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AEROTHERMAL PERFORMANCE OF PARTIAL AND CAVITY SQUEALER TIP IN A LINEAR TURBINE CASCADE

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ABSTRACT

Three-dimensional highly complex flow structure in tip gap between blade tip and casing leads to inefficient turbine performance due to aerothermal loss. Interaction between leakage vortex and secondary flow structures is the substantial source of that loss. So as to improve the turbine performance, different kinds of squealer tip geometries have been tried in the literature. The current research deals with comparison of partial and cavity squealer tip concepts for higher aerothermal performance. Effects of squealer tip have been examined comprehensively for an unshrouded HP turbine blade tip geometry in a linear cascade. In the present paper, flow structure through the tip gap have been comprehensively investigated by Computational Fluid Dynamic (CFD) methods. Numerical calculations have been obtained by solving three-dimensional, incompressible, steady and turbulent form of the Reynolds-Averaged Navier-Stokes (RANS) equations using ANSYS CFX. Two equation turbulence model, Shear Stress Transport (SST) has been used. The axial turbine blade tip profile belongs to the Pennsylvania State University Axial Flow Turbine Research Facility (AFTRF). The tip profile of the AFTRF that was used to create an extruded solid model of the axial turbine. For identifying dimensions of squealer rim in terms of squealer height and squealer width, our previous studies about aerothermal investigation of cavity squealer tip have been examined. In order to generate the mesh, an effective parametric grid generation has been performed using a multizone structured mesh. Numerical calculations indicate that partial and cavity squealer designs can be effective to reduce the aerodynamic loss and heat transfer to the blade tip. Future efforts will include novel squealer shapes for higher aerothermal performance.

INTRODUCTION

In order to allow the relative motion of blades and to prevent the blade tip surface from rubbing, clearance gap between blade and casing is required in turbomachinery. The overall performance of the turbomachines is strongly related to the flow within tip gap. The flow in this gap is 3D and highly complex. The pressure difference across the pressure and suction side of the blade forms a leakage flow passed over the blade tip surface. The pressure driven flow throughout the gap results in approximately one-third of the aerodynamic loss in the rotor of an axial gas turbine [1]. The flow structure in the tip gap is a significant source of inefficiency in terms of aerodynamic loss and heat transfer to the blade tip and casing. The leakage flow passes over the blade tip without being turned as the passage flow, thus a reduction in work extracted from the turbine is observed [1-4]. The leakage flow is also a significant source of higher thermal loads on the blade tip platform which is exposed to the hot gas stream [4,5].

There are many studies in order to clarify the structure of the tip leakage flow and to reduce its adverse effects. In an early investigation Moore and Tilton investigated the leakage flow both analytically and experimentally considering the flow through the tip gap as a flow through an orifice [6]. Bindon and

