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Numerical investigations into the effect of squealer–winglet blade tip modifications on aerodynamic and heat transfer performance

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Numerical investigations have been performed to investigate the heat transfer characteristic on the squealer–winglet tip, which is also compared with the conventional squealer tip and squealer tip without pressure-side rim. The validations and verifications of the numerical methods are carried out based on the existing experimental data. At a range of winglet leading edge angles and winglet coverage percentages, the total pressure losses in the cascade, as well as the flow structures in the tip gap, are analyzed in detail. The numerical results show that, by removing the pressure side rim from the conventional squealer tip, the high heat transfer area on the tip cavity floor near leading edge has disappeared, and the total pressure loss in the cascade has been reduced. If the conventional squealer tip is modified into a full-coverage of pressure side winglet configuration, the area-averaged total pressure loss in the cascade can be reduced by 12.2%, and the area-averaged heat transfer coefficient on the tip can be reduced by about 10% ($PR = 1.236$). For the squealer tip configured with pressure-side winglet, the heat transfer distributions as well as the total pressure loss in the blade are not sensitive to the winglet leading edge angle. By choosing proper winglet leading edge angle and winglet coverage percentage, the area-averaged heat transfer coefficient on the tip can be reduced by 15.8%, and the area-averaged total pressure loss in the blade can be reduced by 13.8%, in contrast to the conventional squealer tip.

1. Introduction

In modern gas turbine engines, the combustor outlet temperatures are far beyond the allowable temperature of the blade materials. Therefore, turbine blades working in the high temperature gas undergo severe thermal stress and fatigue, especially for the rotor working in the first stage. In the rotor blade, tip is exposed to the hot gas on all sides, which results in high heat load and non-uniform heat transfer in the nearby region. Due to these reasons, in the gas turbine engine, the blade tip has become one of the most frequent inspected and repaired regions and is critical for the blade design [1]. Moreover, due to the inevitable clearance between the blade tip and stationary casing, the hot leakage gas is crossing over the tip gap, resulting in aerodynamic loss in the turbine blade. Evidence has shown that the stage loss associated with the tip clearance reaches about 4% of the stage efficiency [2]. The contradiction between the economy and safety operation presents great challenge for the blade design. In order to extend the service life while improving the aerodynamic efficiency of the rotor blade, two kinds of blade tip design have been proposed in the modern gas turbine engine [4]. One blade tip design is the recessed tip, which is also called squealer tip. The rims in the squealer tip are believed to act as two labyrinth fins thus increasing the resistance to the leakage flow [4,5]. Therefore, the leakage loss and heat transfer can be effectively reduced [3], and most importantly, the tip cap can be designed much smaller thus reduces the risk of contacting onto the casing [4]. Apart from the squealer tip, the winglet tip is also under active research and has received the researchers' attention. The winglet geometry is usually extended from the side (pressure side or suction side or both sides) of the tip and perpendicular to the blade surface [4]. It is believed to reduce the driving pressure between the pressure side and suction side thus effectively controls the leakage rate through the tip gap [6].

Over the past several decades, many attempts have been made to understand the flow, heat transfer and film cooling effect in the blade with squealer tip. The representative experimental work carried out by Bunker et al. [7] revealed that a high heat transfer region is located near the suction side of the squealer tip, and the inlet turbulence intensity has a significant effect on the heat transfer performance of the squealer tip. Later, Kwak and Han [8,9] utilized a transient crystal technique to measure the heat

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Nomenclature

C	axial chord length of the blade [m]
C_r	clearance [m]
$h = \frac{q}{T_w - T_\infty}$	local heat transfer coefficient [W/m^2 K]
P	pressure [Pa]
$PR = \frac{P_{t,in}}{P_{static,out}}$	pressure ratio [–]
q	local heat flux [W/m^2]
T	Temperature [K]
V	velocity [m/s]
w	percentage of winglet coverage [%]
x	axial direction
y+	dimensionless distance from the wall [-]

Greek symbols

α	winglet leading edge angle [°]
$\xi = \frac{P_{t,in} - P_{t,local}}{P_{t,in}}$	total pressure loss [–]
ρ	density [kg/m^3]

