International Journal of Heat and Fluid Flow 50 (2014) 369–377

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

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

Tip gap flow characteristics in a turbine cascade equipped with pressure-side partial squealer rims

Sang Woo Lee *, Seong Eun Lee

Department of Mechanical Engineering, Kumoh National Institute of Technology, 61 Daehak-ro, Gumi, Gyeongbuk 730-701, Republic of Korea

ARTICLE INFO

Article history:
Received 16 January 2014
Received in revised form 21 July 2014
Accepted 22 September 2014
Available online 12 October 2014

Keywords:
Turbine blade
Pressure-side squealer tip
Squealer rim height
Tip gap flow
Aerodynamic loss

ABSTRACT

Tip gap flow characteristics and aerodynamic loss generations in a turbine cascade equipped with pressure-side partial squealer rims have been investigated with the variation of its rim height-to-span ratio (h_p/s) for a tip gap height of $h/s = 1.36\%$. The results show that the tip gap flow is characterized not only by the incoming leakage flow over the pressure-side squealer rim but also by the upstream flow intrusion behind the rim. The incoming leakage flow tends to decelerate through the divergent tip gap flow channel and can hardly reach the blade suction side upstream of the mid-chord, due to the interaction with the upstream flow intrusion as well as due to the flow deceleration. A tip gap flow model has been proposed for $h_p/s = 3.75\%$, and the effect of h_p/s on the tip surface flow is discussed in detail. With increasing h_p/s, the total-pressure loss coefficient mass-averaged all over the present measurement plane decreases steeply, has a minimum value for $h_p/s = 1.88\%$, and then increases gradually. Its maximum reduction with respect to the plane tip result is evaluated to be 11.6%, which is found not better than that in the cavity squealer tip case.

1. Introduction

Turbine rotor blades have a clearance gap between the rotating blade tip and the stationary casing wall. It is inevitable that there exists a strong tip leakage flow through the tip gap from the blade pressure side to the suction one, due to the pressure gradient between them. This leakage flow forms a tip leakage vortex near the blade suction surface as a result of the interaction with the main blade passage flow, which leads to considerable tip-leakage aerodynamic loss generation.

The tip leakage flow and/or heat transfer for plane (flat) tip gaps have been investigated by Sjolander and Amrud (1987), Bindon (1989), Yamamoto (1989), Bindon and Morphis (1992), Azad et al. (2000a), Bunker et al. (2000), Ameri and Bunker (2000), Tallman and Lakshminarayana (2001), Matsunuma (2006), and Lee et al. (2009). Recently, Lee et al. (2012) reported a schematic tip gap flow sketch for the plane tip.

A cavity squealer tip is enclosed by a full-length squealer rim and thus has a recessed cavity on the tip surface. On the other hand, partial squealer tips have a squealer rim or squealer rims of different coverage, height, and shape on the tip surface.

Tip leakage aerodynamics and/or heat transfer over the cavity squealer tip have been investigated by Ameri et al. (1998), Azad et al. (2000b), Key and Arts (2006), Mischo et al. (2008), and Lee and Chae (2008). Lee and Kim (2010) suggested a qualitative tip gap flow structure over the cavity squealer tip based on flow visualizations, and Lee and Choi (2010) concluded that the cavity squealer tip provides lower tip leakage aerodynamic loss than the plane tip regardless of tip gap height. Li et al. (2014) carried out numerical simulations on the squealer tip leakage flow characteristics in transonic condition.

Flow and heat transfer characteristics over turbine blade tips having various kinds of partial squealers have been studied by Heyes et al. (1992) for plane tips, suction-side and pressure-side squealer tips, by Ameri (2001) for a mean camberline squealer, by Kwak et al. (2003) for single or double squealer for tip gap-to-span ratios of $h/s = 1.0\%$, 1.5%, and 2.5%, and by Nasir et al. (2004) for full squealer and four different squealer arrangements located along the pressure side and/or suction side in the cases of $h/s = 1.0\%$ and 2.6%. Nasir et al. (2004) showed that overall averaged heat transfer coefficient for the pressure-side partial squealer rim is highest among the tested squealer arrangements. Kwak et al. (2004) investigated the effects of rim location, rim height, and tip clearance on the tip heat transfer for a cavity, a pressure-side and a suction-side squealer tips. They showed that the suction-side rim case provides lower heat transfer coefficients than the cavity squealer rim case. Camci et al. (2005) investigated aerodynamic characteristics of turbine tips with suction-side squealer rims and channel arrangements of varying lengths. They found that

---

* Corresponding author. Tel.: +82 54 478 7296; fax: +82 54 478 7319.
E-mail address: swlee@kumoh.ac.kr (S.W. Lee).

http://dx.doi.org/10.1016/j.ijheatfluidflow.2014.09.008
0142-727X/© 2014 Elsevier Inc. All rights reserved.

