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Effect of ejection angle and blowing ratio on heat transfer and film cooling effect on a winglet tip

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ABSTRACT

Effects of ejection angle and blowing ratio on heat transfer and film cooling effect on a winglet tip were numerically investigated with the RANS (Reynolds Averaged Navier-Stokes) equations solutions. The total pressure loss in cascade, and heat transfer coefficient and film cooling effectiveness on the winglet tip with both tip and pressure side holes were computed at a range of pitchwise ejection angles and streamwise ejection angles. At three blowing ratios ($M = 0.5$, 1.0, 2.0), the sensitivity of heat transfer coefficient and film cooling effectiveness distributions on winglet tip to the variation of blowing ratio was also investigated. The results indicate that the heat transfer coefficient and film cooling effectiveness on the winglet tip are much sensitive to the pitchwise and streamwise ejection angles and blowing ratio. A better heat transfer and film cooling effect on the winglet tip can be achieved as the pitchwise ejection angle is less than 30° and streamwise ejection angle is around 120°. The heat transfer and film cooling effect on winglet tip is not sensitive to the pitchwise ejection angle if it is larger than 45°. If vertical ejection direction is chosen for the cooling flow, a small blowing ratio ($M = 0.5$ in this study) is beneficial for the reduction of disturbance to pass-over leakage. However, in the case of a small pitchwise ejection angle, a medium blowing ratio ($M = 1.0$ in this study) is profitable to gain a wider coolant coverage on the cavity floor in pitchwise direction.

1. Introduction

In gas turbine engines, clearance between blade tip and casing is required to allow inevitable thermal and rotating expansions of rotor blade [1–4]. However, due to the pressure gradient between tip pressure side and suction side, leakage flow is driven across the tip gap and then interacted with the mainstream, causing pronounced aerodynamic loss [5,6]. Moreover, the over-tip leakage flow makes the rotor tip expose to hot gas on all sides, causing notable thermal load on blade tip. In order to reduce the heat load in tip gap, two main strategies have been developed in the modern gas turbine engines. One such strategy would utilize efficient tip geometry to improve heat transfer characteristic near tip gap, for example, squealer tip, winglet tip, etc. The other strategy is to adopt a proper film cooling arrangement to reduce heat load on the tip. Evidences have shown that the effective film cooling arrangement is critical to protect tip region in high temperature environment [1].

For the winglet tip, it is believed that it has an effect of reducing leakage flow in tip gap if it is properly designed [7,8]. Up to present, many types of winglet tip have been developed to improve the aerodynamic performance of turbine blade, for example, the pressure side winglet [9], suction side winglet [10], full coverage of winglet [11–13], partial winglet [14], and even the winglet shroud tip [15], etc. The research issues for winglet tip cover the aerodynamic performance [7–19], heat transfer [20–25] and film cooling effect [26,27] in tip region. Beside these, the designs and optimizations of the winglet tip are also under active research in the opening publications [14,15,28,29].

To account for the improvement of winglet tip on aerodynamic performance in turbine blade, Yaras and Sjolander [8] measured the leakage loss in winglet tip. They found that the total pressure loss in cascade with winglet tip could be reduced by 10% compared with the flat tip. However, the experimental and numerical work carried out by Schabowski and Hodson [19] showed that the aerodynamic loss slope of a winglet-squealer tip configuration can be reduced by 22% in contrast to the flat tip. In the rotating test rig, Dey and Camci [16] measured the total pressure loss in a turbine stage with different winglet configurations. Their experiments indicated that, in contrast to the flat tip, the use of pressure-side

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Nomenclature

C	blade axial chord length [m]
C_r	clearance [m]
h	local heat transfer coefficient [W/m^2 K]
M	blowing ratio [–]
P	pressure [Pa]
q	local heat flux [W/m^2]
T	temperature [K]
V	velocity [m/s]
x	axial direction
y+	dimensionless distance from the wall [–]

Greek symbols

α	streamwise ejection angle [°]
β	pitchwise ejection angle [°]
η	adiabatic film cooling effectiveness [–]
ξ	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
t	total value
w	wall
∞	inflow condition

