International Journal of Heat and Mass Transfer 115 (2017) 955–978

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

# Investigations into heat transfer and film cooling effect on a squealer-winglet blade tip

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ARTICLE INFO

*Article history:*
Received 2 April 2017
Received in revised form 28 July 2017
Accepted 26 August 2017
Available online 4 September 2017

*Keywords:*
Squealer tip
Winglet
Heat transfer
Film cooling

ABSTRACT

Numerical investigations of heat transfer and film cooling effect on the conventional squealer tip, no P.S. rim squealer tip and P.S. winglet squealer tip have been performed at three different cooling-hole arrangements (i.e. no film cooling, only tip holes, and both tip and pressure side holes) and two tip clearances. The flow structures, as well as the total pressure loss, in the cascades with three tip configurations (i.e. conventional squealer tip, no P.S. rim tip and P.S. winglet tip) were obtained and compared to analyze the effect of tip pressure-side geometries on the aerodynamic performance near the tip gap. With the existed experimental data for the conventional squealer tip, the numerical methods were carefully validated with respect to the turbulence model and mesh independency. The results indicate that the total pressure loss in the cascade with P.S. winglet tip is lower than that with conventional squealer tip by 5.0–6.7%, and the no P.S. rim tip shows a very close aerodynamic performance with the P.S. winglet tip configuration. In no film cooling case, the area-averaged heat transfer coefficient on the P.S. winglet tip surface is lower than that on the conventional squealer tip by 14.1–15.6%. In the tip holes only case, the area-averaged heat transfer coefficient on the P.S. winglet tip can be reduced by about 10% compared with the conventional squealer tip. As the tip clearance increases, the area-averaged heat transfer coefficient on no P.S. rim tip is getting lower than that on the P.S. winglet tip. With both tip and pressure side holes, the no P.S. rim and P.S. winglet tips still exhibit better film coolant coverage on the cavity floor than on conventional squealer tip, especially near the cavity pressure side. As the clearance gap increases, the film cooling effects on no P.S. rim and P.S. winglet tips become even better than that on the conventional squealer tip. As the clearance gap increases from 1% to 2.5% of blade span, the area-averaged film cooling effectiveness on the P.S. winglet and no P.S. rim tips are higher than the conventional squealer tip by 7.1–57.8%.

## 1. Introduction

In gas turbine engines, the first stage blades are exposed to severe thermal load due to the oncoming combustion gas, for which the temperature is far higher than the material melting point [1]. In high speed rotor blades, the combined mechanical and thermal constraints have driven many manufactures to adopt unshrouded blades instead of shrouded configurations [1–3]. In the unshrouded blade, the over-tip leakage flow has a high velocity and temperature, which makes the tip expose to hot gas on all sides, leading to high heat transfer and complex flow structures in the clearance gap [4]. In order to prevent rubbing between the rotating tip and stationary casing, enough tip clearance has to be guaranteed to accommodate the thermal and rotating expansions of the rotor blade [1–4]. However, due to a large pressure difference between the pressure side and suction side, the inevitable leakage flow across the tip gap will cause a large amount of aerodynamic loss in the turbine stage (account for 1/3 of the turbine stage loss [5,6]). Therefore, to meet the requirements of heat transfer and aerodynamic performance of the rotor blade, many attempts have been made to improve the aerothermal characteristic in the tip gap with proper tip designs [1–4]. One tip design in current use consists of a recessed tip which is known as squealer tip [1]. Other blade tip designs make use of winglet, which is usually extended from the side (pressure side or suction side or both sides) of the tip and perpendicular to the blade surface [4]. Evidences have shown that using a squealer or winglet or a combination of the two generally improves the aerodynamic performance of the blade compared to the flat tip [1,7]. Further studies about the heat transfer and film cooling effect on these two types of tip are also under active research in the published literature, aiming at improving the

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.08.090
0017-9310/

## Nomenclature

| | |
|---|---|
| Arc | distance from the leading edge along blade profile [m] |
| $C$ | blade axial chord length [m] |
| $C_r$ | clearance [m] |
| $h$ | local heat transfer coefficient [W/m$^2$ K] |
| $\dot{m}$ | mass flow rate [kg/s] |
| $M$ | blowing ratio [–] |
| $P$ | pressure [Pa] |
| $q$ | local heat flux [W/m$^2$] |
| $S$ | area [m$^2$] |
| $T$ | temperature [K] |
| $V$ | velocity [m/s] |
| $x$ | axial direction |
| $y$ | pitch direction |
| y+ | dimensionless distance from the wall [–] |

*Greek symbols*

| | |
|---|---|
| $\eta$ | adiabatic film cooling effectiveness [–] |
| $\xi$ | total pressure loss coefficient [–] |
| ρ | density [kg/m$^3$] |

*Superscripts*

| | |
|---|---|
| $\bar{\ }$ | area-averaged value |

*Subscripts*

| | |
|---|---|
| *aw* | adiabatic wall condition |
| *c* | coolant |
| *in* | inlet condition |
| *local* | local value |
| *m* | main flow |
| *s* | static value |
| *t* | total value |
| *w* | wall |
| $\infty$ | inflow condition |

*Abbreviations*

| | |
|---|---|
| M | million |
| P.S. | pressure side |
| RSM | Reynolds Stress Model |
| S.S. | suction side |

aerodynamic efficiency while enhancing the heat transfer performance in the tip region [4,8–24,32–41].