Nomenclature

b	axial chord length
c	chord length
c_c	total length of the camberline
C_{Pt}	total-pressure loss coefficient
$\bar{C}_{Pt}$	total-pressure loss coefficient mass-averaged all over the present measurement plane
$\bar{C}_{Pt,z}$	total-pressure loss coefficient mass-averaged in the pitch-wise direction
h	tip gap height
h_p	pressure-side squealer rim height
h_{ps}	cavity squealer rim height
h_s	suction-side squealer rim height
p	pitch of the cascade
P_t	local total pressure
$P_{t,0}$	reference total pressure
Re	Reynolds number ($U_\infty c/\nu$)
s	span of the turbine blade
U, V, W	x, y, z-directional velocities
U_∞	inlet free-stream velocity
x, y, z	cascade coordinates
x_c	curvilinear coordinate along the camberline
y_m	y-directional coordinate at $x/b = 1.2$
Greek symbols	
β	local flow yaw angle
$\bar{\beta}_z$	flow yaw angle mass-averaged in the pitch-wise direction
ν	kinematic viscosity of air
ρ	density of air

the suction-side squealers are aerodynamically superior to the channel arrangements. Newton et al. (2006) carried out local measurements of heat transfer coefficient and pressure coefficient for a plane tip, a cavity squealer and a suction-side squealer. The two squealers were found to reduce heat transfer in the tip gap. Krishnababu et al. (2009) conducted a numerical investigation for a plane tip, a cavity squealer tip, and a suction-side squealer tip. They showed that compared to the plane tip, the cavity squealer tip reduces the tip leakage flow meanwhile the suction-side squealer increases it. Lee et al. (2011) investigated tip-leakage aerodynamics over stepped squealer tips in a turbine cascade.

The literature survey shows that there are little available measured data about the tip gap flow and aerodynamic loss generation over pressure-side partial squealer tips. Moreover, the influences of its rim height (h_p) upon the tip leakage aerodynamics are not known yet. In this study, detailed tip gap flow characteristics and aerodynamic loss generations for the pressure-side squealer tips have been investigated for a fixed value of h/s. Major objectives of this study are (i) to understand tip gap flow characteristics within the pressure-side partial squealer tip gap, (ii) to know how the tip gap flow behaves with the variation of h_p, and (iii) to find a best rim height by examining how h_p influences aerodynamic loss generation. In order to do these, detailed three-dimensional flow measurements with a five-hole probe as well as surface flow visualizations were carried out.

2. Experimental apparatus and procedure

2.1. Turbine cascade wind tunnel

In this experiment, we employed a stationary turbine rotor blade cascade wind tunnel, although there exists a relative motion between the blade tip surface and the casing wall. As shown in Fig. 1, the uniform flow from a blow-down wind tunnel develops into a turbulent boundary layer flow in the inlet duct, enters the turbine cascade, and then discharges through the exit duct. The inlet duct has a cross section of 0.42 m × 0.32 m, and the exit one has tailboards to adjust periodicity among the blade passage flows.

The turbine cascade has six large-scale linear turbine rotor blades. They are made of aluminum and are fabricated based on the profile of a high pressure turbine rotor blade for power generation. The chord length, c, axial chord, b, pitch, p, and span, s, of the large-scale blade are 217.8 mm, 196.0 mm, 151.6 mm, and 320.0 mm, respectively. The span is chosen based on an aspect ratio of original blade of $s/c = 1.47$. The blade inlet and outlet angles are 56.4° and −62.6°, respectively. The blade profile used in this study is presented in Lee and Chae (2008). As can be seen in Fig. 1, the central four blades are inserted into the indents machined on the bottom wall, and thus they have a tip gap at the top end, meanwhile the blades #1 and #6 are attached to the top and bottom walls with no tip gaps. As shown in Fig. 2, x, y, and z are in the axial, pitch-wise and span-wise directions of the cascade, respectively. In addition, a downstream coordinate, y_m, is in parallel with the y-axis and has its origin at the intersection of a line of $x/b = 1.2$ with a line drawn from the trailing edge center at the blade outlet angle.

2.2. Tested pressure-side squealer tips

Four pressure-side squealer tips as shown in Fig. 3 are tested in this study. The tip gap height-to-span (chord) ratio is maintained at $h/s = 1.36\%$ ($h/c = 2.0\%$) throughout the experiments. The pressure-side squealer rims have a fixed value of 4.0 mm in thickness (t) and extend all the way from the geometric stagnation point of the blade to the trailing edge center point along the pressure-side tip edge. The height of the pressure-side squealer rim is changed to be $h_p = 3.0$, 6.0, 12.0 and 18.0 mm, which corresponds to $h_p/s = 0.94\%$, 1.88%, 3.75%, and 5.63% ($h_p/c = 1.38\%$, 2.75%, 5.51%, and 8.26%), respectively.

2.3. Three dimensional flow measurements

For the three-dimensional flow measurement, a cone-type five-hole probe of 3.18 mm (0.125 in.) in head diameter, custom-made by United Sensor Corp., is employed. This five-hole probe has a straight probe stem, and its head shape is the same as that of its DC125 model as can be seen in Fig. 2.

The instrumentation systems are controlled by a computer equipped with a Multi-Function I/O Board (NI, PCI-6036E) and a Digital I/O board (NI, PCI-6503). Measured pressures are transformed into DC voltage signals by a high-accuracy differential pressure transducer (MKS, Type 120AD-00010-R-EB) and power supply/readout (MKS, Type 501B). The DC voltages are sampled by a 16-bit A-D converter in the Multi-Function I/O Board, and transferred into the computer. A three-dimensional automatic probe traverse unit used in this experiment has three linear motion guides (Samik, SAR1615T), stepping motors (Oriental Motor, UPH599-A), and stepping motor drivers (Oriental Motor, UDX5114). This unit is controlled by six-channel digital-out pulses from the Multi-Function I/O Board. A multi-channel pressure