1. Introduction

Thermodynamic study of gas turbine 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. To enhance fatigue life of gas turbine blade many cooling techniques can be used on the blade exterior such as internal convective cooling and 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 of this region is a challenging task as enough coolant can’t be guided. Additional constraints due to structural integrity and manufacturing difficulty for internal cooling passage geometry in this thin section also arise. One of the cooling techniques frequently used by turbine designers for the trailing edge is using twisted tape inserts. Among the different heat transfer techniques, twisted tape is widely used due to their simple configuration and easy installation. Twisted tapes generates swirl in tubes which enhance the heat transfer by generating swirl within the tube\(^3\). Date and Saha\(^4,5\) investigated the thermal energy transfer and fluid flow performance with aid of Navier Stokes and energy equations by means of a uniform heat flux tube fitted with repeatedly spaced twisted tapes. In\(^6\) matched the outcomes of serrated and broken tape inserts with smooth twisted inserts. Results showed that thermal energy transfer can be improved with usage of serrated twisted tape. It is also shown that heat transfer coefficient, Fanning friction factor and heat assessment factor of the tube were increased in a particular Re range. Kini et al. in earlier research work\(^7-13\) established from CFD analysis...
Numerical Simulation of Internal Cooling Effect of Gas Turbine Blades using Twisted Tape Inserts

that helicoidal cooling duct and buttress shaped grooved configuration provided a significant improvement in turbine blade cooling.

2. Validation of the Tool

The geometries of the conventional twisted tape are shown in Figure 1. Twisted tape having thickness ($\delta$) of 1 millimeter is fitted in the circular tube of diameter 20 mm and length of 500 mm are used for the validation of the software tool. Different width ratio ($W = W/D$) starting from $W = 0.9$ to $W = 0.2$ are considered. The 180 degree ($H$) twist pitch is 0.05 m and comparative twist pitch is $2.5^{14}$.

Figure 1. Conventional twisted tape.

2.1 Governing Equation

The essential governing equations for fluid flow and energy transfer in a flow passage are Navier-Stokes energy and continuity equations along with the equations for modeling the turbulence magnitudes.

The Mass Conservation Equation:

$$\nabla \cdot (\rho \mathbf{v}) = 0$$  \hspace{1cm} (1)

Navier - Stokes Equations:

$$\nabla \cdot (\rho \mathbf{v} \nabla \mathbf{v}) = - \nabla p + \nabla \cdot \mathbf{\tau} + \rho \mathbf{g}$$  \hspace{1cm} (2)

The stress tensor $\mathbf{\tau}$ is given by,

$$\mathbf{\tau} = \mu \left[ \left( \nabla \mathbf{v} + (\nabla \mathbf{v})^T \right) - \frac{2}{3} \nabla (\mathbf{v} \cdot \mathbf{v}) \right]$$  \hspace{1cm} (3)

The second term on the right hand side is the effect of volume dilation. For incompressible flow, $[\nabla (\mathbf{v} \cdot \mathbf{v})]$ becomes zero.

The Energy Equation:

The energy equation in the following form:

$$\nabla \cdot \left( \mathbf{v} \left( \rho E + p \right) \right) = \nabla \cdot \left( \kappa_{eff} \nabla T - \sum_{i} \mathbf{K_i} \frac{\mathbf{r}_i}{r_i^3} + \frac{\mathbf{\tau}}{\rho} \right)$$  \hspace{1cm} (4)

2.2 Numerical Methods

CFD tool is used for this work. The above-mentioned governing equations supplemented with boundary environments are solved using FVM. The numerical model employs customary pressure and discretization schemes viz. second order upwind scheme for momentum and energy. ‘SIMPLE’ algorithm is employed to couple pressure and velocity. A convergence condition of 10e-5 for continuity and velocity residuals, 10e-6 for energy are employed$^{15}$.

2.3 Boundary Conditions

Table 1. Boundary conditions for validation of tool$^{14}$

|                       |Velocity inlet          | Heat Transfer Co-efficient | Viscous Model | Material | Working fluid |
|-----------------------|------------------------|-----------------------------|---------------|----------|---------------|
| Re=500                | 0.02512 m/s            | 20 W/m²k                    | Laminar       | Aluminium | Water         |
| Re=1000               | 0.05024 m/s            |                             |               |          |               |

The analysis under deliberation is to be three dimensional, steady and laminar as shown in Table 1. No slip boundary state is applied on the surface of the wall and tape insert. Pressure-outlet condition is been defined at the outlet.

Interface boundary condition is enacted amongst circular duct and the twisted tape. Temperature difference of 25 degree Celsius is considered. The tetrahedral mesh is employed for individually for tube and twisted tape insert with T grid type as shown in Figure 2. 0.7 spacing is maintained for both the elements.

Figure 2. Tetrahedral element is used for meshing.