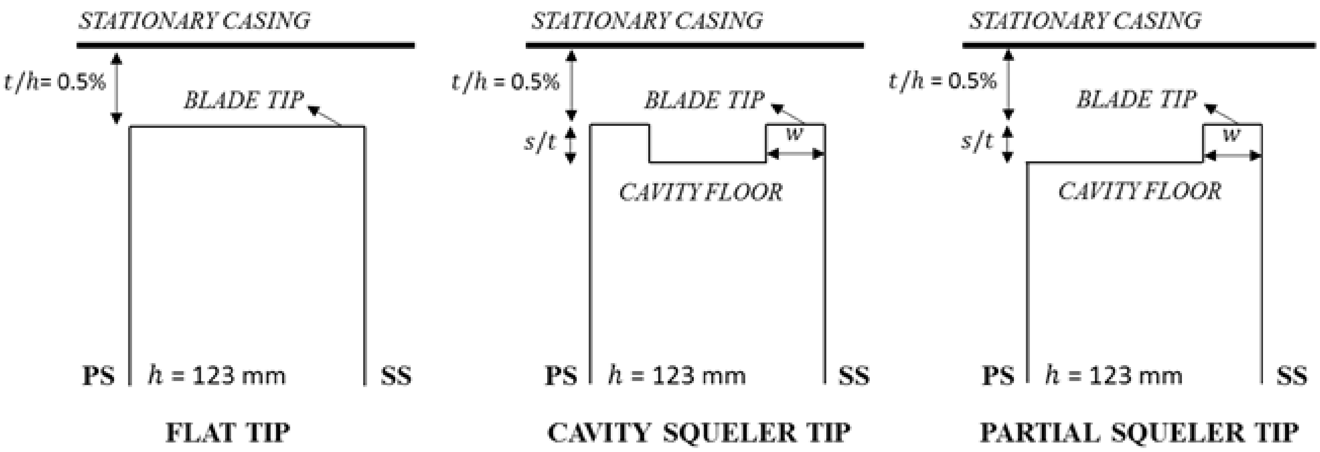

FIGURE 1: CONSEPTUAL VIEW OF BLADE TIP DESIGNS

Morphis revealed the effects of tip geometries and radius at the pressure side corner on aerodynamic loss [7]. Yaras and Slojander investigated the effect of relative motion between blades and casing and experiments revealed that the leakage flow rate was decreased by the effect of rotation [8]. Passive control methods such as squealer, partial squealer and winglet blade tip designs are widely used in order to reduce the effects of leakage flow. Heyes at al. figured out that the implementation of squealer tip geometries could be effective in reducing the leakage flow since a separation bubble blocks the flow [2]. Ameri et al. numerically investigated the effect of a squealer geometry on heat transfer and efficiency and obtained that the leakage flow rate was reduced whereas the heat transfer to the blade tip was increased [9]. Azad et al. investigated different types of squealer geometries in a linear turbine cascade experimentally and indicated that a suction side squealer had better results with respect to a pressure side squealer [4]. Krishnababu et al. [3] studied numerically different types of geometries including both cavity tip squealer geometry and suction side squealer geometry. Numerical results showed that a cavity squealer reduced aerodynamic loss and heat transfer to the blade tip. In this study, it was stated that width of the squealer could be effective in determining the performance of the squealer. Lee and Kim investigated the flow structure over a cavity squealer tip experimentally for a linear turbine cascade [10]. Zhou numerically studied the thermal performance of the baseline cavity tip with wider and higher cavity tip. In this research, thin and low rim yielded the lowest aerodynamic loss [11]. Wei et al. simulated the aerodynamic performance of five passive control methods: pressure side winglet, suction side winglet, cavity squealer, inclined pressure side squealer and partial suction side squealer tip [12]. They revealed that inclined pressure side squealer had the best turbine efficiency. Camci et al. carried out an experimental and numerical study in a rotational test rig (AFTRF) for aerodynamic performance of full and partial-length squealer rims [13-15]. Schabowski and Hodson investigated both numerically and experimentally the aerodynamic performance of various blade tip designs including squealer and winglet geometries [16].

In this paper, the effect of a squealer tip section has been examined comprehensively for an unshrouded HP turbine blade in a linear cascade. A special emphasis is placed on obtaining three dimensional and complex grid systems in a parametric effort. The parametric approach in tip leakage mitigation studies provides significant time savings for the construction of the solid model and its associated flow grid. Conceptual view of flat, partial squealer and cavity squealer tip designs has been given in Fig. 1.

METHOD

A numerical study has been conducted in present paper. Computational Fluid Dynamics (CFD) is an important tool to make a better understanding flow in turbomachines whereas experimental measurements may become difficult, expensive and time consuming.

Three different tip designs have been studied: flat tip (FLAT), squealer (SqBASE), suction side squealer (SS-SqBASE) in Fig.1

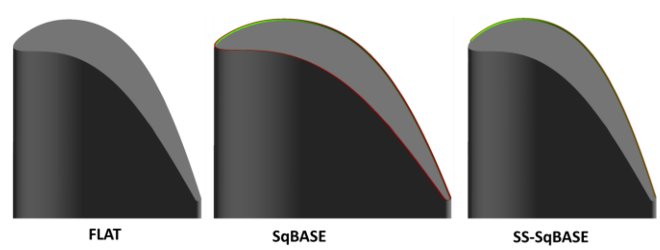

Fig. 1: Flat tip and squealer tip geometries

Axial blade geometry belongs to Pennsylvania State University Axial Flow Turbine Research Facility (AFTRF). Tip profile of the turbine in AFTRF was used to form solid model of axial turbine. Some design features of turbine blade is given in Table 1.

