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Arrangement effects of inclined teardrop-shaped dimples on film cooling performance of dimpled cutback surface at airfoil trailing edge

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ABSTRACT

Cooling at trailing edge of gas turbine airfoil is one of the most difficult problems because of its thin shape: high thermal load from both surfaces, hard-to-cool geometry of narrow passages, and at the same time demand for structural strength are the reasons. In this study, heat transfer coefficient and film cooling effectiveness on pressure-side cutback surface were measured by a transient infrared thermography technique with consideration of three-dimensional heat conduction. The cutback surface was roughened by teardrop-shaped dimples. Three different rotation angles (30, 45, and 60 deg) of the dimpled surface with in-line and staggered arrangements were examined for blowing ratio of 0.5, 1.0, 1.5, and 2.0. Within the present arrangements, the film cooling effectiveness remained almost constant, although the heat transfer coefficient became a maximum at 30 deg in-line arrangement. The overall film cooling performance evaluated by net heat flux reduction was the highest for the 30 deg in-line arrangement and it was 14–24% higher than the 30 deg staggered arrangement. Three-component PTV results explained this effect by the suppression of flow separation in the 30 deg in-line arrangement and it attained the favorable inflow condition on the downstream dimples.

1. Introduction

In order to achieve higher thermal efficiency, typical operating temperatures of aero engines and gas turbines are becoming much higher than the allowable metal temperature. This necessitates more intensive and effective cooling methods to provide thermal protection to the hot section components and to securely maintain the temperature of the component below the allowable temperature. In terms of the intensive and effective cooling, airfoil trailing edge is one of the most difficult regions to achieve these goals, particularly because the cooling needs to be implemented in a relatively small and thin space of the airfoil (see Fig. 1). Current cooling technology for airfoil trailing edges relies primarily on the coolant air introduced from the upstream airfoil main-body. To bring trailing-edge cooling designs within the available design solution-space, several methods are used today. These are internal heat transfer enhancement by various cooling schemes, optimization of the parameters to minimize film-cooling degradation, and structural design integrated in these cooling schemes to reduce stresses. All of the aspects need to be considered together to satisfy the design requirements.

Here, previous studies on the trailing-edge film cooling are briefly reviewed. Cunha and Chyu [1] developed analytical solutions for four most representative trailing-edge configurations and provided fundamental insight into the characteristics for each configuration. They concluded that, among the alternatives, only the cutback design (Fig. 1) realized all the features to enhance the cooling performance with structural integrity being ensured and with the additional benefits in aero-performance. Actually, the cutback configuration is most widely used in practical application of the modern aero-engines/gas-turbines. As compared to the researches on the film cooling of airfoil surface, only limited number of publications exist that deal with coolant ejection on a trailing edge pressure-side cutback. Taslim et al. [2] investigated the film cooling effectiveness downstream of trailing-edge slots disrupted by lands in the transverse direction. The influence of density ratio, lip thickness, slot width, and ejection angles were examined. Their study found that the density ratio and slot width did not display a strong impact on measured film cooling effectiveness and ejection angle had some effect with an optimum angle of 8.5 deg. They concluded that the strongest dependency was seen in the lip thickness and the film cooling effectiveness considerably decreased as the lip thickness was increased.

Martini et al. [3] applied a detached eddy simulation (DES) to the film cooling flow at the airfoil trailing edge. They found a

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Nomenclature

a	thermal diffusivity of wall
h	heat transfer coefficient
H	height of cooling-flow passage
M	blowing ratio
$NHFR$	net heat flux reduction
Nu	Nusselt number
q	wall heat flux
Re	Reynolds number
T	temperature
v	velocity in y direction
U	mean velocity
W	width of channel
x	streamwise coordinate
y	cutback-surface normal coordinate
z	lateral coordinate
η	film cooling effectiveness
Θ	dimensionless temperature
λ	thermal conductivity
ρ	density
ϕ	rotation angle of dimpled surface

Subscripts

aw	adiabatic wall
c	cooling flow
h	high-temperature main flow
L	local value
m	surface-averaged value
w	wall
z	laterally averaged value
0	without film cooling
∞	fully developed value for smooth pipe

strong interaction between the coolant and main flows which was influenced by the thick blunt lip. For the film cooling flow over cutback surface, alternating large scale vortices were shed from the lip edge and steady/unsteady RANS (Reynolds averaged Navier-Stokes) could not reproduce the film cooling performance affected by the unsteady large-scale vortices [4,5]. Therefore, recent numerical studies are shifted to LES (Large Eddy Simulation) from RANS. Schneider et al. [5–7] applied LES to the same flow field, and they found that the blowing ratio of 0.95 was a special condition at which the vortex shedding from the ejection lip was the strongest and the highest deterioration of the film cooling effectiveness occurred at this blowing ratio [7].

