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Thermo-Structural Investigation of Gas Turbine Blade Provided with Helicoidal Passages

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Abstract

By having helicoidal shape for the cooling passage, it is possible to provide more surface area for cooling per unit passage length. In addition to this, by providing turbulators within the helicoidal passages, it is possible to augment an increase in heat transfer from the blade surface to the cooling fluid. Since FSI is the objective of this analysis, the blade loading corresponding to the static pressure as well as temperature field on the blades surfaces are obtained using CFD run. The output results are then used as structural boundary condition to solve FSI, using finite element method. The present work brings out thermal and structural distortion of the HP stage gas turbine blade. A parametric approach is used for varying the cooling passage geometry to optimize the cooling process. It can be concluded from FSI analysis that circular helicoidal cooling passage (4 mm Φ) of pitch 6 mm with turbulators of size e/D = 0.08 with rib thickness 0.75mm effect in improved cooling properties and in turn reduce structural deformation.

Keywords: Gas Turbine Blade Cooling, Helicoidal Passages, Turbulators, Thermo-Structural Investigation

1. Introduction

Gas turbines are extremely operative prime movers widely used for generating electrical power and aircraft propulsion. Increase in temperature of the hot gas entering the turbine bade results in increase of power output and thermal efficiency of the gas turbine power plant. In the progressive gas turbines that are in being in place these days, the turbine entry temperature can be as high as 1773 K; though, this temperature surpasses the melting temperature of the gas turbine blades. It is clear from Brayton cycle that the major objective is to increase the turbine pressure ratio which increases the gas turbine thermal efficiency, accompanied by an increase in TET. As TET increases, the heat transferred to the blades in the turbine also increases[1]. The temperature level and variations on the turbine blade cause thermal stresses which must be limited to achieve reasonable durability goals. Numerous research are being supported to report the above anomalies[2-7]. Kini et al. in previous research work[8-11] established from computational fluid dynamics investigation that helicoidal passage of circular and elliptical geometry offers a substantial enhancement in cooling of gas turbine blade. This investigation has been carried out with an opinion to evaluate the structural solidity of the blade having a novel helicoidal passages exposed to high pressure, high temperature of the hot gases on the blades based on temperature dependent physical properties.

2. Computational domain for the FSI analysis

The helicoidal cooling passages used for the computational domain having parametrically varying geometries shown in table 1 are made as per objectives of present work. The typical geometry of cooling passages having ribs is as shown in Figure 1.

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Table 1. Computational domain

Helicoidal passage geometry						
Cross-section	Pitch Length	Hole diameter	Turbulator rib thickness	e/D	Major axis	Minor axis
Circular ○	6 mm	3 mm & 4 mm	0.75mm	0.08		
Elliptical ⬭	6 mm				3 mm	5 mm
					4 mm	5 mm

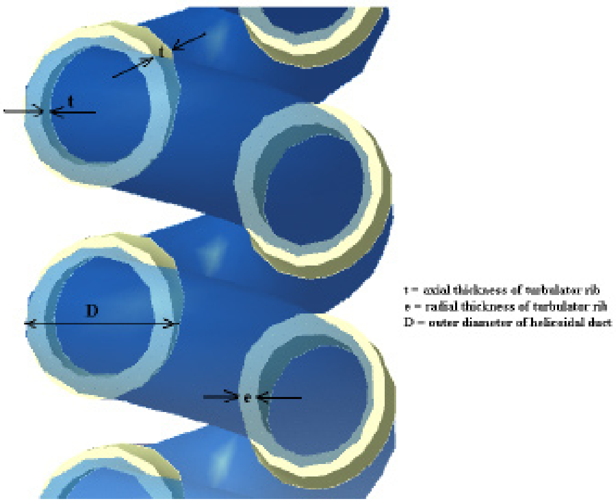

Figure 1. Model of passages with rib turbulator.

3. Numerical Model and Solution Procedure

At the outset, a CFD analysis was performed on gas turbine cooling passage to capture temperature and pressure field related to cooling air medium present within the passage. This was followed by a FEA of the gas turbine blade structure for steady state thermal cooling of the blade for which the results of CFD[12,15,16] was used as thermal boundary condition to capture temperature stresses that are developed due to relatively hot blade. The pressure loading over the blade surface due to ambient hot combustion gases were applied over the outer blade surface[12], whereas pressure loads at the interface from the passage were imported from CFD run. The steady state blade temperatures were introduced in order to perform static structural analysis. The hub being fixed to rotor disc is assumed to be fully constrained and the rated speed of the turbine blade was taken as 3600 rpm[13]. The physical properties of the blade material were inputted in tabular form[14].