Table 1 Blade specifications

Blade Height [mm]	123.615
Tip Gap Height [mm]	0.615
Axial Chord [mm]	85.04
Flow Angle (º) (inlet)	71.3
Pitch [mm]	99.274
Number of Rotor Blades	29
Rotational Speed [rpm]	1300

In this study squealer height is 0.615 mm while the tip gap height is 0.615 mm which corresponds to a tight tip clearance (t/h=0.5%). Width of the squealer has been defined as 0.4 mm.

Computational domain was obtained in SpaceClaim module in ANSYS as a linear cascade arrangement. Computational domain for squealer is given in Fig. 2. There have been there basic domains: inlet, blade and outlet. Inlet length has been defined as one axial chord while outlet length was equal to two axial chord. Length of inlet and outlet domains have been reduced to 1 and 2 axial chords respectively from 3 and 6 axial chord. In order to reduce the number of elements, these lengths have been shortened.

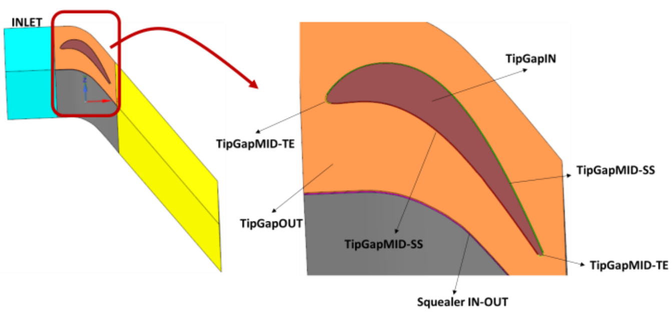

Fig. 2: Computational domain.

Blade domain has been divided into 9 blocks to generate a fully hexagonal grid in a simple way. Fully hexagonal elements have been used in calculation to reduce solution time and obtain more accurate results. Creating multi blocked flow domain enables to use multizone method in ANSYS Meshing module. Multizone method can be defined as a type of blocking approach similar to ICEM CFD. Automated topology decomposition is used so as to generate structured hexa mesh where blocking topology is available [17]. Also, boundary layer mesh similar to O-Grid in ICEM CFD has been performed to keep y^+ at desired level whereas it as around 1 in present study. Tip gap region has been divided into two subdomains named squealer and tip gap as seen from Fig.2. These two subdomains have also been separated into multi blocks. Number of division in tip gap has been selected 36 totally by employing equal divisions for squealer and casing heights.

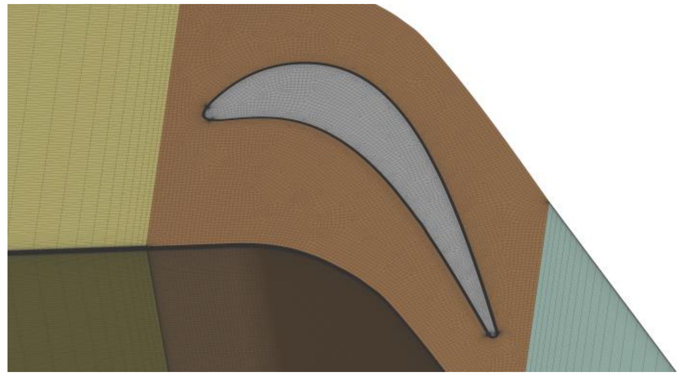

Fig. 3: Multi blocked grid generated using Multizone.