The rims in the conventional squealer tip are believed to act as two labyrinth fins in the gap [4,8]. With this configuration, the leakage rate can be significantly reduced and also the rub in the tip can be mitigated in contrast to the flat tip. Therefore, in published literature, heat transfer and film cooling effect on the conventional squealer tip have been extensively studied on linear cascades and rotating test rigs. On a stationary cascade, Bunker et al. [8] measured the heat transfer coefficient distributions on the conventional squealer tip with a hue detection based liquid crystal method. Then, Kwak and Han [9,10] experimentally explored the heat transfer and film cooling effect on the squealer tip at various clearances, turbulence intensities and blowing ratios. The results showed that the leakage flow in tip gap and heat transfer coefficients on tip surface were significantly reduced by using the squealer geometry in contrast to the flat tip configuration. To investigate the film cooling and heat transfer characteristics on the squealer tip at high blowing ratio conditions, Narzary et al. [11] measured the adiabatic film cooling effectiveness and heat transfer coefficient distributions on the squealer tip with various suction side rails, four blowing ratios and three gap sizes. They found that the ratio of heat transfer coefficient with film cooling to that without film cooling is in the range of 0.9–0.95 depending on tip geometry, gap size and blowing ratio. On a rotating test rig, Rezasoltani et al. [12] presented the measured film cooling effectiveness on the (rotating) rotor blade tip in a three-stage research turbine. It showed that the film cooling ejections on both flat tip and squealer tip dramatically affect the flow behaviors in the tip gap, and strong interactions between the cooling jets and the leakage flow were observed in the near tip region. Besides the experimental research, the numerical methods were also adopted by many researchers to predict the flow structures, heat transfer and film cooling performance in the squealer tip gap, e.g. Acharya et al. [13], Mumic et al. [14], Ghandour et al. [15], Wang et al. [16] and He [17]. Their numerical results revealed that the flow and heat transfer performance are greatly affected by the squealer geometries and operation conditions (i.e. blowing ratio, pressure ratios, etc.). Apart from these, a few studies were concentrating on investigating the effect of cooling hole-array arrangement on heat transfer and film cooling effect on the squealer tip, e.g. Kim et al. [18] and Yang et al. [19]. While some other researchers mainly focused on the leakage performance in squealer tip gap at choked condition, e.g. Li et al. [20]. To better understand the unsteady interactions between the coolant and leakage flow, Mischo et al. [21,22] carried out numerical simulations to predict the aerodynamic and heat transfer performance in the turbine stage. Their results indicated that the time-averaged Nusselt number on the squealer tip in unsteady prediction is about 6% lower than that in steady case. To further improve the aerodynamic performance as well as to reduce heat transfer on the traditional squealer tip, some researchers tried to modify/optimize the squealer geometries to control leakage flow in the tip gap. For instance, Nho et al. [23] and Maesschalck et al. [24]'s work indicated that the aerodynamic loss and heat transfer on the tip can be reduced simultaneously through squealer tip geometry optimizations.

Although the squealer tip has a superior performance in leakage control and heat transfer performance compared with the flat tip, it still has some disadvantages, for example, high heat transfer near the tip leading edge [8–10], non-uniform heat transfer coefficient distributions on tip surface [9,10], over-tip-leakage loss is not effectively reduced in the tip region in some cases [20], etc. To overcome these shortcomings, the squealer-winglet tip has generated a lot of interests in the last decade. Researchers found that proper winglet tip design would reduce the driving pressure difference between the tip pressure side and suction side, thus effectively control the leakage rate through the tip gap [4,7,25]. Early research about the winglet tip started with the aerodynamic consideration by using this design. For example, Yaras and Sjolander [26] and Liu et al. [27]'s experimental work showed that the leakage loss could be reduced by 10% [26] and the stage efficiency can be reduced by 0.6% [27] by using the winglet tip design. While Dey and Camci [28]'s measurements showed that the turbine stage efficiency is slightly reduced by adopting the suction side winglet in contrast to the flat tip. Coull et al. [29]'s numerical results revealed that the winglet-squealer tip reduces the leakage loss by 45% in contrast to the plain-tip configuration. Cheon and Lee [30]'s measurements indicated that, compared with the conventional squealer tip, the maximum reduction of total pressure loss in the cascade reaches up to 5.8% by using winglet configuration with a certain