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Effects of squealer rim height on heat/mass transfer on the floor of cavity squealer tip in a high turning turbine blade cascade

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ABSTRACT

The effects of h_{st}/s (squealer rim height-to-span ratio) on heat/mass transfer rate on the floor of the cavity squealer tip have been investigated in a high turning turbine blade cascade by employing the naphthalene sublimation technique along with oil film flow visualizations. Tested squealer rim heights are $h_{st}/s = 0.00\%$ (plane tip), 0.94%, 1.88%, 3.75%, and 5.63% for a tip gap height-to-span ratio of $h/s = 1.02\%$. For comparison purpose, the tip gap height is changed from $h/s = 0.34\%$ to 1.70% for $h_{st}/s = 3.75\%$. Heat/mass transfer rate on the cavity floor upstream of the mid-chord is affected by the leading edge tip gap vortices as well as by the reattachment of the incoming tip leakage flow to the cavity floor for lower h_{st}/s, as in the plane tip case, whereas it is influenced mainly by the impingement of the incoming tip leakage flow onto the cavity floor near the leading edge for higher h_{st}/s. On the other hand, heat/mass transfer rate downstream of the mid-chord is determined by the downwash flow which is entrapped by the suction-side squealer rim. With increasing h_{st}/s, average heat/mass transfer rate on the cavity floor decreases steeply at first and then decreases mildly in the same manner as over-tip leakage loss. Average heat/mass transfer rate on the cavity floor is more sensitive to the squealer rim height than to the tip gap height.

1. Introduction

Higher turbine inlet temperature in a gas turbine leads to an increase in its cycle efficiency. In modern high performance gas turbines, turbine inlet temperature exceeds 1500 °C. Thus, it is inevitable that turbine hot components suffer severe thermal load. Blade tips, in particular, are exposed to high temperature gases not only on the near-tip pressure and suction surfaces but also on the tip surface and need to be cooled. In the design of an efficient tip cooling system, heat transfer coefficient data should be provided.

The tip gap leakage flow over a simple plane (flat) tip have been investigated by Sjolander and Amrud [1], Bindon [2], Yamamoto [3], Matsunuma [4], Lee and Kim [5], Lee and Choi [6], Zhang et al. [7], and Zhang and He [8]. There are many previous studies on tip heat transfer for the plane tip. Ameri et al. [9] performed numerical simulations to understand the effect of tip gap and casing recess on heat transfer and stage efficiency for the plane tip with tip gap-to-span ratios of $h/s = 0.0\%$, 1.0%, 1.5% and 3.0%. Bunker et al. [10] conducted experiments for heat transfer and flow on the first-stage blade tip of a power generation gas turbine and demonstrated a characteristic central sweet spot of low heat transfer on the plane tip. For the same turbine blade, Ameri and Bunker [11] undertook numerical predictions and comparisons with the experimental data of tip heat transfer. Azad et al. [12] investigated the effect of tip gap and inlet turbulence intensity on the detailed local heat transfer coefficient distribution for $h/s = 1.0\%$, 1.5% and 2.5% and provided a better understanding of the local heat transfer behavior on the plane tip surface. Rhee and Cho [13,14] reported plane tip heat/mass transfer distributions in a rotating low-speed annular turbine facility for $h/c = 2.5\%$. Lee et al. [15] measured local heat/mass transfer rate on the tip surface of a turbine blade for power generation and suggested a qualitative tip gap flow model for the plane tip. Zhang et al. [16] investigated transonic turbine blade tip aerothermal performance with different tip gaps. They suggested that for the most part of a transonic blade tip, high heat transfer is dominated by the enhanced turbulence thermal diffusion rather than by a direct increase of wall shear stress.

Tip leakage flow characteristics over turbine blade tips equipped with a cavity squealer or various partial squealers were investigated by Heyes et al. [17], Camci et al. [18], Key and Arts [19], Mischo et al. [20], Lee and Chae [21], Lee and Kim [5], Lee and Choi [6], Lee et al. [22], Lee and Lee [23], and Li et al. [24]. For the cavity squealer tip, it is found that for $h_{st}/s = 3.75\%$, incoming tip leakage flow, especially upstream of the mid-chord, falls

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Nomenclature

b	axial chord
c	chord
c_c	total length of the camberline
$\bar{C}_{Pt}$	mass-averaged total-pressure loss coefficient
D	diffusion coefficient of naphthalene in air
h	tip gap height
h_m	local mass transfer coefficient
h_{st}	squealer rim height
Nu	Nusselt number
p	pitch
Pr	Prandtl number ($\mathrm{Pr} = \nu/\alpha$)
Re_∞	inlet Reynolds number ($\mathrm{Re} = U_\infty c/\nu$)
s	span
Sc	Schmidt number ($\mathrm{Sc} = \nu/D$)
Sh	Sherwood number ($\mathrm{Sh} = h_m c/D$)
$\overline{\mathrm{Sh}}$	Sherwood number averaged on the cavity floor
t	thickness of the squealer rim
U_∞	inlet freestream velocity
x, y, z	cascade coordinates
x_c	curvilinear coordinate along the camberline
Greek symbols	
α	thermal diffusivity of air
ν	kinematic viscosity of air

down into the recessed cavity, moves toward the trailing edge within the cavity, and then comes out of it downstream of the mid-chord [5]. Li et al. [24] confirmed these tip leakage flow phenomena from their transonic numerical simulations and showed that the cavity squealer tip has lower upstream tip leakage outflow rate than the plane tip.