The CFD analysis was conducted using commercial code ANSYS CFX. As soon as the grid generated, the mesh file was transferred to CFX-Pre for modelling and CFX Solver for the simulation. Mass flow inlet and static pressure outlet boundary conditions have been imposed. At inlet turbulence intensity and length scale were defined as 0.5% and 0.123 m respectively. For thermal boundary conditions inlet and wall temperature are introduced as 50°C and 25°C. 3-D RANS equations for incompressible flow were solved using finite volume discretization with the assumption of steady state flow.

Due to being highly turbulent flow, a two equation model was used in the calculations. Shear Stress Transport (SST) turbulence model was performed. SST turbulence model is a combination standard (k-ε) and (k-ω) to overcome the shortcomings of each model by a blending function depending on the distance away from the wall [18]. SST turbulence model requires a condition, $y^+ < 2$ (in some resources 1), that must be satisfied for numerical calculations. In this study, y^+ has been kept at desired level around 1.

In this study, cavity squealer and suction side squealer have been investigated numerically for a tight clearance.

RESULTS AND DISCUSSION

This section gives a detailed information about aerodynamic performance and the heat transfer to the blade tip surface for both cavity and suction side squealer. To make a better understanding for flow structure in tip gap, numerical results for flat tip are also be included.

Aerodynamic Investigation

Total pressure loss is one of the most significant tool to predict the performance of the blade and clarify the loss mechanisms. Total pressure loss computations will be given in terms of ΔC_{P0}, defined as total pressure loss coefficients which denotes total pressure difference at two different sections. ΔC_{P0} is calculated with reference to the exit plane located 0.05 axial chord downstream of the trailing edge and inlet of the computational domain. Mass flow average approach was performed to calculate aerodynamic loss.

Total pressure contour at the exit plane is plotted in Fig.4 non-dimensionally. Total pressure distribution reveals that there are slight differences between the flat tip and squealer tip designs. The tip leakage vortex in the case of cavity squealer (SqBASE) has weakened with respect to the FLAT and SS-SqBASE cases. Also, a distinct change in passage vortex has been observed. As seen in Fig. 4, the passage vortex becomes smaller compared to the flat case for both cavity and partial squealer tip designs.

A loss coefficient has been defined in order to compare the aerodynamic performances of the cases. Total pressure loss coefficient is calculated as the difference of total pressure between the inlet and exit plane of the cascade located at at 0.05 C_x distance downstream of the trailing edge.

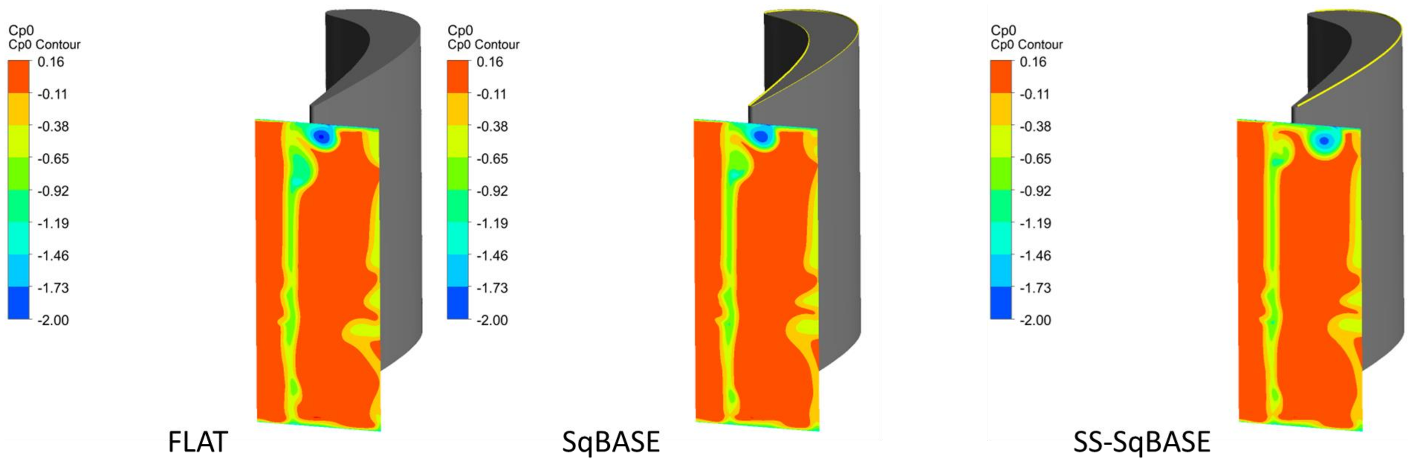

Fig. 4: Total pressure coefficient at exit plane.