Abbreviations

M	million
P.S.	pressure side
S.S.	suction side

winglet significantly affects the flow field in tip gap by weakening the leakage vortex. For the cascade with full coverage of winglet tip, Coull et al. [17,21] found that the rotor efficiency could be improved by 0.6% by varying the thickness of winglet compared with the flat tip. By adding a cavity on the winglet tip, the leakage loss can be reduced by about 45%. Cheon and Lee [11] carried out the experiments for a cascade configured with a full coverage of winglet. Their work showed that, if the winglet is designed with a proper value of width-to-pitch ratio, the total pressure loss in the cascade can be reduced by 5.8% compared with the conventional squealer tip. Ledezma et al. [7] compared the aerodynamic performance between the conventional squealer tip, squealer tip without pressure side rim, and squealer tip with pressure-side winglet. They found that the cascade with pressure-side winglet has a close aerodynamic performance with the conventional squealer tip. Zhang et al. [15] performed the aerodynamic optimizations of a cascade with partial winglet shroud tip. Their numerical results revealed that the mass-averaged total pressure loss in the cascade with optimized winglet tip can be reduced by 2.61% compared to the plain tip. Zhong and Zhou [18] carried out the experiments and CFD predictions to investigate the aerodynamic performance of a high-pressure turbine cascade with cavity-winglet tip. Their work indicated that the tip leakage loss in cavity-winglet tip can be reduced by 16.7%, 16.1% and 12.0% compared with the conventional squealer tip at three different gap sizes, respectively.

However, the design of winglet tip does not only rely on aerodynamic considerations, heat transfer and film cooling on blade tip are also crucial to the designer. The representative experimental work carried out by Papa et al. [4] indicated that the pressure side winglet has an effect of reducing heat and mass transfer on tip cavity floor. Silva and Tomita [20] numerically investigated the aerodynamic and heat transfer performance in a turbine stage with flat, squealer and winglet tips. It showed that the efficiency of turbine stage with winglet tip can be improved by 0.3% compared to squealer tip. The tip geometry has a pronounced effect on the tip heat transfer coefficient distributions. Zhou et al. [10,18,22,23,26] carried out a series of numerical simulations to investigate the aero-thermal performance in a HP turbine winglet tip. The effects of endwall motion [22], cooling condition [26] and winglet geometries [10,18,23] on the aerodynamic performance and heat transfer in the tip gap were investigated in detail. O'Dowd et al. [24] experimentally and numerically investigated the aero-thermal performance in a transonic blade winglet tip. They found that the aerodynamic loss of the cooled winglet tip is lower than that in un-cooled configuration, and low film cooling effectiveness is occurred at the tip crown and pressure side trailing edge. Joo and Lee's [12,13] experiments indicated that the discrepancy of heat/-mass transfer rate between the cavity floor and winglet top surface decreases rapidly as the gap-to-span ratio increases for the full coverage winglet tip. Yan et al.'s [25,27] numerical studies show that the averaged heat transfer coefficient on the winglet tip without film cooling can be reduced by 15.8% and the total pressure loss in cascade can be reduced by 13.8% compared to the conventional squealer tip. For the cooled winglet tip, the averaged heat transfer coefficient on the winglet tip can be reduced by about 10% compared with the conventional squealer tip.

This paper is an extension of the authors' previous study [25,27], in which the authors have pointed out the heat transfer and film cooling effect on winglet tip are much sensitive to the blowing ratio and ejection angle compared with the conventional squealer tip. Therefore, the overall performance (aerodynamic, heat transfer and film cooling) in the winglet tip gap at a range of ejection angles and blowing ratios are investigated in this study. At first, the numerical methods, which are based on the previous studies [25,27], are described. Then, the effect of ejection angles (pitchwise ejection angle and streamwise ejection angle) variations on the heat transfer and film cooling effectiveness on winglet tip with two hole-arrays is discussed. Finally, by adopting three blowing ratios (low blowing ratio, medium blowing ratio and high blowing ratio), the flow patterns in the tip gap and heat transfer and film cooling effectiveness on the winglet tip with different ejection configurations are investigated.

2. Numerical methods

In this paper, the squealer tip with pressure side winglet (P.S. winglet) is selected as the research objective. The geometrical model is the same with the authors' previous studies [25,27]. The blade profile is taken from the GE-E^3 rotor blade (first stage) tip section [30]. The geometrical dimensions of the blade are listed in Table 1. The geometrical dimensions of the winglet tip are shown in Fig. 1.

The multi-block structured grids are generated with ANSYS ICEMCFD 11.0 (see Fig. 2). In the computational cases with pitchwise ejection angle $\beta = 15°$, the minimum orthogonalities of the