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Heat/mass transfer over the plane tip equipped with a full coverage winglet in a turbine cascade: Part 2 – Tip surface data

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ABSTRACT

The effects of h/s (tip gap height-to-span ratio) on heat/mass transfer on the plane (flat) tip surface of a full coverage (FC) winglet have been investigated by employing the naphthalene sublimation technique along with oil film flow visualizations. For a winglet width-to-pitch ratio of $w/p = 10.55\%$, the tip gap is widely changed to be $h/s = 0.68\%$, 1.02%, 1.36%, 1.70% and 2.04%. The result shows that regardless of h/s, local heat/mass transfer rate on the tip surface is very high on the protruding winglet top surface at the leading edge and on the pressure side. On the other hand, there is relatively low local heat/mass transfer rate on the protruding winglet top surface on the suction side as well as in an area behind the leading edge separation bubble. The tip surface inside the baseline blade profile with the FC winglet is exposed to much less severe thermal load than the baseline plane tip surface with no winglet, whereas total thermal load on the protruding FC winglet is more severe than thermal load on the baseline plane tip surface with no winglet.

1. Introduction

Turbine near-tip surfaces are exposed to severe thermal load from high temperature combustion gas. For extending the life of these turbine hot components, sophisticated turbine tip cooling systems need to be employed. Heat transfer data on their surfaces are essential in the design of the turbine tip cooling system.

Previous studies on turbine tip heat transfer for a plane (flat) tip, a cavity squealer tip, and various partial squealer tips were reviewed in detail by Kang and Lee [1]. Aerodynamic investigations for turbine blade tips equipped with various kinds of winglets were carried out by Patel [2], Booth et al. [3], Dey and Camci [4], Harvey and Ramsden [5], Harvey et al. [6,7], Schabowski and Hodson [8], Schabowski et al. [9], Lee et al. [10], Zhou et al. [11], Lee et al. [12], Schabowski and Hodson [13] and Schabowski et al. [14]. Lee et al. [12] reported tip leakage loss data for the plane tip with a full coverage (FC) winglet with the variation of winglet width-to-pitch ratio (w/p). They showed that with increasing w/p, tip leakage loss decreases steeply up to $w/p = 10.55\%$ and the FC winglet performs positively in flow turning within the turbine passage.

There are several previous investigations of heat transfer on the near-tip surfaces equipped with the winglets. Papa et al. [15] measured heat/mass transfer on the baseline blade tip surface 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. [16] carried out numerical simulations to explore the effect of a pressure-side winglet on flow and heat transfer over a plane, cavity squealer, and suction-side squealer tips. O'Dowd et al. [17,18] reported transonic heat transfer over a winglet tip without and with cooling, respectively. It has not only a centerline gutter but also a small recessed cavity on its pressure-side overhang. O'Dowd et al. [17] concluded that the turbine blade tip heat transfer is greatly influenced by the shock wave structure inside the tip gap. O'Dowd et al. [18] showed that tip Nusselt number increases with coolant injection, and it also increases with increase tip clearance. Coull et al. [19] investigated the designs of winglet tips for 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. In the companion paper of this study (part 1), Kang and Lee [1] reported heat/mass transfer on the winglet bottom surface of a plane tip equipped with the FC winglet with the variation of tip gap height-to-span ratio (h/s). They showed

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Nomenclature

b	axial chord
c	chord
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 ($\mathrm{Pr} = \nu/\alpha$)
Re_∞	inlet Reynolds number ($\mathrm{Re} = U_\infty c/\nu$)
s	span
Sc	Schmidt number ($\mathrm{Sc} = \nu/D$)
Sh	Sherwood number ($\mathrm{Sh} = h_\mathrm{m}c/D$)
$\overline{\mathrm{Sh}}_{\mathrm{BLTS}}$	Sherwood number averaged on the tip surface inside the baseline blade profile with the FC winglet
$\overline{\mathrm{Sh}}_{\mathrm{ETS}}$	Sherwood number averaged on the entire tip surface with the FC winglet
$\overline{\mathrm{Sh}}_{\mathrm{NOW}}$	Sherwood number averaged on the baseline plane tip surface with no winglet
$\mathrm{Sh}_{\mathrm{TS}}$	Sherwood number on the tip surface
$\mathrm{Sh}_{\mathrm{WBS}}$	Sherwood number on the winglet bottom surface
$\overline{\mathrm{Sh}}_{\mathrm{WBS}}$	Sherwood number averaged on the winglet bottom surface
$\overline{\mathrm{Sh}}_{\mathrm{WBS,x}}$	Sherwood number pitch-wise averaged on the winglet bottom surface
$\mathrm{Sh}_{\mathrm{WBTS}}$	sum of $\mathrm{Sh}_{\mathrm{WBS}}$ and $\mathrm{Sh}_{\mathrm{WTS}}$
$\overline{\mathrm{Sh}}_{\mathrm{WBTS}}$	sum of $\overline{\mathrm{Sh}}_{\mathrm{WBS}}$ and $\overline{\mathrm{Sh}}_{\mathrm{WTS}}$
$\overline{\mathrm{Sh}}_{\mathrm{WBTS,x}}$	sum of $\overline{\mathrm{Sh}}_{\mathrm{WBS,x}}$ and $\overline{\mathrm{Sh}}_{\mathrm{WTS,x}}$
$\mathrm{Sh}_{\mathrm{WTS}}$	Sherwood number on the protruding winglet top surface
$\overline{\mathrm{Sh}}_{\mathrm{WTS}}$	Sherwood number averaged on the protruding winglet top surface
$\overline{\mathrm{Sh}}_{\mathrm{WTS,x}}$	Sherwood number pitch-wise averaged on the protruding winglet top surface
t	thickness of the FC winglet
U_∞	inlet free-stream velocity
w	width of the FC winglet
x, y, z	cascade coordinates

