VOL. 14, NO. 23, DECEMBER 2019 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

NUMERICAL ANALYSIS OF NOVEL TIP SHAPES IN A TURBINE CASCADE

Sarath R. S. and Sijin D.
Department of Mechanical Engineering, Amrita Vishwa Vidyapeetham, Amritapuri, India
E-Mail: sarathrs@am.amrita.edu

ABSTRACT

The work aims at analyzing the blade tip modification effects in a gas turbine flow. The high losses associated with turbine flows will drastically influence the performance parameters of gas turbines. A small amount of loss reduction will bring about greater efficiency and higher cost reduction in gas turbine industries. In the present work, tip modifications in the form of plane tip, double side squealer tip and pressure side squealer tip were numerically analyzed. The analysis was done using the commercial software ANSYS 14. Three tip clearance cases was analysed and compared in the present study. The results showed that tip modifications reduced the aerodynamic losses considerably. The modified blade geometries can be considered as a potential candidate in gas turbine industry which can bring about greater loss reduction in blade tip areas.

Keywords: tip leakage vortex, total pressure loss, squealer tip, secondary flow.

INTRODUCTION

Turbo machines having a small clearance between the tip region of the blade andthe fixed end wall is referred to as tip clearance. This clearance actually provides some losses as the flow escapes through the clearance area. This flow which leaks through the clearance gap is known as tip leakage flows. The efficiency of the turbo machine decreases proportionate to the tip gap. Natural flow of the working fluid takes place from the suction region to the pressure region of the blade due to pressure difference. The static pressure difference across the flow near the end walls results in the generation of circulatory flow which gets superimposed on the main flow through the blade passage and as a consequence, secondary vortices are formed in the stream wise direction [10]. This could cause high aerodynamic loss (due to secondary flow establishment) and heat load (due to tip leakage flow bringing high temperature, unexpanded flow from the pressure side to the suction side) on the tip of the rotating blade (Figure-1).

The modifications on the tip shapes are referred to as treatment of tip configurations. Cascades of linear arrangements of blades which ease the analysis and captures flow physics in a better manner is used here. Computational Fluid Dynamics (CFD) is a very efficient tool to analyze the flow characteristics numerically.

The main stream flow changes abruptly due to the action of leakage flow. The high heat load at the tip regions because of the non-expanded leakage flow will create metallurgical problems and eventually leads to failure. The temperature of the working fluid entering the turbine will be in the rangeof 1200K-1500K. These aspects have high impact on many researchers to investigate the effects of blade tip shapes on the secondary flow losses and this paper deals with the necessity of the tip clearance losses estimated and minimized.

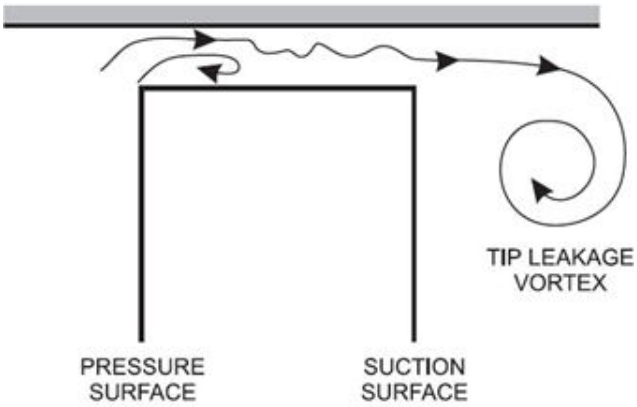

Figure-1. Tip clearance effect [6].

Young *et al*. [1] investigated the effects of turbine blade tip shape on the total pressure loss and secondary flow of a linear turbine cascade. The paper [1] analyzed the effects of tip clearance experimentally for eleven variety tip configurations such as plain (PLN), squealer, chamfered, grooved, dimpled etc. The experiment was done with different tip heights such as 0%, 1.5%, and 2.3% of the blade span. The experimental results insisted that the squealer tip blade shows better performance results. Lee *et al*. [2] analyzed the aerodynamic performance of tip gap covering with two different winglet configurations such as "Leading Edge Pressure Side "(LEPS) and Pressure Side (PS) winglets for different width-to pitch ratios. The result shows that the additional coverage around the pressure side will give more reduction to the secondary losses. Kim *et al*. [3] studied the influence of tip gap of a cavity squealer tip in a turbine cascade in comparison with plane tip. The paper [3] shows a clear cut idea about the variation of the pressure losses and secondary flows at the end wall region. Tip clearance stature consequences for the flow in a cavity squealer tip in a turbine cascade in examination with plane tip: Section 1-tip crevice stream structures were dissected by Kim *et al* [4]. The different tip heights with respect to