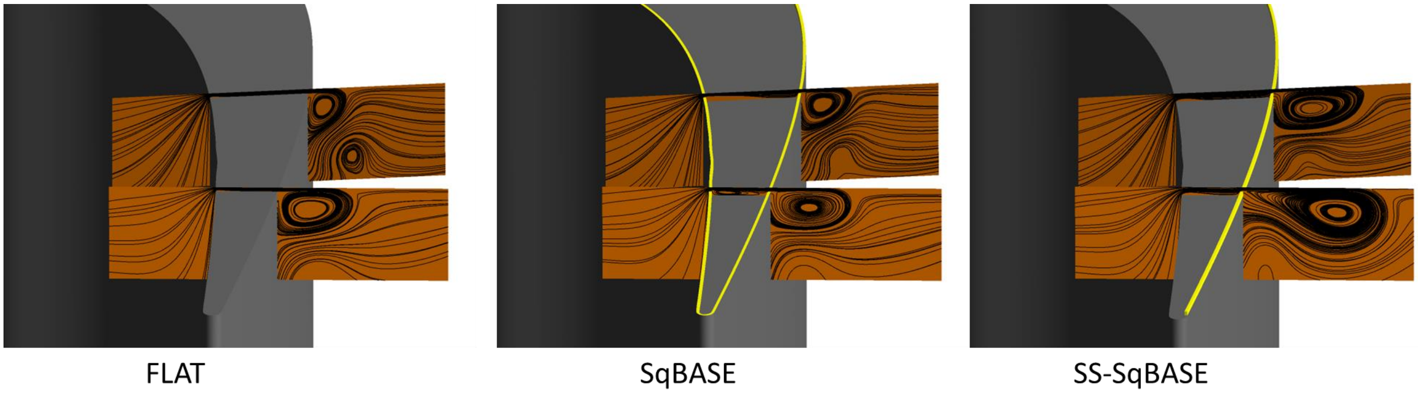

Fig. 5: Flow visualization on axially located planes.

Total pressure loss coefficient is defined

$$\Delta C_{p0} = C_{p0,inlet} - C_{p0,outlet} \quad \textbf{(1)}$$

where C_{p0} is total pressure coefficient. Table 2 provides further detail to compare the aerodynamic performances of the tip designs. Both squealer tip configurations provides a slight improvement with respect to the flat case. However, it is hardly to distinguish the aerodynamic performances of the SqBASE and SS-SqBASE. Suction side squealer provided a decrease in the core of the tip leakage vortex similar to Wei et al. [12]. However, the tip leakage vortex occupies a larger region compared to the SqBASE case.

Table 2 Aerodynamic loss

	Aerodynamic Loss	Change [%]
Flat	0.130	-
SqBASE	0.126	3.28
SS-SqBASE	0.127	2.09

Flow visualization using streamlines can be functional to clarify the flow structure in tip gap. Two planes have been located in streamwise direction at x/Ca=0.59 and x/Ca=0.77 to be perpendicular to the camber line. Flow passes over pressure side in the tip gap results in a recirculatory region. Due to entrance effect of pressure side flow separates over the pressure side and reattaches towards the camber line. Squealer tip geometries block the flow passes over the blade tip. Briefly, squealer treats as sealing mechanism to the leakage flow. Fig. 5 indicates that a wider circulation zone formation for squealer tip. Fig. 5 reveals that passage vortex weakens considerably. It was observed that occupied region by the tip vortex increased considerably for the suction side squealer. However, total pressure distribution at exit plane has shown a weak vortex core in comparison with cavity squealer.

