Numerical analysis of turbine tip modifications in a linear turbine cascade

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Abstract: Turbine blade tips are subject to burn out owing to leakage flow. Tip clearance flow arises due to the flow of unexpanded hot combustion gas through the interstice between turbine rotor blade tip and fixed shroud. In the present study we are numerically analyzing the effect of 4 tip modifications like dimpled tip (DIM), double squealer tip (DSS), pressure side squealer tip (PSS), and suction side squealer tip (SSS) on a plain tip. The influence of tip modifications on the effectiveness of turbine was estimated using parameters such as total pressure loss coefficient and vorticity magnitude and loss estimation using correlations. The study was conducted for various tip clearances such as 0%, 1.5%, 2.3% and 5% with respect to the blade span. Linear turbine cascade with 5 blades were used for this study. Simulations are carried out using commercial CFD solver, ANSYS FLUENT 14.0. Standard cascade loss estimation correlation was used. In the midst of tip shapes tested, double squealer tip and dimpled tip seemed to have the pre-eminent total pressure loss coefficient diminution. Both tip modifications significantly reduces the clearance leakage through the space between tip and casing, which consecutively depreciate the secondary losses adjacent to the convex surface of the blade. Correlation for losses through cascade showed a linear relationship between tip clearance loss and tip clearance gap. These tip modifications can be used in any kind of turbo machines for better performance with improved efficiency.

1. Introduction
When turbine blade tips are exposed to unexpanded flow, it could be subjected to aerodynamic losses and high heat load near the blade tip region. Increased inlet temperature will result in increased power output and efficiency but with the expense of certain aerodynamic losses in turbines.

Efficiency is the most important performance parameter in any turbo machinery. Aerodynamic losses cause reduction in efficiency in turbo machinery. If we want to estimate losses in a turbine we should target different losses, and to minimize these losses we need to know what the contribution of these losses in turbine is. But it is not easy to segregate these different losses. There are certain empirical correlations for estimating all these different losses.

Even though hot combustion gas passes through different components of a turbine, the turbine tip is more susceptible for failure. This is the case for a conventionally cooled blade, because turbine tip is...
very difficult to cool using conventional cooling technique. Leakage flow is the main reason for high heat load near the turbine tip. Leakage flow is the flow of hot combustion gas throughout the entire space between turbine rotor tip and the shroud without expanding through the turbine blades. This leakage flow is the main reason for traditional classes of losses like profile loss, secondary loss and tip clearance loss. The actual cause of clearance flow is the dissimilarity in pressure between both side of rotor blade.

Over the last few decades, researches are going on in turbine blades to reduce aerodynamic losses and high heat load near the turbine blade tip. Lot of experimental investigations are performed on turbine blades to curtail the losses due to leakage flow through clearance. Young et al. [1] carried out experimental analysis of different turbine tip modifications on clearance flow (tip leakage flow) and total pressure loss. A total of 11 tip modifications were tested using a linear cascade with 5 airfoils. The tip modifications are dimpled tip (DIM), double squealer tip (DSS), pressure side squealer tip (PSS), suction side squealer tip (SSS), grooved along camber line tip (GCL), grooved along pressure side tip(GPS), grooved along suction side tip(GSS), chamfered from pressure side tip (CPS), chamfered from suction side tip (CSS) and trailing edge chamfered tip (TEC). They analysed the space between the turbine rotor blade tip and shroud of about 1.5% and 2.3% with respect to blade height. From the results they concluded that the DSS and the GPS tip showed lower Cptot than the plain tip. Sang Woo Lee et al. [2] experimentally inquired the impact of various rim height of squealer tip on clearance flow and found that as rim height to chord ratio (hst/c) increases, tip leakage vortex becomes weaker and thereby reduces aerodynamic losses. But this reduction in losses limited to near tip region. Pressure side winglet (PS) and a leading edge and pressure side winglet (LEPS) have been used for this investigation. J. D. Denton [3] discusses different loss mechanisms in turbo machines which is very helpful for researchers to find different methods to overcome these losses. Hai-Ping Wang et al. [4] observed periodically fluctuating horseshoe vortex system by conducting visualisation techniques to visualise the flow through a linear turbine cascade having high execution turbine blades.

Stationary cascades are usually employed for most experimental studies on tip leakage flow. Yaras and Sjolander [5] and Yaras et al. [6] considered the experimental studies on the relative motion between turbine rotor blade and shroud. Numerical investigations are also performed by researchers on secondary flow and loss mechanisms in turbo machines. Sumanta Acharya et al. [7] performed numerical simulation of leakage flow and heat transfer on double squealer tip in a linear turbine blade. They considered a squealer tip having 3.77% recess of the blade span for their investigation. They found that the heat transfer coefficient reduces considerably on the shroud and suction surface of rotor blade. Researchers found that certain tip modifications are very helpful to reduce the heat load as well as aerodynamic losses. So in order to find an efficient turbine blade design and to reduce losses at tip clearance region a 3D analysis of 4 tip modifications such as pressure side squealer tip, dimpled tip, double squealer tip and suction side squealer tip was done using CFD by applying tip modifications in a linear turbine cascade.