Greek symbols

α	thermal diffusivity of air
ν	kinematic viscosity of air

that with increasing h/s, heat/mass transfer rate averaged on the winglet bottom surface decreases consistently in almost linear proportion to h/s, and it is much lower than that averaged on the baseline blade tip surface with no winglet.

In this paper (part 2), the effect of h/s on heat/mass transfer over the tip surface of the plane tip equipped with the FC winglet has been investigated experimentally with the wide variation of h/s. In order to do this, the naphthalene sublimation technique is employed along with tip surface oil film visualizations.

2. Experiment

2.1. Linear turbine cascade with tip gap

The present cascade wind tunnel comprises of a blowdown wind tunnel, an inlet duct, a linear turbine blade cascade, and an exhaust duct. Details of the test rig are reported by Kang and Lee [1]. The turbine cascade has six large-scale blades of $s/c = 1.47$. The blades are made of aluminum 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 angle of −62.6° as shown in Fig. 1. The coordinates of the blade profile were reported by Lee and Chae [20]. The four blades in the middle have a tip gap near the cascade top endwall and are equipped with the FC winglet as in Fig. 1. The FC winglet tested in this study is the same as that employed by Kang and Lee [1]. Each FC winglet is flush mounted to the tip surface as shown in Fig. 1, and its thickness and width are fixed at $t/s = 1.25\%$ and $w/p = 10.55\%$, respectively.

2.2. Naphthalene sublimation technique and data reduction procedure

In the naphthalene sublimation technique, mass transfer coefficient, h_m, is obtained from the local sublimation depth of naphthalene. In the mass transfer system, Sherwood number, Sh, is defined as:

$$\mathrm{Sh} = (h_\mathrm{m}c)/D \tag{1}$$

where D is the diffusion coefficient of naphthalene in air. Nusselt number, Nu, can be derived from the following equation:

$$\frac{\mathrm{Nu}}{\mathrm{Sh}} = \left(\frac{\mathrm{Pr}}{\mathrm{Sc}}\right)^n \tag{2}$$

where n is usually taken to be 1/3 for a laminar flow and to be 0.4 for a turbulent one [21]. The boundary condition on the cast naphthalene surface in the mass transfer system is equivalent to constant surface temperature in the heat transfer system.

In order to obtain the distribution of h_m, the test surface should be coated with naphthalene. As shown in Fig. 2, the mold assembly for the naphthalene casting is made up of a mold, a mold holder, and a mold cover having a polished surface. These three are bolted together during the casting process. The mold comprises of a baseline blade portion of 8.0 mm in thickness and a protruding winglet portion of 4.0 mm in thickness. A thin layer of naphthalene is cast on the tip surface inside the 2.0 mm deep recession that is enclosed by a mold shoulder of 2.0 mm in both height and width. As shown in Fig. 2, the inlet of molten naphthalene is located on the winglet bottom surface downstream of the baseline blade trailing edge, in order to avoid flow disturbances by it. The cast winglet tip mold is installed on the top end of the blade #4 as in Fig. 1. Fig. 3 shows the naphthalene coated tip surface.

The present instrumentation system is the same as that used by Kang and Lee [1]. The depth gauge used for the measurement of sublimation depth is an AC-AC ultra-precision LVDT (linear variable differential transformer) (Sensortec, Model S5-AY112HK). Its full scale and linearity are ±1.0 mm and 0.07%, respectively. This depth gauge is mounted on the automatic depth measurement system. Sublimation depth is recorded at 44 points in the x-direction and at 15 points in the y-direction (660 points in total) as shown in Fig. 4. All the instruments are controlled by a computer equipped with a multi-function DI/O board (NI, PCI-6036E) and a GPIB adapter (NI, AT-GPIB). The full descriptions of the instrumentation and data reduction procedure are provided by Kang and Lee [1].