Figure 2 shows grid independence test based on mesh size to check the quality of mesh for solution accuracy. The mean-line temperature was chosen as the dependent parameter for establishing the grid independency. The mean-line temperature corresponding to the blade surface do not differ more than 1.25 % between two mesh densities 0.75 and 0.7. Hence mesh size of 0.75 is taken as appropriate size due to corresponding reduced computational time.

4. Validation of Numerical Result with Corresponding Experimental Result

Figure 3 and 4 show the validation plots comparing numerical result output with corresponding experimental work. Figure 3 shows the surface temperature observed along the span taken at 30 % of chord. The inlet operating conditions at the root of the blade is kept the same for both experimental and numerical analysis. It is seen from the plots that there is very near convergence between numerical results within about 5 % deviation to that of the experiment.

In Figure 4 the variation is non-dimensional surface distortion is shown with respect to various inlet cooling passage operating temperatures. There is a negligible difference between the surface distortions at different operating temperatures. Hence it can be concluded that

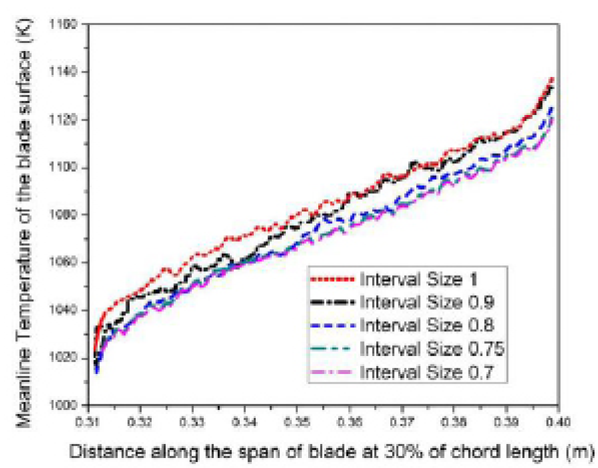

Figure 2. Results of grid independence test.

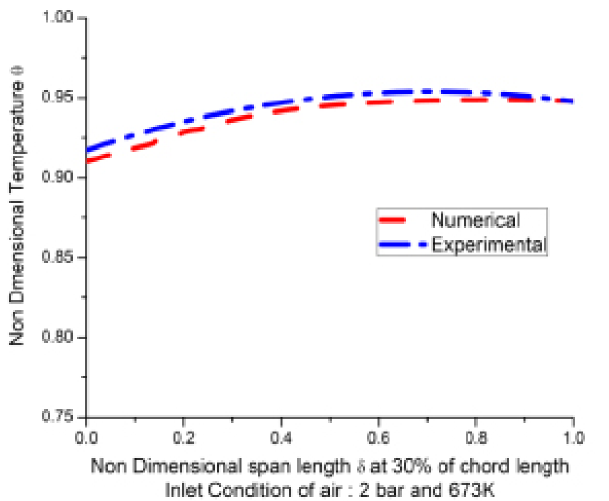

Figure 3. Temperature distribution along non dimensional span at 30% of chord.

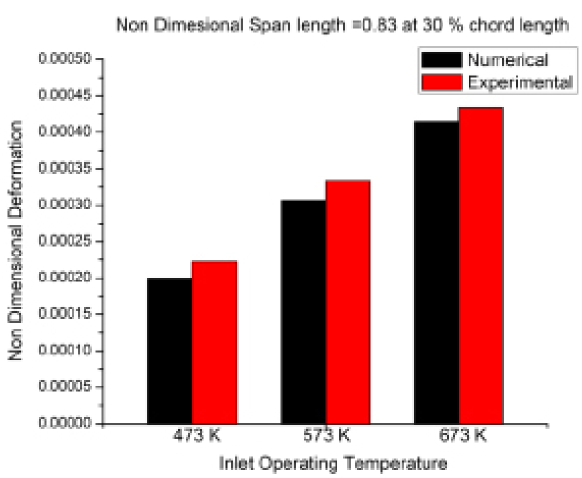

Figure 4. Comparison of distortion of blade surface with different inlet operating temperature of air at 2 bar.

