S., *Heat Transfer Analysis for a Multistage Gas Turbine using Different Blade Cooling Schemes*, J Applied Thermal Engineering, **24**(4), pp. 563-77, 2004.