There are many previous researches on the near-tip surface heat transfer or aerothermal performance for the tip equipped with a cavity squealer or various partial squealers. Ameri et al. [25] performed three-dimensional simulations of flow and heat transfer over a cavity squealer tip. They showed that heat transfer rate on the recessed surface (or cavity floor) is strongly affected by two dominant vortical structures in the recessed region, but there exists no significant effect of the recession on efficiency. Azad et al. [26] investigated the effect of tip gap and inlet turbulence intensity on the detailed local heat transfer coefficient distribution on a cavity squealer tip of 3.77% recess. They showed that the cavity squealer tip blade leads to lower overall heat transfer coefficient when compared to the plane tip blade. Ameri [27] carried out experimental and computational studies for a turbine blade equipped with a mean camberline strip, and he found that sharp edge tip works best among the tested cases in reducing tip leakage flow and heat transfer. Kwak et al. [28] measured local heat transfer coefficients on the tip surface and in the near-tip regions of a gas turbine blade with single or double squealer in the cases of $h/s = 1.0\%$, 1.5%, and 2.5% for a fixed squealer rim height-to-span ratio of $h_{st}/s = 4.16\%$. They found that heat transfer coefficient on the blade tip and the shroud is significantly reduced meanwhile its reduction on the blade pressure and suction sides is not remarkable. Nasir et al. [29] explored the effect of squealer geometry on heat transfer over a turbine blade tip for tip gaps of $h/s = 1.0\%$ and 2.6%. Especially for the cavity squealer geometry, deep and shallow cavities of $h_{st}/s = 4.16\%$ and 1.04% were also tested. They showed that average heat transfer coefficient for the pressure-side partial squealer is highest among the tested squealer arrangements. Kwak et al. [30] studied the effects of rim location, rim height ($h_{st}/s = 2.1\%$, 4.2% and 6.3%), and tip clearance ($h/s = 1.0\%$, 1.5%, and 2.5%) on tip heat transfer for various squealer tips. They showed that overall heat transfer coefficients on the tip and near-tip regions for the suction-side rim case are lower than those of the full-side rim cases. Newton et al. [31] measured heat transfer coefficient and pressure coefficient for a plane tip, a cavity squealer and a suction-side squealer and showed that the two squealers reduce heat transfer in the tip gap. Krishnababu et al. [32] conducted computational aerothermal investigations for a plane tip, a cavity squealer tip ($h_{st} = 1.35h$), and a suction-side squealer tip ($h_{st} = 1.35h$) in the cases of $h/c = 1.6\%$ and 2.8%. They concluded that compared to the other two geometries, the cavity squealer tip is advantageous both from the aerodynamic and from the heat transfer perspectives by providing lower leakage flow rate.

Turbine blades equipped with a winglet in the form of tip surface extension into the turbine flow passage are considered as one of potential tip treatments for better stage efficiency. Aerodynamics over various kinds of winglets were investigated by Dey and Camci [33], Harvey and Ramsden [34], Harvey et al. [35,36], Schabowski and Hodson [37], Schabowski et al. [38], Lee et al. [39], Zhou et al. [40], Lee et al. [41], Schabowski and Hodson [42], and Schabowski et al. [43]. These studies reported that in general, winglets have a role to reduce over-tip leakage loss to a certain degree. Researches such as Papa et al. [44], Saha et al. [45], O'Dowd et al. [46], O'Dowd et al. [47], Coull et al. [48], Kang and Lee [49], and Seo and Lee [50] focused on heat transfer or aerothermal performance of the winglet tips. Recent investigations [49,50] showed that thermal load on the tip surface inside the baseline blade profile with a full-coverage winglet is much less severe but total thermal load on the protruding winglet is more severe, in comparison with the result on the tip surface with no winglet.

Lee and Chae [21] reported that with the increment of the squealer rim height (h_{st}), the total-pressure loss coefficient mass-averaged all over the measurement area between the mid-span and the casing, $\bar{C}_{Pt}$, tends to decrease steeply up to $h_{st}/s = 3.75\%$ and then becomes almost unchanged, as shown in Fig. 1. The present study focuses on heat/mass transfer on the cavity floor for the high turning blade employed by Lee and Chae [21].

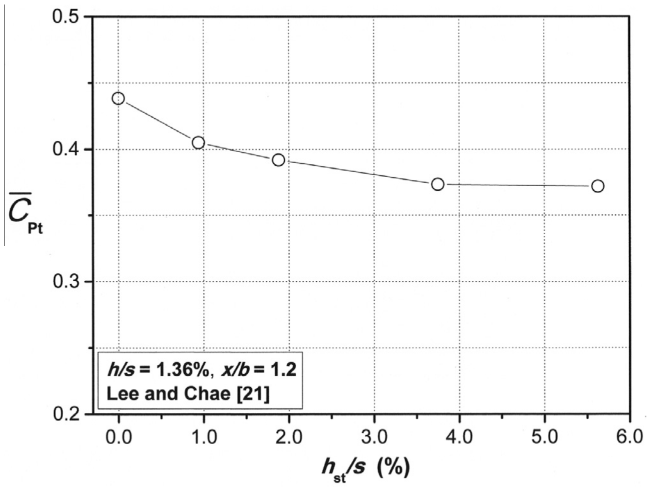

Fig. 1. Over-tip leakage loss as a function of h_{st}/s.