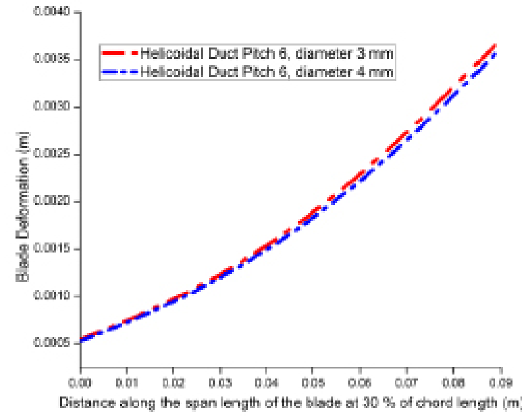

Figure 5. Blade Distortion along the span of the blade.

numerical model used for the study is quite valid. The boundary conditions applied on the blade is also justified from the analysis of validation.

5. Results and Discussions

Case 1: Structural investigation of the blade with helicoidal circular cross section passage of pitch 6 millimeter and hole diameter of 3 millimeter and 4 millimeter.

Figure 5 shows distortion of HP stage blade along span of the blade typically taken at 30% of the chord for comparison purposes. It is clear from the plot that a helicoidal passage with superior diameter (3.6442 millimeter) has comparatively less distortion than corresponding blade with a passage diameter of 3 millimeter cross section (3.7231 millimeter). This is very clearly due to better rate of cooling by larger cross section passage blade than the smaller. A larger cross section passage cooled blade provides not only larger area for heat transfer but also carries larger mass flow rate of coolant air. Hence heat removal capacity increases for the case of blades provided with passages of larger diameter. This is in turn induces less thermal stresses along span till tip of the blade.

With respect to blade loading that is applied to ambient pressure over the blade surface, the stresses on the blade surface will not be mitigated due to pressure acting from the inner surface of the cooling passage due to relatively very large pressure loading on the blade surface. Hence it can be stated that the distortion of the blade is not dependent on pressure field inside the passages and the thermal stresses on the blade could be partially mitigated with relatively larger diameter helicoidal passages. Figure 6 and 7 shows the total distortion for helicoidal passages without turbulators.

Case 2: Structural investigation of the blade with helicoidal circular cross section passages of pitch 6 millimeter with hole diameter 4 millimeter with and without turbulators (e/D of 0.08 and 0.75 millimeter rib thickness).

Figure 8 shows distortion of HP stage blade along span of the blade for helicoidal circular cross section passages with and absence of turbulators. The placement of turbulators in the passages has reduced the blade distortion (3.6257 millimeter) due to augmented coefficient of heat transfer. In general it can be seen that helicoidal passages

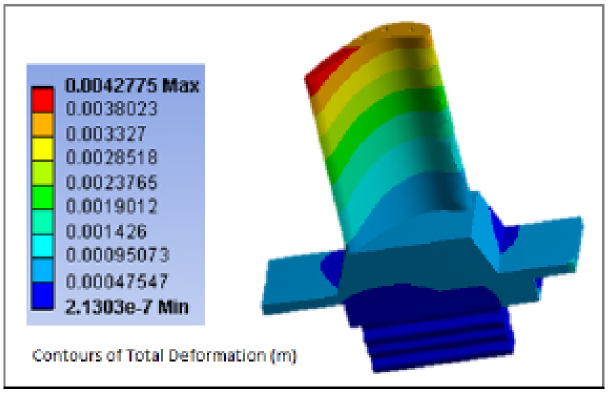

Figure 6. Blade distortion contours for Helicoidal circular cross section passages of Pitch 6 millimeter and diameter of 3 millimeter.