Here in this paper, novel turbine rotor blade tip modifications which can fabulize for high heat load at the tip region are proposed and their vorticity magnitude performance and total pressure loss reduction performance was investigated. Four tip modifications are analysed for tip clearances of 0%, 1.5%, 2.3% and 5% of blade span. Total pressure loss coefficient and vorticity magnitude were measured at a plane created along span-wise direction at a distance of 150 mm from the middle blade positioned adjacent to inlet of the cascade. The tip clearance effect on aerodynamic losses was also analysed. Standard cascade loss estimation correlation was used to show the linear relationship between tip clearance loss and tip clearance gap.

2. Methodology
2.1 Computations and Validation
Figure 1 shows the linear turbine cascade with 5 blades used for this numerical analysis. The cascade geometry and blade specifications are summarized in table 1. By using SOLIDWORKS, cascade geometry was created.
Figure 1. Linear turbine cascade.

Table 1. Cascade geometry and blade specifications.

| Parameters                        | Dimensions |
|-----------------------------------|------------|
| Chord length of blade (mm)        | 378        |
| Blade spacing (mm)                | 308.1      |
| Blade height (mm)                 | 160        |
| Chord length/ blade spacing       | 1.226      |
| Total blades                      | 5          |
| Flow angle at inlet of cascade (deg) | 32        |
| Flow angle at outlet of cascade (deg) | -65.7     |
| Turning angle of cascade (°)      | 97.7       |

Air velocities at inlet and exit of cascade are 15 m/s and 29.5 m/s. Reynolds number with respect to blade chord length and velocity at the outlet of turbine cascade is $7.943 \times 10^5$. Figure 2 represents the geometry and transectional view of 4 different turbine tip modifications.
Figure 2. Geometry and transectional view of tip modifications (a) DSS, (b) DIM, (c) PSS, (d) SSS.

Plain tip is modified into 4 tip modifications using the dimensions given in Figure 2. The domain with the above mentioned blades are modelled for tip clearance of 0%, 1.5% (2.4 mm), 2.3% (3.68 mm) and 5% (8 mm) of blade span. Numerical simulations of these tip modifications are done using ANSYS FLUENT 14.0 software in a 5 bladed linear turbine cascade.

Grid independency test was conducted in order to find accurate mesh size for study. Total pressure loss was considered over blade for conducting grid independency test. Number of elements was taken to be 23,49,013 for all models considered for study. From the result it is evident that the total pressure becomes constant when the number of elements increased from 23,49,013 to 39,98,610. So we choose the least number of elements among them to run the solution. It helps to decrease the computational time. Figure 3 shows the plot for grid independency test.

Figure 3. Grid independency test.

Linear turbine cascade used in the experimental analysis of Sang Woo Lee et al.[2] is used in the validation study. 0% tip clearance with respect to blade span was selected for validation work. Static pressure coefficient at the midst-span of instrumented blade was measured and plotted as L/C versus Cps. The results were found in accordance with the experimental results. Figure 4 shows midst-span static pressure distribution on instrumented blade.
2.2 Numerical Procedure

Commercial software ANSYS FLUENT 14.0 is used for the simulation of this study. Equations are discretised by solving equations (RANS) using a finite volume approach. A pressure based solver, SIMPLE is used to solve the discretised equations.

Computational domain consists of 5 blades provided with inlet temperature 1473K and a turbulence intensity level of 5%. SST k-ω turbulence model was taken for the simulation. $10^{-4}$ residual levels are required for all 20 cases used in this numerical analysis to achieve convergence.

3. Results and discussion

The loss mechanism in this study was examined by using the total pressure loss coefficient ($C_{p_{tot}}$) and $C_{p_{tot}}$ is described by

$$C_{p_{tot}} = \frac{P_{t0} - P_{t}}{0.5\rho_0 U_0^2}$$  \hspace{1cm} (1)

Figure 5 shows mass averaged loss coefficient in terms of total pressure for squealer tip and plane tip along pitch-wise direction for 1.5% tip clearance. The PLN tip has higher $C_{p_{tot}}$ when compared with squealer tip at the tip clearance region ($y/H > 0.9$). Since the squealer tip have weaker tip vortex flow. The flow rate of hot combustion gas along the tip clearance is low for squealer tip when compared with plain tip. Tip leakage vortex adjacent to the convex surface of blade become weaker helps to form stronger passage vortex. Impuissant turbine rotor tip leakage vortex give rise to stronger antagonistic trundle main stream vortex. Weaker turbine rotor clearance vortex antecedent high heat load and aerodynamic loss near the turbine blade clearance region.
Figure 5. Mass averaged loss coefficient in terms of total pressure for squealer tip and plain tip along pitch-wise direction.

