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Heat/mass transfer over the plane tip equipped with a full coverage winglet in a turbine cascade: Part 1 – Winglet bottom surface data

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ABSTRACT

The effects of h/s (tip gap height-to-span ratio) on heat/mass transfer on the bottom surface of a full coverage (FC) winglet, which is installed on a plane (flat) tip, have been investigated by employing the naphthalene sublimation technique along with oil film flow visualizations. In this study, the tip gap is widely changed to be $h/s = 0.68\%$, 1.02%, 1.36%, 1.70% and 2.04% for a winglet width-to-pitch ratio of $w/p = 10.55\%$. From the present measurements, several high heat/mass transfer rate regions are identified on the winglet bottom surface, and various flow phenomena in these regions are discussed in detail. For $h/s = 0.68\%$, heat/mass transfer rate is relatively high even outside the high heat/mass transfer regions. On the contrary, for $h/s = 2.04\%$, there exist relatively low heat/mass transfer rate outside the high heat/mass transfer regions and in particular, very low heat/mass transfer rate is observed on the downstream half of the pressure-side winglet bottom surface. As h/s increases, heat/mass transfer rate averaged on the winglet bottom surface decreases consistently in almost linear proportion to h/s.

1. Introduction

Turbine blades are subject to severe thermal load from hot combustion gases. In particular, the blade tip is exposed to high temperature gas on its three faces of a pressure surface, suction surface, and tip surface. In order to keep surface temperatures under an allowable limit, the blade tip needs to be cooled. In this sense, heat transfer data on the near-tip surfaces are essential in the design of an efficient tip cooling system.

For a plane (flat) tip, Ameri et al. [1] carried out numerical simulations on heat transfer and stage efficiency of the turbine blade with casing recesses for tip gaps of $h/s = 0\%$, 1.0%, 1.5% and 3%. They reported an increase in thermal load on all heat transfer surfaces with increasing h/s. Bunker et al. [2] measured heat transfer over the plane tip of a gas turbine for power generation, and showed heat transfer coefficient distributions on the plane tip surfaces with both sharp and rounded edges. For the same turbine blade, Ameri and Bunker [3] performed numerical studies on flow and heat transfer. Detailed tip surface heat transfer distributions and tip gap flow patterns were provided. Azad et al. [4] reported tip surface heat transfer coefficient distributions employing a transient liquid crystal technique for $h/s = 1.0\%$, 1.5% and 2.5%. It is shown that tip gap has a significant influence on local tip heat transfer. Rhee and Cho [5,6] reported heat/mass transfer distributions on the near-tip surfaces and shroud for a plane tip in a rotating low-speed annular turbine facility for $h/c = 2.5\%$. Lee et al. [7] investigated tip gap height effects on the flow structure and heat/mass transfer over the tip surface of a turbine blade for power generation. Zhang et al. [8] investigated transonic turbine blade tip heat transfer with different tip gaps.

Cavity squealer tips have a recessed cavity enclosed by a full-length squealer. It is known that the cavity squealer tip reduces tip gap flow rate by increasing flow resistance and protects the tip surface from high temperature leakage flow. Heat transfer on the cavity squealer tip was performed by Ameri et al. [9] and by Azad et al. [10]. Heat transfer characteristics over blade tips with partial squealers were investigated by Ameri [11] for a mean camberline strip, by Kwak et al.[12] for single and double squealers, by Nasir et al. [13] for various partial squealers, by Camci et al. [14] for single and channel-type squealers, and by Krishnababu et al. [15] for cavity and suction-side squealers.

Turbine blades can be equipped with a winglet in the form of tip surface extension into the neighboring turbine flow passage. Many investigators such as Patel [16], Booth et al.[17], Dey and Camci [18], Harvey and Ramsden [19], Harvey et al. [20,21], Schabowski and Hodson [22], Schabowski et al. [23], Lee et al. [24], Zhou et al. [25], Lee et al. [26], Schabowski and Hodson [27], and Schabowski et al. [28] were interested in aerodynamic performances of various kinds of winglets.

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Nomenclature

b	axial chord
c	chord
c_c	total length of the baseline blade camberline
D	diffusion coefficient of naphthalene in air
h	tip gap height
h_m	local mass transfer coefficient
Nu	Nusselt number
p	pitch of the cascade
Pr	Prandtl number (Pr = ν/α)
Re_∞	inlet Reynolds number (Re = $U_\infty c/\nu$)
s	span
Sc	Schmidt number (Sc = ν/D)
Sh	Sherwood number (Sh = $h_m c/D$)
$\overline{Sh}_{NOW}$	Sherwood number averaged on the baseline plane tip surface with no winglet
Sh_{WBS}	Sherwood number on the winglet bottom surface
$\overline{Sh}_{WBS,x}$	Sherwood number pitch-wise averaged on the winglet bottom surface
$\overline{Sh}_{WBS}$	Sherwood number averaged on the winglet bottom surface
t	thickness of the FC winglet
U	local potential velocity on the blade surface
U_e	cascade exit mean velocity
U_∞	inlet free-stream velocity
w	width of the FC winglet
x, y, z	cascade coordinates
x_c	curvilinear coordinate along the baseline blade camberline