Superscripts

-	area-averaged value

Subscripts

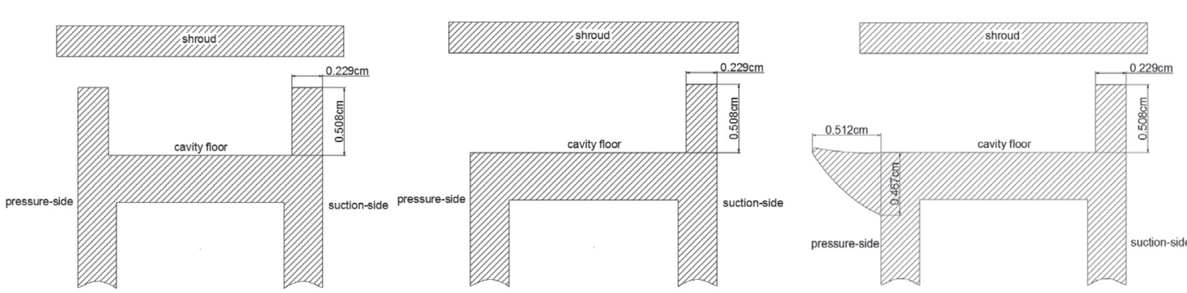
in	inlet condition
local	local value
out	outlet condition
static	static value
t	total value
w	wall surface
∞	inflow condition

Abbreviations

P.S.	pressure side
S.S.	suction side

transfer [8,9] and film cooling effect [9] on the squealer tip configured with film cooling holes. Then, Acharya et al. [10], Mumic et al. [11], Ghandour et al. [12], and Wang et al. [13] did a lot of numerical work which gave a deep insight into the flow structures, heat transfer and film cooling performance in the subsonic squealer tip gap. Their research revealed that the flow and heat transfer performance are greatly affected by the squealer geometry and blowing ratio. Beside these, a few researchers concentrated on investigating how the cooling hole-array affects the heat transfer and cooling effect on the squealer tip [14,15]. The representative numerical work carried out by Yang et al. [15] showed that a lower heat transfer coefficient region is occurred downstream the discrete holes, and the hole-arrangement has a pronounced effect on the blade tip cooling especially at the high blowing ratio conditions. While some other researchers mainly focused on the squealer tip leakage in the choked condition. For example, Li et al. [16] investigated the leakage flow characteristic in a transonic squealer tip gap (without cooling holes) and found that the squealer tip has a pronounced effect on the leakage flow even at choked conditions. Regarding the unsteady interactions between the coolant and leakage flow, Mischo et al. [17,18] found that the time-averaged Nusselt number on the tip in unsteady prediction is about 6% lower than that of steady case. In order to further improve the aerodynamic performance of the cascade as well as reduce heat transfer on the traditional squealer tip, some researchers tried to modify the squealer geometries to control leakage flow in the tip gap. The representative experimental work carried out by Nho et al. [19] indicates that the blade tip shape has a great influence on the secondary flow and total pressure loss in the cascade. Among the 11 tested tip shapes, the double squealer tip and the grooved along pressure side tip have the smallest total pressure loss coefficients.

For the studies of winglet tip, the represent experimental work carried out by Yaras and Sjolander [20] and Liu et al. [21] showed that the leakage loss could be reduced by 10% [20] and the stage efficiency can be reduced by 0.6% [21] by using the winglet tip design. Then, Papa et al. [4] carried out the experimental investigations on mass/heat transfer performance in the squealer–winglet tip gap of a gas turbine blade. The measurements showed that the traditional squealer tip has a higher averaged heat/mass transfer than the squealer–winglet tip. Coull et al. [22] investigated the aerodynamic performance of an un-cooled HP rotor blade with squealer–winglet tip. Their numerical results revealed that the combined winglet and squealer on the tip reduces the sensitivity of aerodynamic efficiency to the gap size by about 46% in contrast to the plain-tip configuration. In their study, they concluded that the squealer–winglet tip may bring a potential reduction of coolant flow and thermal stress in the tip region. Cheon and Lee [23] experimentally investigated the aerodynamic performance of the un-cooled turbine cascade squealer tip with a full coverage winglet. Their results indicated that, compared with the squealer tip without winglet, the maximum reduction of total pressure loss reaches



(a) conventional squealer tip (b) no P.S. rim (c) P.S. winglet

Fig. 1. Schematics of three tip configurations.