International Journal of Heat and Mass Transfer 52 (2009) 5922–5931

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Effects of incidence angle on endwall convective transport within a high-turning turbine rotor passage

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ARTICLE INFO

Article history:
Received 8 August 2008
Received in revised form 7 January 2009
Accepted 1 July 2009
Available online 11 September 2009

Keywords:
Gas turbine
Off-design condition
Turbine rotor cascade
Incidence angle
Endwall heat transfer

ABSTRACT

Effects of incidence angle on the endwall convective transport within a high-turning turbine rotor passage have been investigated. Surface flow visualizations and heat/mass transfer measurements at off-design conditions are carried out at a fixed inlet Reynolds number of 2.78×10^5 for the incidence angles of $-10°$, $-5°$, 0, 5°, and 10°. The result shows that the incidence angle has considerable influences on the endwall local transport phenomena and on the behaviors of various endwall vortices. In the negative incidence case, convective transport is less influenced by the leading edge horseshoe vortex and by the suction-side corner vortex along their loci but is increased along the pressure-side corner vortex. In the case of positive incidence, however, convective transport is augmented remarkably along the leading edge horseshoe vortex, and is much influenced by the suction-side corner vortex. Moreover, heat/mass transfer is enhanced significantly along the pressure-side leading edge corner vortex. Local endwall convective transport in the area other than the endwall vortex sites is influenced significantly by the cascade inlet-to-exit velocity ratio which depends strongly on the incidence angle.

1. Introduction

For the advances in gas turbine performance, turbine durability due to hot gas temperature should be enhanced. Higher turbine inlet temperature generally causes increased metal temperature and steeper temperature gradients in the turbine hot components. Recent combustor design, which aims for reduced emissions, provides higher gas temperature near the turbine endwall with a flattened temperature distribution [1]. The turbine endwall thus needs a sophisticated cooling scheme as found in turbine blade cooling. For an efficient cooling configuration for the turbine endwall, it is essential to have a detailed description of heat transfer coefficient.

One of the earliest studies on the endwall heat transfer is presented by Blair [2], who conducted experiments to determine the film cooling effectiveness and heat transfer coefficient on a simulated turbine vane endwall with a cooling slot injection. Graziani et al. [3] measured local Stanton numbers on an electrically heated turbine endwall and blade surface for two different inlet boundary layer thicknesses. They found that the endwall heat transfer is affected strongly by the passage vortex, and the inlet boundary layer thickness on the endwall has a significant effect on the endwall and suction surface heat transfer. According to Gaugler and Russell [4], there is an obvious correlation between the visualized secondary flow and measured endwall Stanton number distribution near a vane cascade entrance, but the effects of the secondary flow are not obvious in the passage. York et al. [5] measured local Stanton numbers on a vane endwall with thermocouples for different Mach and Reynolds numbers. Employing the naphthalene sublimation technique, Goldstein and Spores [6] provided much detailed distributions of local endwall transport coefficient for a turbine rotor cascade. At a low turbulence level of about 1.2%, they investigated the effects of Reynolds number and inlet boundary layer thickness. Giel et al. [7] measured local endwall heat transfer coefficients for a transonic rotor cascade using a steady-state liquid crystal technique at low and elevated turbulence intensities of 0.25 and 7.0%. Kang et al. [8] and Kang and Thole [9] showed through endwall heat transfer measurements for a first-stage vane cascade that the peak heat transfer coefficient occurs coincidentally at the downward legs of both the horseshoe vortex and passage vortex. Radomsky and Thole [10] measured the endwall heat transfer under a combustor-level high turbulence intensity of 19.5% for the same vane cascade as Kang et al. [8] used. Their results show that the high turbulence enhances the endwall heat transfer, but the augmentation is either small or nonexistent in the leading edge region and near the suction-side of the blade. Lee et al. [11] studied effects of combustor-level high inlet turbulence on the endwall flow and heat transfer of a high-turning turbine rotor cascade. They successfully explained the endwall transport phenomena with flow visualization and heat/mass transfer data.

Gas turbines are sometimes at off-design conditions during their operation. At these off-design conditions, in general, incidence angle, *i*, may not be zero deg. Langston et al. [12] presented

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doi:10.1016/j.ijheatmasstransfer.2009.07.015