One of the objectives for squealer tip geometry is to reduce leakage flow rate through the tip gap. Flow rate in tip clearance in streamwise direction is plotted in Fig. 6. Leakage flow rate tends to increase up to 90 % of the axial chord. Leakage flow distribution of the three tip configurations are similar to each other. Fig. 6 indicates that cavity squealer configuration had better performance in reducing the flow rate among all designs. Around the trailing edge flow rate for the flat tip corresponds to the highest flow rate whereas from the leading edge to the 65 % of the axial chord, higher flow rate was calculated for the partial squealer on the suction side.

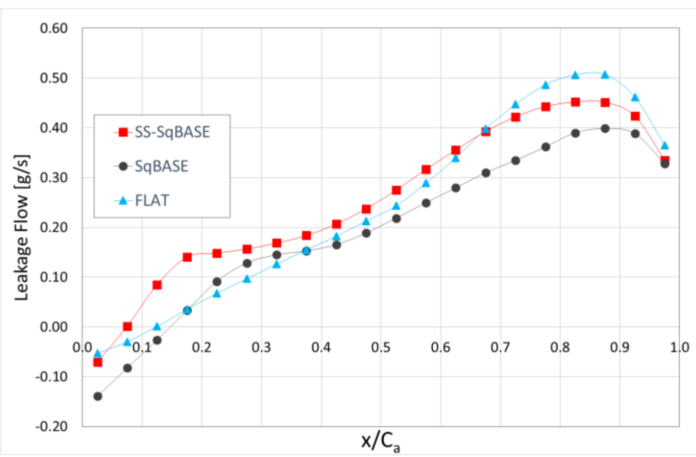

Fig. 6: Leakage flow rate through the tip gap.

Sq-BASE case provides a considerable reduction in leakage flow rate. However, SS-SqBASE results in an increase in the leakage flow rate as seen from Table 3.

Tip clearance in present study corresponds to a tight clearance. Previous experimental and numerical studies show that improvement in aerodynamic performance of squealer tip designs increases at higher tip gaps [10, 16]. The numerical results agrees with the observation of in the literature such as Lee & Choi and Schabowski & Hodson.

Table 3 Change in leakage flow rate

	Leakage Flow Rate [g/s]	Change [%]
Flat	4.835	–
SqBASE	3.915	-19.0
SS-SqBASE	5.122	+5.9

Thermal Investigation

Heat transfer coefficient on blade tip and squealer upper side has been calculated for thermal investigation. Heat transfer coefficient is calculated from equation given below:

$$h = q_w / (T_w - T_{0,in}) \quad \textbf{(2)}$$

where $T_{0,in}$ is the inlet total temperature. Ameri and Bunker [19], and Krishnababu et al [3] used inlet total temperature as reference temperature. Heat transfer coefficient for flat tip is calculated 367.8 W/m^{2}K. Performing different squealer tip configurations has reduced heat transfer coefficient remarkably. Different from aerodynamic perspective, it was concluded that SS-SqBASE had reduced thermal load more than the SqBASE. Heat transfer coefficient at blade tip has been calculated 279.9 and 241.6 W/m^{2}K respectively for cavity squealer and suction side squealer.

Table 4 Heat transfer coefficients

	Heat Transfer Coeff. [W/m^{2}K]	Change [%]
Flat	367.8	–
SqBASE	277.9	-24.4
SS-SqBASE	241.6	-34.3

Heat transfer coefficient distribution at blade tip (Fig.7) reveals that SS-SqBASE performs better than SqBASE similar to Azad et al [4]. Suction side squealer provides a better cooling at blade tip surface. Locally high heat transfer regions are observed downstream of the pressure side for FLAT. This is due to vertical flow structures form passing over the pressure side. Because of the entrance effect of pressure side, a recirculatory region forms downstream. Flow separated on the pressure side reattaches on the bottom of the cavity. Leakage flow may have an impingement effect at this region. Therefore, locally high heat transfer regions have been observed towards camber line of the blade. High heat transfer regions downstream of the leading edge for cavity squealer is due to formation two different vortex. Flow passes over the leading edge impinges on the blade tip surface in the vicinity of the leading edge and separates into two flow paths. Because of the impingement of the hot fluid flow, locally high heat transfer regions are observed. Similar flow structures have been determined both numerically and experimentally in the literature.