blade span were analyzed. Lee *et al*. [5] performed blade tip height impacts on the flow over a squealer tip in a turbine course in examination with plane tip. Tip leakage flow of an unshrouded high pressure turbine blade with tip cooling was performed by Zhou *et al.* [6]. ElBatch *et al*. [7] did an experimental and numerical study of the effect of tip clearance on three dimensional flow fields through linear turbine cascade. R. S. Sarath *et al*. [9] conducted a detailed analysis on various tip modifications in a liner turbine cascade. They also investigated the different losses in a linear turbine cascade and the interaction of leakage flow and secondary flow in the tip region. From the above literatures, it is observed that the numerical simulation on the effect of tip shape variation was not carried out in the past studies and hence, taken up for the present study.

The modelling of geometries and the domain discretization were finished utilizing SOLID WORKS. The investigation was done utilizing ANSYS FLUENT 14.0 [10] on Workbench platform.

The paper depicts a detailed numerical analysis to compare the conventional plain tip blade with squealer tip blade. The secondary losses were quantified by vorticity - based investigation. The tip clearance effects on aerodynamic loss were also analyzed. The configurations like blade tip with 0%, 1.5%, and 2.3% of blade span were used to compare the effects of plain tip with squealer tip.

NUMERICAL MODELLING

Conservation equations

The conservation of mass, momentum and energy are used in the study. The equations are solved using pressure-velocity coupling [8] and solution is obtained using the SIMPLE (Semi Implicit Method for Pressure Linked Equations) approach. Turbulence modelling is done using the standard k-ε model.

Geometry and domain discretization

Table-1. Blade profile specifications.

Blade Chord(mm)	**126**
Blade Pitch(mm)	102.7
Blade Span(mm)	160
Solidity(chord/pitch)	1.23
Number of blades	5
Inlet angle(degree)	32
Outletangle(degree)	65.7

The model used for the study has 5 blades. The blade profile selected was that of NACA 2512 airfoil. The key dimensions and angles of this blade geometry are listed in Table-1.

The blade profile is drawn with the data points as of NACA 2512. The clearances are chosen on the basis of the blade span (160mm).

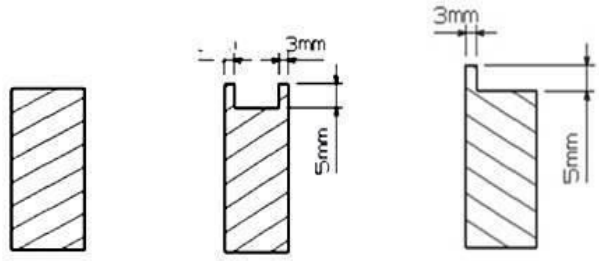

Figure-2. Cross sectional view of blade models (a) PLN tip (b) DSS tip and (c) PSS tip.

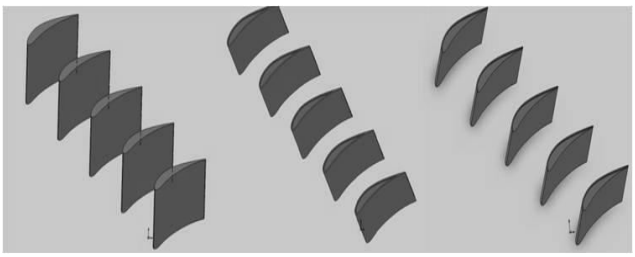

Figure-3. Blade cascade models (a) PLN tip (b) DSS tip (c) PSS tip.

The Figures 2 (b) and (c) shows the rim details of the squealer blades, and which has squealer of 5mm depth. The three different configurations of the cascade model of five blades are also shown on Figure-3. The squealer tip helps to reduce the secondary flows near the tip region which was proved experimentally [1] and hence increase the life of the blade tip.

