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Research Paper

Numerical study of the effect of the cavity depth on the leakage control in a cooled honeycomb-tip turbine cascade

Yabo Wang, Yanping Song, Jianyang Yu*, Fu Chen

Institute of Propulsion Theory and Technology, Harbin Institute of Technology, Harbin 150001, China

HIGHLIGHTS

- The effect of the cavity depth is studied in a honeycomb-tip turbine cascade.
- The honeycomb tip is cooled by the injection from the bottom center.
- The cavity depth affects the leakage flow and the total pressure loss.
- The internal flow in the gap and cavities varies with increasing the depth.
- The heat transfer condition is better improved in relatively deep cavities.

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ABSTRACT

The effect of the cavity depth on the leakage flow and tip cooling has been numerically investigated in a honeycomb-tip turbine cascade with cooling injection. Coolant is ejected through the center holes on the honeycomb cavity bottoms. Three dimensional flow fields were simulated using the Reynolds-averaged Navier-Stokes (RANS) method and the k-ω turbulence model. Then the tip configurations are evaluated according to several performance parameters, such as leakage mass flow rate, total pressure loss and film cooling effectiveness, in the upper passage, the gap and the honeycomb cavities. Furthermore, the secondary velocity streamlines are plotted at the cascade exit to characterize the upper passage vortices. The isothermal surface and contours of dimensional temperature are presented to explore the mixing between the coolant and the cavity vortices. The numerical results show that the aerodynamic and thermodynamic performance differs significantly with the cavity depth.

1. Introduction

The increasing inlet temperature has been unaffordable to the materials for the modern gas turbine, especially on the tip [1] and the endwall [2]. For unshrouded turbine blades, tip design is a most important method to control the tip leakage flow (TLF) and improve the heat transfer condition of the turbine rotor blades. These designs mainly include squealer tip, tip winglet [3], combined squealer-winglet [4] and so on.

The wide studies on the squealer tip are referential to the other similar tip design methods. Among them, geometric parameters of the squealer tip itself, such as the cavity depth, width and location, have drawn great attention from the beginning. Especially, the cavity depth has a significant effect in controlling the TLF [5] and improving the heat transfer performance. Ameri et al. [6] numerically compared the effect of the squealer tip of two cavity depths and found that the reduction of the tip leakage mass flow rate (TLMFR) was slightly higher with a deeper cavity. Yang et al. [7] found that no further reduction of the TLMFR occurred when the cavity depth reached 3% of the blade span. Lee et al. [8] measured the total pressure loss downstream the turbine cascade and summarized that the loss decreased with increasing the rim height until the rim height reached about 3.75% of the blade span. Another numerical research by El-Ghandour et al. [9] on the internal vortex and the tip leakage vortex (TLV) showed that the cavity vortex was strengthened with deepening the suction-side cavity and more leakage fluid above the cavity was entrained towards the bottom. Silva de al [10] discussed the effect of the cavity depth on the tip heat transfer in an axial turbine stage equipped with squealer tip and pointed out that local heat transfer was better in a specific cavity depth. In the recent study by Zou et al. [11], it was presented that the squealer tip affected the TLF through the scraping vortex in the cavity. Moreover, the casing movement, the near-tip load and the cavity depth all

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* Corresponding author.
E-mail address: yujianyang@hit.edu.cn (J. Yu).

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Nomenclature

C_{ax}	blade axial chord [m]
C_p	static pressure coefficient [–]
H	blade span [m]
k	turbulent kinetic energy [–]
m	mass flow rate [kg s^{-1}]
$m_{leakage}$	tip leakage mass flow rate [kg s^{-1}]
p	static pressure [Pa]
p^*	total pressure [Pa]
T	temperature [K]
t	blade pitch [m]
V	velocity [m s^{-1}]
v	fluctuation velocity [m s^{-1}]
x	span-wise direction
y	pitch-wise direction
y^+	dimensionless wall distance [–]
z	axial direction

Greek

α_c	cooling injection angle [°]
δ_{hc}	honeycomb depth [mm]
θ	non-dimensional temperature [–]
η	adiabatic film cooling effectiveness [–]
$\overline{\overline{\eta}}$	area-averaged adiabatic film cooling effectiveness [–]
τ	tip gap height [m]
$\omega_\perp$	the normal vorticity [s^{-1}]
ϖ	total pressure loss coefficient [–]
$\overline{\overline{\varpi}}$	mass flow averaged total pressure coefficient [–]

Subscripts

0	cascade inlet
1	cascade outlet
aw	adiabatic wall
c	injection inlet

had a certain impact on the strength, location and affected region of the scraping vortex.