Figure 6 shows mass averaged total loss coefficient in terms of total pressure along pitch-wise direction for dimpled tip. At T= 1.5%, DIM tip exhibits lower Cptot than the PLN tip as a result of feasible tip leakage vortex. 18 dew drop shaped dimples at the rotor blade tip of turbines induces intricate flow phenomena and there by increases flow resistance. These dimples were fabricated in the anticipated clearance flow direction and also the crown of dimples are positioned upstream of the leakage flow which helps to create larger separation region within the dimples. By aligning dimples in the expected leakage flow direction we can diminish the mass flow rate through the tip clearance region. This help to depreciate tip leakage flow and tip leakage vortex.

Figure 6. Mass averaged loss coefficient in terms of total pressure for dimpled tip along pitch-wise direction.

Nevertheless, at T=2.3% PLN and DIM have nearly similar values for Cptot. The flow characteristics of hot combustion gas within the dimple depend on the configuration of dimples and the alignment of dimples on the tip surface. Figure 7 shows mass averaged loss coefficient in terms of total pressure along pitch-wise direction for different tip modifications like DIM, PLN and DS.

Figure 7. Mass averaged loss coefficient in terms of total pressure for different tip modifications along pitch-wise direction.
Increased tip clearance results in increased $C_{ptot}$ when tip clearance increases the flow rate of hot combustion gases along the clearance in the midst of tip of turbine rotor blade and the shroud increases resulting high heat load and aerodynamic losses near the tip region as well as near the convex surface of turbine blade due to stronger clearance vortex. Increased tip clearance also causes increase in vorticity magnitude due to high flow rate and stronger clearance vortex.

Figure 9 shows the vorticity magnitude chart for 1.5% tip clearances for all tip modifications used in this analysis and the observations were in comparison with plain tip having a tip clearance of 1.5%. By seeing this result it is evident that the vorticity magnitude reduces for each tip modifications. At $T=1.5\%$ the plane tip have higher vorticity magnitude than the different tip modifications.

Therefore by using tip modifications we can reduce the flow rate along the tip clearance region. It helps to weaken the clearance vortex near the convex surface of the blade. Hence we can reduce aerodynamic losses and high heat load near the blade tip region and adjacent to the convex surface of the blade.

Figure 10 shows the vorticity magnitude for different tip clearances for plane tip. Increased tip clearance will increase the flow rate along the clearance and stronger tip clearance vortices are formed near in the clock-wise direction i.e, negative vortex formation adjacent to the convex surface of turbine rotor blade as observed in Sarath et.al [9].
Stronger negative vortices increases aerodynamic losses and also high heat load adjacent to the blade tip region increases due to increased flow rate along the tip clearance region. Figure 11 shows the loss coefficient in terms of total pressure for different tip clearances for plane tip. Increased tip clearance will increase the tip leakage flow and there will be formation of stronger leakage vortex associated with aerodynamic losses adjacent to the convex surface of turbine blade. The increase in loss is clearly seen in the plot by increase in loss coefficient in terms of total pressure.

![Figure 10](image)

*Figure 10. Loss coefficient in terms of total pressure for different tip clearances for plain tip.*

Different correlations are available for estimating losses through cascade. The correlation estimated by Ainley and Mathieson [8] is used in this study.

\[
C_{PTC} = 0.5 \left( \frac{T}{H} \right) \left( \frac{L}{5} \right)^2 C_L^2 \left( \frac{\cos^2 \beta_2}{\cos^2 \beta_m} \right) \left( \frac{Re}{2 \times 10^5} \right)^{-0.2} \tag{2}
\]

\[\beta_m = \tan^{-1} \left( \frac{\tan \beta_2 - \tan \beta_1}{2} \right) \tag{3}\]

Figure 8 shows losses through linear turbine cascade. There is a beeline analogy with the tip leakage loss and tip clearance. This correlation also supports increased tip clearance increases tip clearance losses due to high mass flow rate.

![Figure 11](image)

*Figure 11. Losses through cascade.*
4. Conclusions
numerical analysis carried out in order to find the effect of different turbine tip modifications and also to find an efficient turbine blade design that helps to reduce tip clearance loss and secondary losses by means of measuring $C_{p_{tot}}$ and vorticity magnitude, the following conclusions are made:

- Efficient use of dimpled tip reduces losses at different tip clearances when compared with plain tip in a very effective manner.
- There is a linear relationship between tip clearance loss and tip clearance gap indicating that increased tip clearance causes increased losses through cascade.
- Use of different tip modifications helps to reduce tip clearance flow and also reduces tip leakage vortex and efficiency increases.

5. References

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