The blades are arranged in the domain with the required angle shown in the Figure-4. The blades are fixed between the hub and the shroud with a tip clearance. The clearances selected for this analysis are 1.5%, 2.3% of blade span, via 2.4 mm and 3.68 mm. The clearance is provided at the shroud end to represent the exact domain. So three different configurations with three different clearances was analyzed numerically. The effect of blade rotation is neglected here because we are dealing with cascade analysis where the blades are stationary. Though the flow physics might be different for plain and squealer tip blades when rotation is considered, it is thought that, the effect of rotation would a common feature for all these blade types and hence, in the final comparison to deduce the effect of blade tip shape it won't bring notable differences.

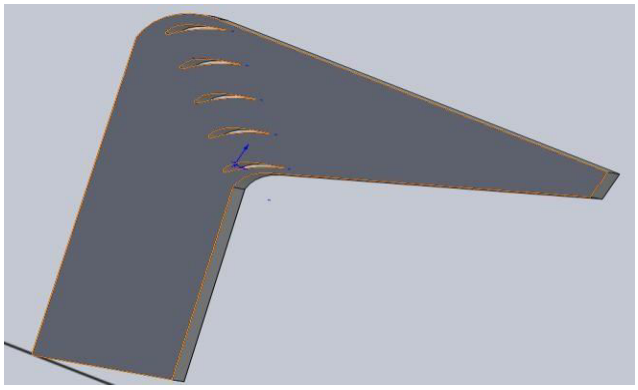

Figure-4. Cascade model formed using squealer tip with 0% clearance.

The meshing was done for all the cases by using ANSYS Fluent.14.0. The mesh size for the geometry was calculated by grid independency test. As general criteria, the mesh volumes are increased by almost 1.5 times in each case and as a measurement criterion, the mass averaged total pressure loss across the cascade was selected.

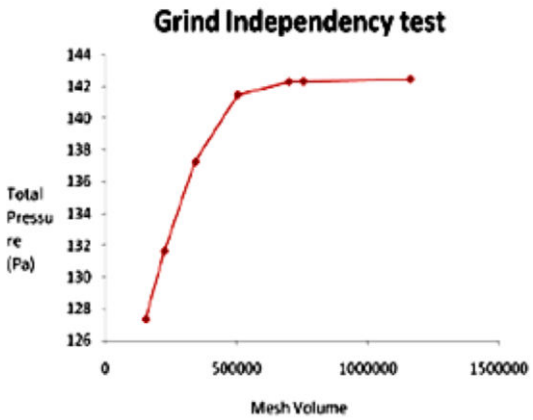

Figure-5. Grid independency test.

The Figure-5 shows the total pressure variation with respect to the mesh volume. The mesh generation was done using standard mesher of ANSYS Fluent.14.0. As per the grid independency test result; the total pressure is showing not much variation after 11, 62,891 of mesh volume and the corresponding value as 142.4718 Pa. So the mesh volume the present analysis was selected as 11, 62, 891. The Fig 6 and 7 shows the computational grid.

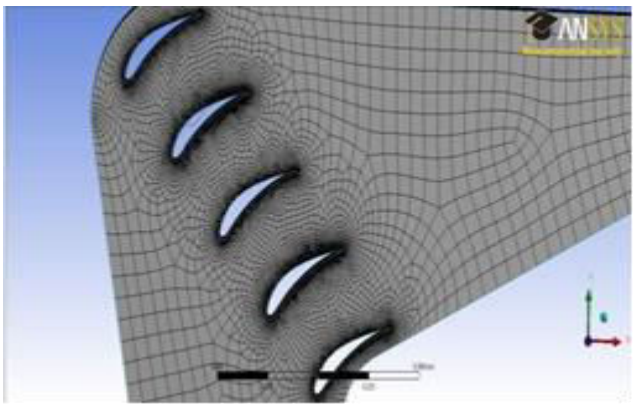

Figure-6. The grid at the root.