Even though a suppressed TLF and improved heat transfer have already been provided by the above tip designs, sophisticated cooling technology is still needed to protect the tip from thermal failure due to the local severe heat transfer. In fact, the cooling injection from the tip not only can reduce the thermal load, but also has the potential to obstruct the TLF [12]. Kwak et al. [1] measured in detail the distributions of the heat transfer coefficient and film cooling effectiveness in a squealer-tip turbine cascade. Later on, He [13] conducted the numerical study on the flow field in the same cascade. Lu et al. [14] applied the cooling injection into a real turbine rotor and concluded that the coolant interacted with the TLF and induced a more uniform pressure field and larger cooled area. Furthermore, Rezasoltani et al. [15] investigated the same ejection configurations in a three-stage research turbine and found that the interaction differed with the tip design. Wang et al. [16] discussed the influence of the injection location and angle on the film cooling effectiveness in a transonic turbine and mentioned that the TLMFR was lower in cooled flat tip. Zhang et al. [17] numerically studied the film cooling in a turbine cascade with cut back squealer tip. It was noted that the cooling ability of the dust purging holes was weaker in the fore part of the cavity and increased with the cavity depth. Arisi et al. [18] carried out the study on the aerothermal characteristics of the ribbed transonic turbine blade and confirmed the blockage effect of the purge flow. Tamunobere et al. [19,20] compared the stationary and rotating cooling effects and introduced the casing injection into the tip cooling. Volino [21] performed an experiment to discuss the effect of the blowing on the total pressure loss. The blowing of about 0.4% of the main flow could provide about 20% reduction of the total pressure drop.

The honeycomb tip, presented by Fu et al. [22], had the potential to reduce both the TLMFR and the total pressure loss in a high-pressure turbine cascade. Recently, Wang et al. [23] applied cooling injection into the honeycomb tip and obtained further suppressed TLF and improved heat transfer condition. Yet the effect of the cavity depth on the cavity vortices and tip cooling still need further work to be determined. The current study aims to discuss the mixing between the cooling injection and the cavity vortices at different cavity depth. The effect on the flow field around and downstream the blade tip is also analyzed in detail.

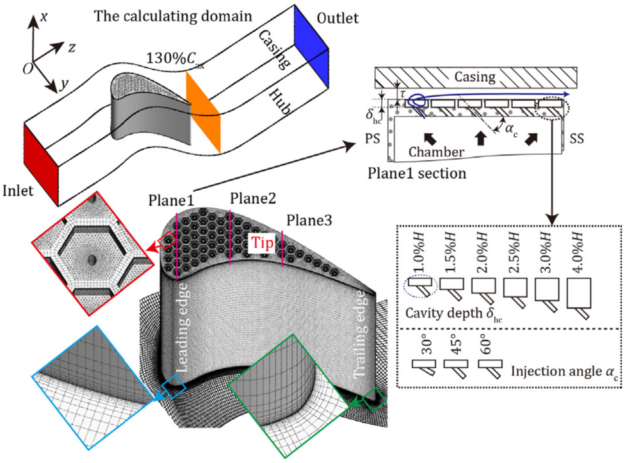

Fig. 1. Schematic diagram of the simulated domain.

Table 1
Boundary settings.

Boundary	Description	Value
Cascade inlet	Total temperature (K)	300.0
	Total pressure (Pa)	104642.7
	Turbulence intensity (%)	5.0
	Main flow rate (kg/s)	0.448
Cascade outlet	Static pressure (Pa)	101903.4
Blade surface	Adiabatic	–
Hub and casing	Adiabatic	–
Injection inlet	Total temperature (K)	330.0
	Total pressure (Pa)	103500.0
	Total MFR (g/s)	about 1.6

2. Numerical model and method

2.1. Geometry and boundary conditions

The geometric parameters of the honeycomb-tip turbine cascade in the current study have been described by Wang et al. [23] in detail. Fig. 1 shows the schematic diagram of the simulated model and the arranged cavities and cooling pipes. Totally six cavity depths (δ_{hc}) and three injection angles (α_c) are selected in the current study. The cavity depth varies from 1% to 4% of the blade span (H), while the injection angles, raising from the cavity bottom to the pipe axis, are 30°, 45° and 60°, respectively. Each pipe outlet is fixed at the bottom center of the