The most unique feature in the trailing-edge cooling problem is that the overall cooling performance is a combination of thermal shield and convective cooling. The ejected cooling film does not only act as an insulating layer to prevent hot gas from impinging onto the wall, but also serves as a convective heat sink for the heat load to the suction surface (bottom surface in Fig. 1). To maximize the cooling performance in the trailing-edge region, most works in the past focused on improving the performance of the coolant film as an insulating layer, as summarized above.

The authors' group proposed the heat transfer enhancement of the cutback surface by roughening the cutback surface itself. We have been working on this problem by performing heat transfer experiments using a transient technique [8–11], particle tracking velocimetry measurements [12,13], and LES [14]. From these previous results, we have confirmed that the concave dimples enhanced the convective heat transfer without deteriorating the thermal shield (film cooling effectiveness). As for the shape of dimples, teardrop-shaped dimples gave higher performance, and the inclination of the teardrop-shaped dimples further enhanced the convective heat transfer without lowering the film cooling effectiveness. When the rotation angle of the teardrop-shaped dimpled surface was changed from 0 to 75 deg with maintaining high number density of dimples, the angle of 30 deg gave the highest Net Heat Flux Reduction (NHFR) at which the dimples were aligned in in-line arrangement in the streamwise direction [11]. In our previous study [11], however, the effects of the dimple rotation angle and the dimple arrangement (in-line/staggered) could not separately be discussed because the dimpled surface as a whole was rotated maintaining the dimple arrangement.

In this study, in order to examine the effects of the teardrop-shaped dimple arrangement in addition to the dimple rotation angle on the film cooling performance, three different rotation angles of the dimpled surface were examined (30, 45, and 60 deg) with changing the dimple arrangement between in-line and staggered arrangements. Heat transfer coefficient and film cooling effectiveness on pressure-side cutback surface were measured by a transient infrared thermography technique with consideration of three-dimensional heat conduction in wall. The heat transfer experiments were conducted in a low-speed wind tunnel facility by changing the cooling-flow blowing ratio. Furthermore, in order to examine the reason of the heat transfer results, three-component particle tracking velocimetry (PTV) measurements were performed at multiple lateral locations.

2. Experiments

2.1. Heat transfer experiments

The procedure of the heat transfer experiment is the same as that of Yano et al. [11]. Schematic of experimental apparatus is shown in Fig. 2. Air was sucked by a blower installed at downstream and main flow was driven by the blower. As for cooling flow, another blower installed upstream of cooling-flow passage

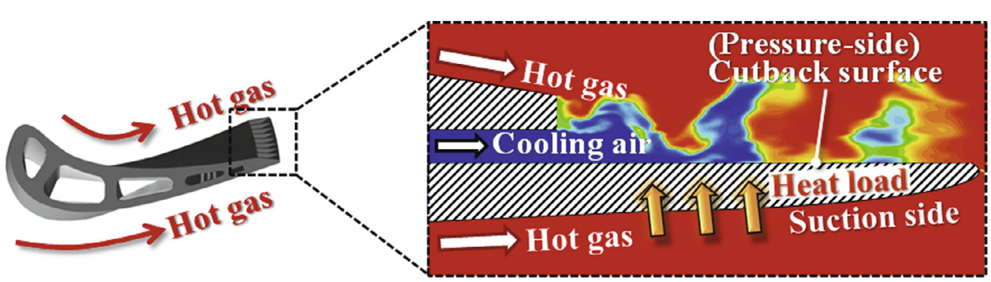

Fig. 1. Schematic of film cooling at trailing edge of aero-engine/gas-turbine airfoil.