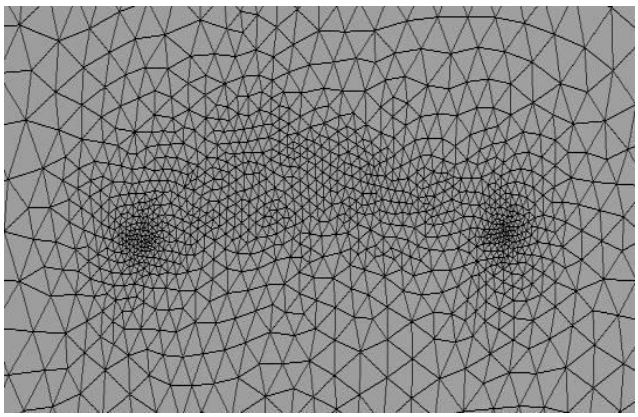

Figure-7. Tip clearance grid.

Validation

The experimental result of [1] was analyzed numerically for a tip clearance of 0% of blade span. The validation procedure was done for a mesh volume of 11, 62,891. The static pressure coefficient on the two sides of the blade i.e., pressure side (PS) and suction side (SS) was analyzed numerically and compared with the experimental results. The results are plotted in the Figure-8. The CFD results ith the selected mesh volume were almost in accordance with the experimental observations.

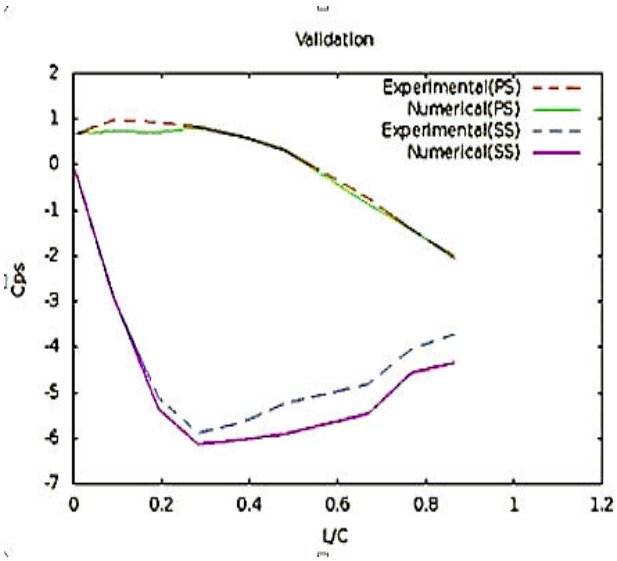

Figure-8. Comparison of experimental and CFD results of Static pressure coefficient on Pressure side (PS) and Suction side (SS) on a plain tip with no clearance.

NUMERICAL ANALYSIS

The analysis was done with ANSYS FLUENT workbench 14.0 [8]. The run was made with double precision. The steady state flow is set to analyze the secondary flows and boundary layer formation for the present cascade problem. The ideal fluid, air is used for the analysis. The consideration is made that all the properties of the air are constant. The inlet velocity 15m/s, temperature 1200K, turbulent intensity 5%, and hydraulic diameter of 226.7mm were set as inlet boundary conditions. The outlet flow conditions are atmospheric with a turbulent intensity of 5% and a hydraulic diameter of 167.6mm. The domain outer layer and blades are treated as adiabatic wall.

A pressure based solver, SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) is used for the analysis. A convergent criterion of 1.00e-5 is set for all residuals and second order discretization was used for the equations.

RESULTS AND DISCUSSIONS

The numerical analysis on effects of leakage flows in the linear turbine cascade was done. Three different blade tips with three distinct configurations were compared in the 5-blade cascade (a total of nine blade models). The parameters such as total pressure loss coefficient and vorticity magnitude in a plane at the downstream flow were calculated and compared for the plain, double squealer and pressure side squealer blade tip of clearances 0%, 1.5% and 2.3% in the present analysis.

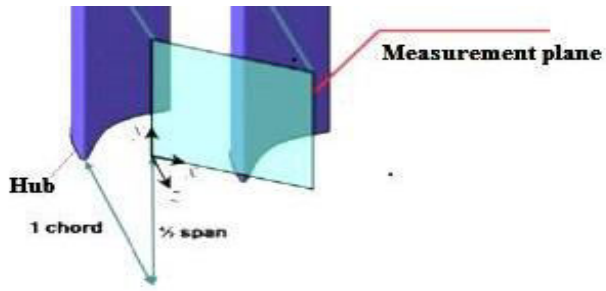

Figure-9. Location of plane [1].