2.3 Results and Discussion

Analysis is carried out for Reynolds number 500 and 1000 for the various width ratios of twisted tape inserts. A plot is drawn between Nusselt number and friction factor vs. different width ratio as shown in Figures 3 and 4.
It is observed that for $W = 0.9$, friction factor and Nusselt number is high but as width ratio is decreases the ‘$Nu$’ and ‘$f$’ is also decreases. Even though Nusselt number is high for $W = 0.9$, the friction factor is high that may cause damage to the twisted tape. Hence suitable twisted tape with width ratio is selected for the heat transfer.

### 3. Physical Model

CFD preprocessor is powerful design tool to define CFD simulations which can be later exported to CFD solvers and postprocessors like Fluent, Polyflow and Star-Cd for analysis purpose.

#### 3.1 Modeling of Gas Turbine Blade having Twisted Tape Inserts

After modelling of gas turbine blade as shown in Figure 5, various twisted tape insert configurations are placed in the gas turbine blade only in top half region. This is because to check the influence of twisted tape insert in the leading edge, suction side and pressure side of the gas turbine blade. Twisted tape inserts can be used in gas turbine blade which gives better heat transfer results as discussed in previous chapter.

Twisted tape inserts starting from width ratio $W = 0.3$, 0.25, 0.2 and 0.15 are placed in the top half part of the gas turbine blade as shown in Figure 6. It is not possible to place twisted tape insert of $W = 0.9$ due to space.
constrains in gas turbine blade. Four twisted tape inserts are placed in the blade and the results are compared with different width ratio. By increasing the number of twisted tape insert it possible to increase the cooling effect but only for few width ratios. Because of space constrains it is not possible to place more number of twisted tape inserts in gas turbine blade.

3.3 Boundary Conditions
Simulation needs to be conducted under high pressure and high temperature conditions to understand the physics of cooling of gas turbine working under real

Figure 5. Gas turbine blade model and tetrahedral grid generation.

Figure 6. Gas turbine blade with various inserts configurations.
operating environment. The parameters simulating gas turbine operating environment are listed in Table 2. The turbulence model has been explained in\textsuperscript{16} and is summarized in Table 2 without further explanations.

| Boundary condition   |
|----------------------|
| **Inlet velocity**   | 128 m/s |
| **Temperature at inlet** | 644 K |
| **Wall temperature** | 1561 K |
| **Pressure outlet**  | Gauge pressure |
| **Fluid**            | Air |
| **Material**         | Nickel alloy |
| **Viscous Model**    | Standard k–\(\varepsilon\) model |

4. Results and Discussion

4.1 Results of Gas Turbine Blade with Twisted Tape Insert Configurations

Simulation of gas turbine with twisted tape insert configurations of width ratio starting from W = 0.3 till W = 0.15 are carried out in CFD software without placing stacks at the trailing edge. Static temperature contours of W = 0.3, 0.25, 0.2 and 0.15 are shown in Figures 7 to 10. For W = 0.3, it provides the fluid a longer flow path and promotes the generation of secondary circulation hence a large magnitude of heat transfer is taking place in comparison to the other ratio of width. But as the width ratio goes on decreases the rate of heat transfer is also decreases. This is due to the reduction in the swirl flow or disturbance created by the tape inserts.

Results shows that by using twisted tape insert for width ratio (W) = 0.3 gives better cooling effect compared to the others. By using twisted tape inserts of W = 0.3 (without using stacks) the blade temperature is decreased by about 34% at the leading edge i.e. from 1561 K to approx. 1030 K and about 21% at the trailing edge i.e. from 1561 K to approximately 1230 K.
5. Conclusions

- It was found from validation test that the twisted tape is a favourable method for heat transfer improvement. It was also found that heat transfer can be improved with suitable width fraction of twisted tapes. CFD results show that the results are satisfactory when compared with the reference journal paper.
- Simulation is carried out with suitable insert configurations of width ratio and results showed that by using twisted tape insert for width ratio \(W = 0.3\) gives better cooling effect compared to the others.

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Nomenclature

- \(H\) Twist pitch
- \(\delta\) Thickness of the twisted plate
- \(W\) Width of the twisted plate
- \(y\) Twist length
- \(Y\) Twist ratio \((y/W)\)
- \(Re\) Reynolds number
- \(\rho\) Density
- \(\nu\) Volume
- \(E\) Energy
- \(H\) Enthalpy
- \(Nu\) Nusselt Number
- \(L\) Length of the tube
- \(D\) The diameter of the tube
- \(w\) Width ratio \((W/D)\)
- \(h\) Heat transfer coefficient
- \(u\) Flow velocity
- \(\mu\) fluid dynamic viscosity
- \(k\) Thermal conductivity of fluid
- \(\Delta p\) pressure drop between tube entry and exit