Greek symbols

α	thermal diffusivity of air
ν	kinematic viscosity of air

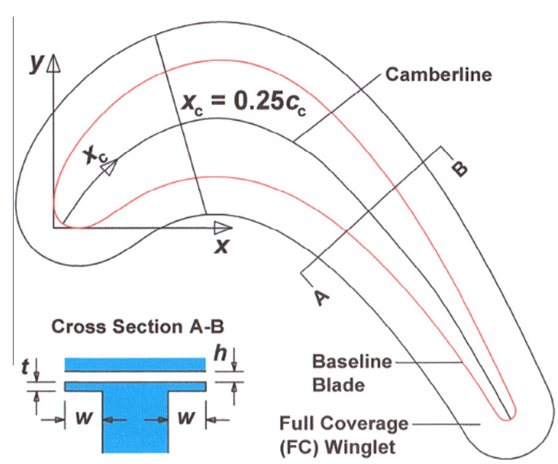
As for heat transfer on the tip surface equipped with the winglet, Papa et al. [29] measured heat/mass transfer for the tip with a suction-side squealer and a pressure-side winglet simultaneously. They showed that the squealer tip has a higher average mass transfer that sensibly decreases with gap level, whereas a more limited variation with gap level is observed for the winglet-squealer tip. Saha et al. [30] carried out numerical simulations to explore the effect of a pressure-side winglet on the flow and heat transfer over a plane, cavity squealer, and suction-side squealer tips. They showed that for the plane tip, the pressure-side winglet reduces the heat transfer coefficients by 30%, meanwhile the average heat transfer coefficient is reduced by about 7%. In the presence of the cavity or suction-side squealer, the role of the winglet decrease significantly. Only the suction-side squealer with constant width winglet showed heat transfer reduction by 5.5%. O'Dowd et al. [31,32] reported transonic heat transfer over a winglet tip without and with cooling, respectively. It has a centerline gutter and a small recessed cavity on the pressure-side overhang. O'Dowd et al. [31] concluded that the turbine blade tip heat transfer is greatly influenced by the shock wave structure inside the tip gap. O'Dowd et al. [32] showed that tip Nusselt number increases with coolant injection, and it also increases with increase tip clearance. Coull et al. [33] investigated the design of winglet tips for an unshrouded high pressure turbine blade, considering aerodynamic and thermal performance simultaneously. They showed that compared to a plane tip, large efficiency gains are realized by employing an overhang around the full parameter of the blade, but overall heat load rises significantly. By employing an overhang on only the early suction surface, significant efficiency improvement can be obtained without increasing the overall heat transfer.

Lee et al. [26] reported tip leakage loss data for the plane tip equipped with a full coverage (FC) winglet as shown in Fig. 1 with the variation of winglet width (w). They showed that with increasing w/p, the loss decreases steeply up to w/p = 10.55%, and the FC winglet provides more benefit in flow turning within the turbine blade passage. Despite these benefits, there seem to be no previous experimental works that dealt with heat transfer not only on the winglet bottom surface but also on the tip surface for the plane tip with the FC winglet. In this study (part 1), the effects of tip gap height-to-span ratio, h/s, on heat/mass transfer on the protruding FC winglet bottom surface have been investigated experimentally with the wide variation of h/s, by employing the naphthalene sublimation technique along with oil film flow visualizations. The companion paper (part 2) [34] will report heat/mass transfer on the tip surface for the plane tip with the FC winglet.

2. Experiment

2.1. Cascade wind tunnel

The overall view of the present test rig is shown in Fig. 2a. It has a blowdown wind tunnel, an inlet duct, a linear turbine blade cascade, and an exhaust duct. At the inlet duct of 0.42 m × 0.32 m in cross section, turbulent boundary layers are developing on its top and bottom surfaces past a trip wire/sand paper. The turbine cascade has six large-scale linear blades of s/c = 1.47. The side walls of the exhaust duct can be adjustable for flow periodicity among the blades. The blades made of aluminum are machined on the basis of the profile of a first-stage turbine blade for power generation. The chord, c, axial chord, b, pitch, p, and span, s, of the blade are 217.8 mm, 196.0 mm, 151.6 mm, and 320.0 mm, respectively. The cascade has an inlet flow angle of 56.4° and an outlet flow



w/p (w/s)	t/s	h/s
10.55% (5.0%)	1.25%	0.68%
		1.02%
		1.36%
		1.70%
		2.04%

Fig. 1. Tested FC winglet.