A plane is taken at a one chord distance from the blades (Figure-9) in which the flow parameters were measured. The variation of the flow properties on span-wise(y/H) direction was compared and plotted. Here H and S are the blade span and the pitch of the blades respectively.

The total pressure loss coefficient is calculated from the equation;

$$Cp_{tot} = \frac{P_{t0} - P_t}{0.5\rho_0 U_0^2}$$

where P_{t0} is the inlet total pressure of the cascade (Pa), Pt is the total pressure at the nodes (Pa), ρ_0 is the density of the air (kg/m3), U_0 is the inlet velocity (m/s). The vorticity gives a measure of the local spinning motion of fluid near some point as seen by an observer moving along with the fluid. This can be used as a measure of the secondary flow. Vorticity is equal to the curl (rotational) ofits velocity field

$$(\vec{\omega}) = \vec{\nabla} \times \vec{V}$$

When the leakage flow interacts with the mainstream flow, local secondary vortices will be generated at the tip clearance region. The vortices so created will affect the flow at the blade trailing edge region. When the intensity of leakage flow increases, the leakage vortex gets strengthened and will oppose the passage vortex which is created by the main stream flow. As the tip clearance increases to 2.3% of blade span, the passage vortex gets weakened and as a result the stronger leakage vortex starts to move towards the pressure side of the adjacent blade.

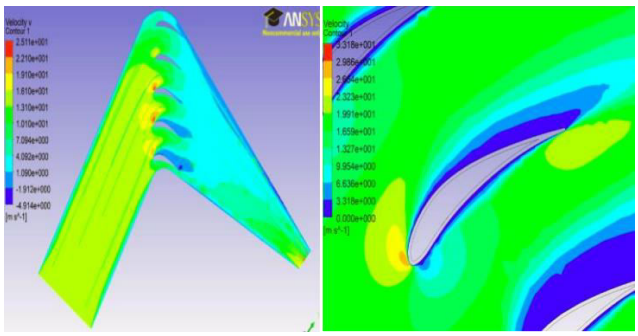

Figure-10. Velocity profile of plain and DSS tip for 2.3% of blade span.

Figure-10 shows the velocity variation for the plain blade and DSS blade tip. Flow circulation and separations were observed in the velocity profile. The vortices were formed in the plain blade at the end wall region was higher when the clearance is increased. The same in the DSS tip is comparatively less since the rim will causes additional resistance in the direction of the leakage flow.

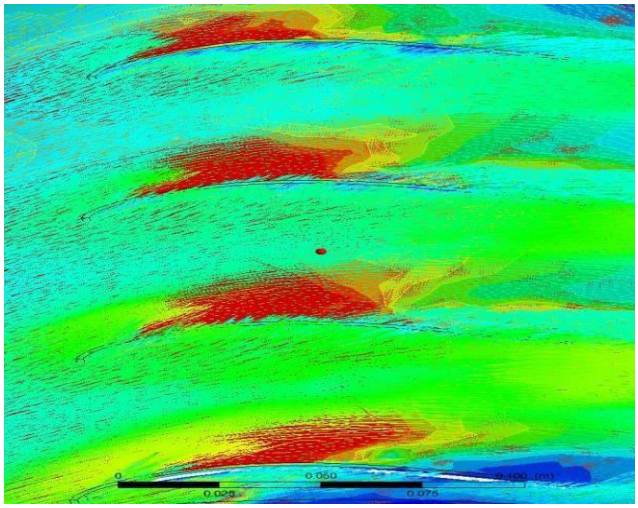

Figure-10(b). Velocity profile of PSS tip for 2.3%.

The Figure-10 (b) shows the velocity contour of the middle blade PSS tip with 2.3% tip clearance. Unless the DSS tip, the vortices are comparatively higher here. Due to the absence of suction side squealer rim, more flow will interacts with the tip pressure side rim so that the PSS tip is under high flow resistance.