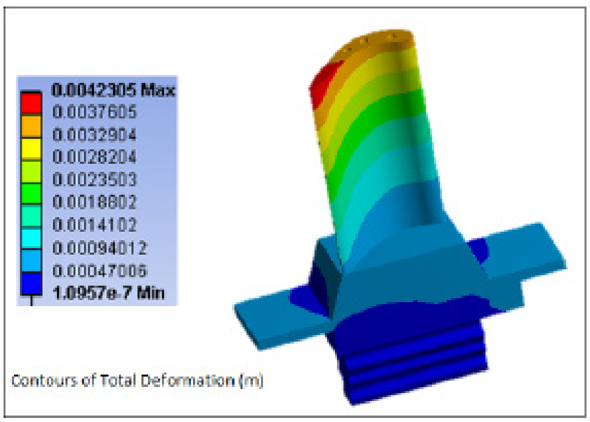

Figure 7. Blade distortion contours for Helicoidal circular cross section passages of Pitch 6 millimeter and diameter of 4 millimeter.

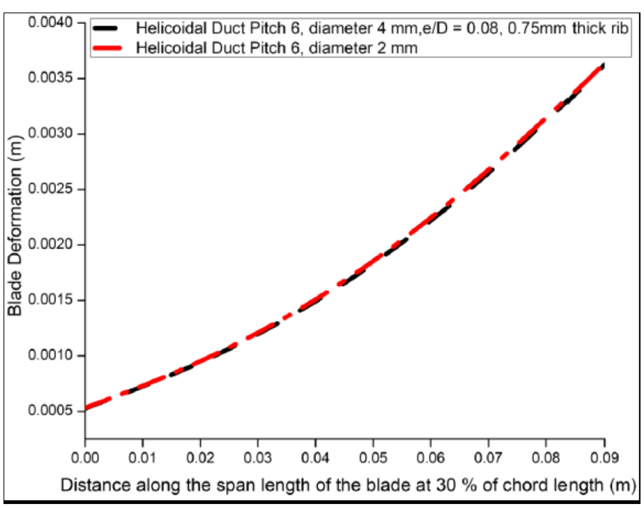

Figure 8. Blade Distortion along the span of the blade.

with turbulators play a vital role in turbine blade cooling development causing lower distortion. Therefore pitch of 6 millimeter, diameter 4 millimeter having turbulators (e/D = 0.08 and 0.75 millimeter rib thickness) has caused in minor distortion due to improved surface area, turbulence and Nusselt number. The total distortion for helicoidal passage having turbulators is shown in Figure 9.

Case 3: Structural investigation of the blade with helicoidal elliptical cross section passage of pitch 6 millimeter with a) major axis 3 millimeter and minor axis 5 millimeter b) major axis 4 millimeter and minor axis 5 millimeter.

The blade distortions for helicoidal passage of various geometries are shown in Figure 10. It is clear that with larger radius (perimeter) and with helicoidal passage of 6 millimeter pitch, distortion (3.73 millimeter) has increased corresponding to increased surface area. Total distortions for helicoidal passages of elliptical cross section are as shown in Figure 11 and 12.

It is clear that for helicoidal passages of pitch 6 millimeter with elliptical cross section of larger dimensions has resulted in higher distortion due to augmented surface area when compared to helicoidal passages of smaller dimension of the elliptical cross section.

Figure 13 shows the comaprison of distortion along the span for the cases discussed above. In the case of helicoidal passages of pitch 6 millimeter with elliptical cross section of larger dimensions even though it has resulted in better cooling of the turbine blade[5], due to increase in surface area of the passage the structural distortion has marginally enlarged. It is clear that helicoidal circular passages of pitch 6 millimeter, diameter 4 millimeter with

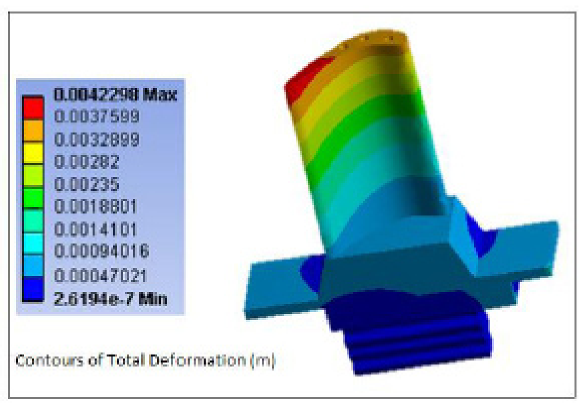

Figure 9. Blade distortion contours for Helicoidal passages of Pitch 6 millimeter and diameter of 4 millimeter with turbulators of e/D = 0.08 and 0.75 millimeter rib thickness.