SUMMARY AND CONCLUSION

A numerical study on aerodynamic loss and heat transfer for different tip squealer geometries has been presented. CFD results indicate that squealer tip designs are effective to reduce aerodynamic loss and heat transfer to the blade tip. Total pressure loss coefficient and heat transfer coefficient have been considered to interpret the numerical results. SqBASE had better aerodynamic performance compared to SS-SqBASE. Both squealer designs have reduced the total pressure loss with respect to the flat tip geometry. However, the effects of squealer designs on aerodynamic performance are not distinct enough because of the tight tip clearance. Leakage flow rate has been reduced by cavity squealer tip whereas an increase has been calculated for the suction side squealer. There has not been a notable improvement in aerodynamic performance for suction side squealer. However a significant reduction has been achieved in heat transfer coefficients. SS-SqBASE has provided a better thermal performance compared to the SqBASE. Both squealer designs provided a remarkable reduction in heat transfer whereas suction side squealer had the best performance.

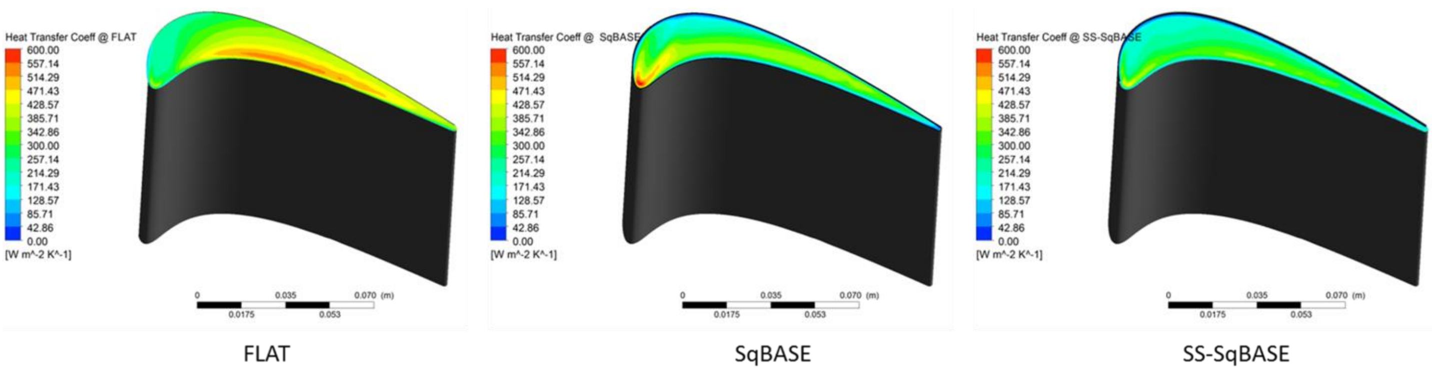

Fig. 7: Heat transfer coefficient distribution at blade tip

NOMENCLATURE

AFTRF	=	Axial Flow Turbine Research Facility in Turbomachinery Heat Transfer Laboratory of The Pennsylvania State University
C	=	blade chord
C_x	=	blade axial chord
C_{p0}	=	total pressure coefficient, $(P_0 - P_{0,ref})/(1/2\rho U_m^2)$
ΔC_{p0}	=	total pressure loss coefficient, $C_{p0,inlet} - C_{p0,outlet}$
h	=	local heat transfer coefficient, $q_w/(T_w-T_{0,in})$
t/h	=	tip clearance
$T_{0,in}$	=	inlet mass flow averaged total temperature
T_w	=	wall temperature
Inlet Plane	=	located at inlet section of computational domain
Exit Plane	=	plane at 0.05Cx downstream of the trailing edge

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