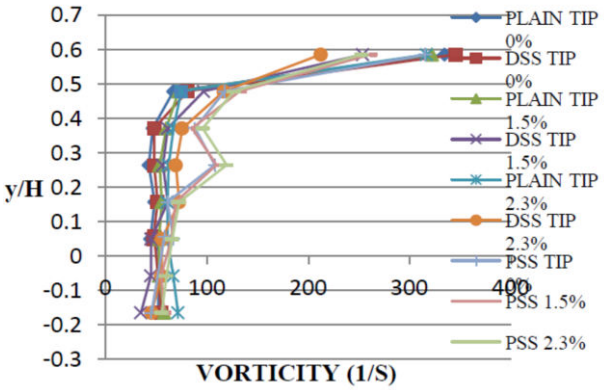

Figure-11. Span-wise variation of vorticity magnitude.

The flow properties were analyzed on the plain which is selected at the downstream of the blade. The vortex magnitude is high at the tip region of the blade which is shown in the Figure-11. The vorticity magnitude along the span of the blade was plotted for all the cases. From the Figure, it can be clearly seen that the region $0.53<y/H<0.6$ where the magnitude of vorticity changes rapidly due to the additional secondary flows. Secondary flows are induced in a turbine cascade blade due to leakage flows at the tip clearance [11].

From the basics of flow physics, the spinning motion of the fluid is called vortex, i.e., the flow is highly rotational in nature. Secondary flow creates these additional vortices at the tip region. In the present analysis, the magnitude of the secondary flow is taken as indicating the magnitude of the vorticity at the tip end.

From the Figure-11, the vorticity magnitude near the tip region for plain tip blade is comparatively higher than that of squealer blade. By using a double squealer blade tip with a tip clearance of 1.5% of blade span, the magnitude of the secondary flow vertices reduced to 21.25% and the same with 2.3% of blade span reduced to 32.93% than that of plain blade tip. The squealer blade rim will acts as an additional resistance in the direction of flow of the leakage flow. When the leakage flow hits on the wall of the squealer rim, it will get deflected back and flows against the incoming leakage flow. This provides a reduction in the magnitude of the leakage flow and eventually will strengthen the passage flow vertices.

The Figure-11 shows the results of PSS tip blade also. By using a pressure side squealer blade tip with a tip clearance of 1.5% of blade span, the magnitude of the secondary flow vertices reduced to 18.86% and the same with 2.3% of blade span reduced to20.31% than that of plain blade tip. Here the blade tip region is underhigh pressureloss and flow recirculation and flow separation are higher than DSS tip.

From the results, the squealer tip blades gives more reduction in the leakage flow and there by intensifying the main stream vertices. So to achieve better operational performance for the turbo machines, double side squealer tip blade is good and reliable candidates than plain blades. Secondary flows have compounding effects on promoting early flow separation in the blade suction

surface [10]. So squealer tip blades have great ability to reduce the secondary flows.

The leakage flow creates metallurgical problems at the blade tip due to its high temperature. So to reduce these critical problems of heat load to some extent, squealer tip blade would be a good option and also helps to improve the blade's life.

The region where y/H =0.4, the magnitude of vorticity showing not much difference for the two cases such as plain and squealer tip blade. This is due to the absence of tip clearance. The vorticity magnitude analyzed without tip clearance case is found to be the same for both the tip shapes such as plain as well as squealer tip blade.

The region where y/H =0.4, the magnitude of vortices are higher in the case of PSS tip. This is due to severe recirculation and flow separation.

The Figure-12 shows the variations of pressure loss coefficient of all the blades which were analyzed. An important result observed from the Figure-12 is that the pressure loss coefficient in the case of DSS tip blade with 1.5% and 2.3% shows large value than the same with plain tip blade.