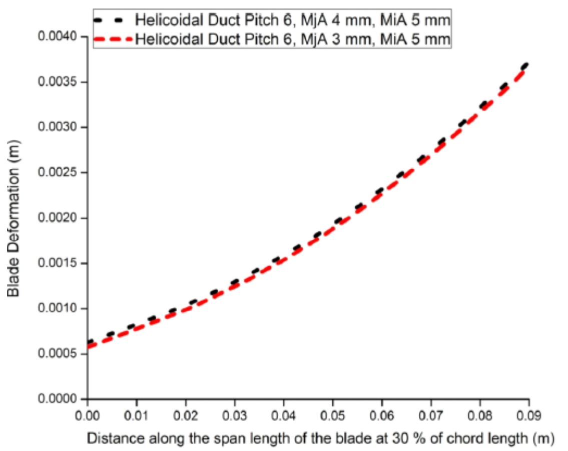

Figure 10. Distortion along the span of the blade.

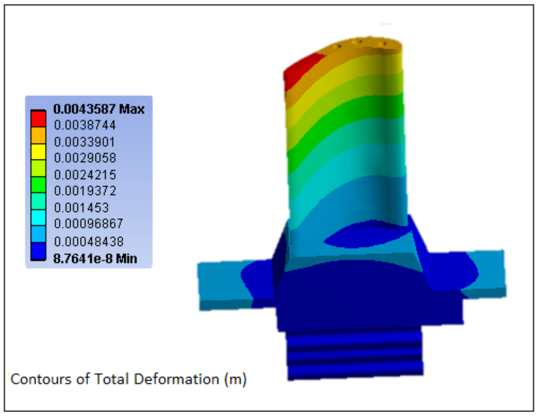

Figure 11. Total distortion contours for Helicoidal passages of elliptical cross section of Pitch 6 millimeter, major axis 3 millimeter and minor axis 5 millimeter.

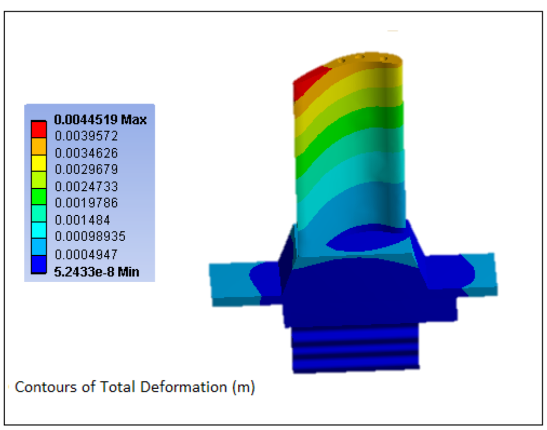

Figure 12. Total distortion contours for Helicoidal passages of elliptical cross section of Pitch 6 millimeter, major axis 4 millimeter and minor axis 5 millimeter.

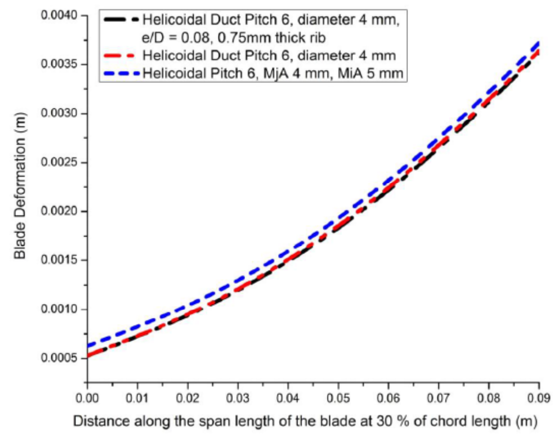

Figure 13. Distortion along the span of the blade.

turbulators (e/D = 0.08 and 0.75 millimeter rib thickness) has caused in minor distortion due to improved surface area and turbulence[8,9].

6. Conclusions

1. It is observed that an inventive helicoidal passage provides a better convective area for enhanced spreading of heat ensuing in minor structural distortion.
2. The geometric parameters of the helicoidal passages play fairly a main part in cooling of the gas turbine blade.
3. Analysis based on temperature dependent physical properties, helicoidal circular passages with turbulators result in better cooling of turbine blade and in turn minimizes structural distortion.

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