Nomenclature

b	axial chord length
c	chord length
c_p	constant-pressure specific heat
d	width of flow passage
D	diffusion coefficient of naphthalene in air
h	local heat transfer coefficient
h_m	local mass transfer coefficient
i	incidence angle ($\equiv (\beta_1 - \beta_1^0)$)
k	thermal conductivity
m	mass flow rate through a turbine
N	number of revolution of turbine rotor
p	pitch
P	pressure
Pr	Prandtl number ($\equiv(\mu c_p)/k$)
r	radial distance from turbine axis
Re_1	inlet Reynolds number ($\equiv(\rho W_{1\infty} c)/\mu$)
Re_2	exit Reynolds number ($\equiv(\rho W_{2\infty} c)/\mu$)
s	span
Sc	Schmidt number ($\equiv\mu/(\rho D)$)
St	local heat transfer Stanton number ($\equiv h/(\rho c_p W)$)
St_m	local mass transfer Stanton number ($\equiv h_m/W$)
St_{m1}	local mass transfer Stanton number based on $W_{1\infty}$ ($\equiv h_m/W_{1\infty}$)
St_{m2}	local mass transfer Stanton number based on $W_{2\infty}$ ($\equiv h_m/W_{1\infty}$)
T	temperature
Tu	turbulence intensity
U	rotational speed of turbine rotor blade ($\equiv r\omega$)
V	absolute velocity
V_a	axial velocity component of V
w	pitch-wise distance between the pressure and suction surfaces
W	relative velocity
$W_{1\infty}$	inlet free-stream relative velocity at the mid-span
$W_{2\infty}$	exit relative velocity at the mid-span ($\equiv(d_1/d_2)W_{1\infty}$)
x, y, z	cascade coordinates
y_p	pitch-wise (y-directional) coordinate from the suction surface

Greek symbols

α	angle of absolute velocity vector
β	angle of relative velocity vector
μ	absolute viscosity of air
ρ	density of air
ω	angular velocity ($\equiv 2\pi N$)

Subscripts

av	averaged over the whole measurement area
av,pch	averaged in the pitch-wise direction
0	total
1	turbine rotor blade inlet
2	turbine rotor blade exit
3	turbine inlet
4	turbine exit

Superscripts

0	zero incidence or design point
+	positive incidence
−	negative incidence

ink-trace flow visualizations on the endwall of a turbine cascade for two incidences of zero and +11.8°. They showed that the saddle point on the inlet endwall moves to the suction-side as the incidence angle increases. Hodson and Dominy [13] investigated internal flow mechanisms of a high-speed linear cascade under various off-design conditions and found that low-momentum endwall fluid migrates more intensely onto the blade suction surface as the incidence angle increases. Yamamoto [14] studied interaction mechanisms between the tip-leakage flow and the passage vortex in a linear turbine cascade with tip clearance gap at off-design conditions. Yamamoto and Nouse [15] investigated the effects of incidence on cascade three-dimensional flows near the endwall of a turbine rotor cascade and the associated loss mechanisms. Yamamoto [16] measured three-dimensional flow and loss data within a linear turbine cascade passage with tip clearance, and also reported the detailed three-dimensional flows within the tip clearance gap and interactions of the tip-leakage flow with the main passage flow. Jouini et al. [17] presented detailed measurements of the mid-span aerodynamic performance of a transonic turbine cascade at off-design conditions. Profile losses were reported for incidence angles of −10°, 0°, 4.5°, 10°, and 14.5°. Brear et al. [18] investigated pressure surface separations at the mid-span of a low-pressure turbine cascade for three incidence angles of −10°, 0°, and 10°. Recently, Rhee and Cho [19,20] reported heat/mass transfer characteristics not only on a near-tip surface [19] but also tip surface and shroud [20] in a low-speed annular cascade for the incidence angles of −15° to 7°.

The previous studies on the turbine endwall heat transfer were conducted only at their design points, and the above-mentioned investigations at off-design conditions were mainly focused on flow phenomena and aerodynamic loss generations, except for the heat/mass transfer measurements on the near-tip blade surface and tip/shroud surface by Rhee and Cho [19,20]. As far as the authors know, there seem to be no heat transfer data on the endwall reported at off-design conditions. In this study, incidence angle effects on the endwall convective transport within a high-turning turbine rotor blade passage have been investigated by using the naphthalene sublimation technique.

2. Velocity triangles at off-design conditions

A turbine is operated at the design point, when it is running at the particular blade rotational speed, pressure ratio, and mass flow rate for which it is designed. However, any turbine is required to operate at conditions far removed from the design point including engine starting, idling, reduced power, increased power, acceleration, and deceleration. Thus it is clear that turbines must be capable of satisfactory operation at off-design conditions over a wide operation range.

Fig. 1 shows typical off-design turbine mass flow characteristics from Cohen et al. [21]. $mT_{03}^{0.5}/P_{03}$ relative to the design point value is plotted against pressure ratio P_{03}/P_{04} with the variation of $N/T_{03}^{0.5}$ relative to the design point value. m and N indicate mass flow rate through the turbine and number of revolution in turn. T_{03} is total temperature at the turbine inlet, and P_{03} and P_{04} are total pressures at the turbine inlet and exit, respectively. At a pressure ratio which produces choking conditions at the turbine nozzle throats, $mT_{03}^{0.5}/P_{03}$ relative to the design point value reaches a maximum value of about unity and the constant $N/T_{03}^{0.5}$ lines merge into a single