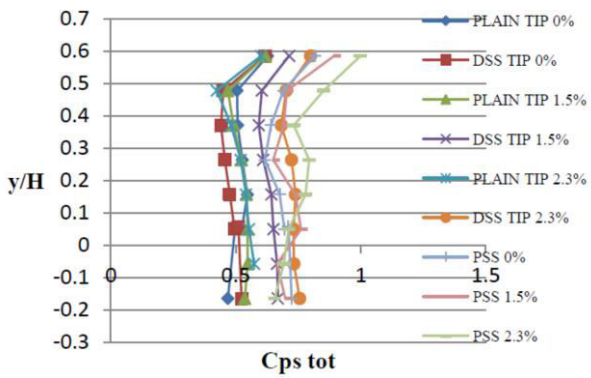

Figure-12. Span-wise variation of total pressure loss coefficient.

But the squealer tip has least total pressure loss coefficient at the tip region (0.4<y/H<0.6). The PSS tip shows the higher loss of pressure coefficient due to the unwanted circulatory flows and flow separation in the end wall region.

CONCLUSIONS

The numerical analysis was done to find out the best blade tip configuration which can reduce the leakage flow losses by accounting the vorticity magnitude along the span of the blade. The major conclusions that have obtained from the present analysis are;

a) The squealer tip blade effectively reduces the secondary flows and leakage losses at the blade tip region than a plain tip blade.

b) By providing the DSS tip blade for the two cases such as 1.5% and 2.3% of the blade span, the secondary losses reduced to 21.25% and 32.93% respectively.

c) The PSS tip blade shows much lesser leakage reduction than DSS tip for 1.5% and 2.3% of the blade span, the secondary losses reduced to almost 19% and 20% for the respective cases.

d) Recirculation and flow separation are high in the PSS tip blade than DSS tip due to the excessive pressure loss in the tip region.

e) To obtain good performance conditions of turbo machines, and to avoid the unwanted secondary flows, and thereby increasing the life of the blade, double squealer tip blade can be a good candidate.

ACKNOWLEDGEMENT

Authors would like to thank all the members of Mechanical Engineering Department, Amrita School of Engineering and to all others who have directly or indirectly helped us in carrying out this work.

REFERENCES

[1] Y. C. Nho, J. S. Park, Y. J. Lee and J. S. Kwak. 2012. Effects of turbine blade tip shape on total pressure loss and secondary flow of a linear turbine cascade. International Journal of Heat and Fluid Flow. 33(1): 92-100.

[2] S. W. Lee, S. U. Kim and K. H. Kim. 2012. Aerodynamic performance of winglets covering the tip gap inlet in a turbine cascade. International Journal of Heat and Fluid Flow. 34: 36-46.

[3] S. E. Lee, S. W. Lee and H. S. Kwak. 2011. Tip leakage aerodynamics over stepped squealer tips in a turbine cascade. Experimental Thermal and Fluid Science. 35(1): 135-145.

[4] S. W. Lee and S. U. Kim. 2010. Tip gap height effects on the aerodynamic performance of a cavity squealer tip in a turbine cascade in comparison with plane tip results: part 1-tip gap flow structure. Experiments in Fluids. 49(5): 1039-1051.

[5] S. W. Lee and M. Y. Choi. 2010. Tip gap height effects on the aerodynamic performance of a cavity squealer tip in a turbine cascade in comparison with plane tip results: part 2-aerodynamic losses. Experiments in Fluids. 49(3): 713-723.

[6] C. Zhou and H. Hodson. 2011. The Tip Leakage Flow of an Unshrouded High Pressure Turbine Blade with Tip Cooling. Journal of Turbo machinery. 133(4): 041028.

[7] M. Niu and S. Zang. 2011. Experimental and numerical investigations of tip injection on tip clearance flow in an axial turbine cascade. Experimental Thermal and Fluid Science. 35(6): 1214-1222.

[8] B. R. Baliga and S. V. Patankar. 1983. A control volume finite-element method for two-dimensional fluid flow and heat transfer. Numerical Heat Transfer. 6(3): 245-261.

[9] R. S. Sarath, R. Ajith Kumar, B. V. S. S. S. Prasad and A. R. Srikrishnan. 2016. Numerical Analysis of Effects of Turbine Blade Tip Shape on Secondary Losses. Lecture Notes in Mechanical Engineering. pp. 871-879.

[10] 2012. ANSYS FLUENT 14.5 Users Guide, ANSYS Inc.

[11] S M Yahya. 2006. Turbines, Compressors and Fans. Tata McGraw Hill Publishers.