International Communications in Heat and Mass Transfer 78 (2016) 101–111

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Heat transfer measurement near endwall region of first stage gas turbine nozzle having platform misalignment at combustor-turbine interface☆

Heeyoon Chung [a], Chang Woo Hong [a], Seon Ho Kim [a], Hyung Hee Cho [a,*], Hee Koo Moon [b]

[a] Yonsei University, 50, Yonsei-ro, Seodaemun-gu, Seoul 120-749, Republic of Korea
[b] Solar Turbines Inc., 2200 Pacific highway, San Diego, CA 92101, USA

ARTICLE INFO

Available online 09 September 2016

Keywords:
Gas turbine
Nozzle guide vane
Endwall
Heat transfer
Misalignment

ABSTRACT

The effect of a misalignment between vane endwall and combustor exit in a gas turbine was investigated using a Computational Fluid Dynamics (CFD) simulation and experimental measurements. The misaligned endwall platform was simulated as a backward facing step in this study. The CFD simulation predicted two legs of the vortex, referred to as a step-induced vortex, created by the step flowing through nozzle passage. Heat transfer measurements demonstrated the effect of the step-induced vortex on the endwall and the vane surface indicated by locally increased heat transfer coefficients which corresponded to the locus of the vortex, as also predicted by the simulation. Although a boundary layer transition occurred early, the locally increased heat transfer persisted to the vane trailing edge. In summary, a misaligned endwall platform causes negative effects on the gas turbine with respect to the thermal design. A vortex was generated by the step, which caused a higher thermal load on the nozzle vane surfaces, especially near the endwall.

1. Introduction

Thermal efficiency and power output of a gas turbine is directly related to the turbine inlet temperature. To achieve a high performance, the combustor outlet temperature (COT) to the first-stage nozzle has been raised up to 1400 °C in some modern gas turbine engines, which far exceeds the melting temperature of turbine materials. Therefore, cooling has become an essential element in gas turbine development that a considerable number of investigations so far have been performed for cooling enhancement, such as rib-turbulator [1,2], jet impingement [3,4] and film cooling [5,6]. Even though the turbine parts are cooled to keep their temperatures sufficiently below their melting point, their service life is still limited from a thermally induced mechanical load by elevated hot gas temperature. Thus, the heat transfer investigations in turbine passages are of great importance to gas turbine engine development.

The first stage nozzle vane is exposed to the highest temperature environment among the turbine parts. The combustion gas coming from the combustor gives rise to severe thermal loads that often cause serious failures on the nozzle vane. Thus, evaluation of heat transfer for the nozzle has always been challenging. Especially, the complex flow field near the nozzle endwall with accompanying secondary flows, such as horseshoe vortex and passage vortex, makes it harder to predict heat transfer for the nozzles. The behaviors of the secondary vortices and its effect near the turbine nozzle endwall were described by Goldstein et al. [7]. Regarding the fluid flow and heat transfer issues associated the vortices are summarized by Langston [8], Chyu [9] and Simon and Piggush [10]. Generally, it is known that secondary vortices in the turbine passage cause aerodynamic losses and excessive thermal loads to the components, therefore, many studies have been performed on the issues (Blair [11], Goldstein and Spore [12] and Takeishi et al. [13]). The secondary vortices originated from the shroud side endwall also influence blade tip region as well (Chyu et al. [14], Cho and Rhee [15]).

To suppress initiation of secondary vortices, modern gas turbines often have a contoured endwall with a smooth transition between the combustor exit and the nozzle entry. Dossena et al. [16] reported that the contoured endwall produced substantially lower loss levels than the planar endwall. In addition, Thrift et al. [17] reported the contoured endwall enhances coolant coverage from the upstream leakage flow and reduces ingestion of hot mainstream flow in the leakage slot. However, it is often inevitable to have some misalignment between the combustor and the turbine nozzle endwall interface because the components experience thermal displacement, simply due to the accumulation of assembly tolerances. Modern industrial gas turbine engines equipped with a low NOx (pre-mixed) combustor have additional thermal load to the nozzle endwall due to its relatively flat gas temperature profile. As a result, accounting for the heat transfer and flow characteristics induced by such misalignments has become more important issue.

☆ Communicated by W.J. Minkowycz.
* Corresponding author.
E-mail address: hhcho@yonsei.ac.kr (H.H. Cho).

http://dx.doi.org/10.1016/j.icheatmasstransfer.2016.08.022
0735-1933/

Nomenclature

C	*true chord length of vane* (=300) [mm]
C_p	*static pressure coefficient* ($=\frac{p-p_0}{0.5\rho V^2}$)
C_x	*axial chord length of vane* (=182.5) [mm]
D_{naph}	*mass diffusion coefficient of naphthalene vapor in air* [m^2/s]
H	*height of nozzle inlet* (=250) [mm]
h	*heat transfer coefficient* [W/m^2K]
h_m	*mass transfer coefficient* [m/s]
k	*thermal conductivity* [W/mK]
$\dot{m}$	*local naphthalene mass transfer rate per unit area* [kg/m^2s]
Nu	*Nusselt number* ($=hC/k$)
Pr	*Prandtl number* ($=\mu C_p/k$)
P	*vane pitch* (=260) [mm]
Re	*Reynolds number based on chord length and inlet velocity* ($=CV/\nu$)
Sc	*Schmidt number* ($=\nu/D_{naph}$)
Sh	*Sherwood number* ($=h_mC/D_{naph}$)
Tu	*turbulence intensity at cascade inlet*
V	*mean velocity at cascade inlet*
s	*distance from leading edge on vane surface* [mm]
x	*coordinate in axial direction* [mm]
y	*coordinate in pitch-wise direction* [mm]
z	*coordinate in vertical direction* [mm]

Greek symbols

ν	*kinematic viscosity* ($=\mu/\rho$) [m^2/s]
μ	*dynamic viscosity* [kg/m s]
ρ	*fluid density* [kg/m^3]
ρ_s	*density of solid naphthalene* [kg/m^3]
$\rho_{v,w}$	*naphthalene vapor density on the surface* [kg/m^3]
$\rho_{v,\infty}$	*naphthalene vapor density at approaching flow* [kg/m^3]

The misalignments between the combustor and turbine interface were identified as a backward-facing and a forward-facing step. Several studies have aimed to analyze the characteristics of the fluid flow affected by misalignments. The first work on the misalignment effect on the enwall flow is reported by de la Rosa Blanco et al. [18]. They captured the flow motion and pressure losses under the misaligned conditions. The step gives rise to higher losses by the presence of three dimensional bubble behind the step which produces stronger passage vortex. Successive work has been published by the authors considering leakage flow from a gap between combustor and nozzle interface [19]. In the work of Piggush and Simon [20], that the forward facing step increases heat transfer rate on the endwall by thinning the boundary layer and the backward facing step shows opposite effect. The measurement of cooling coverage by the leakage flow with backward facing slot was reported by Colban et al. [21]. The difference in total pressure between upstream and downstream of the backward-facing step caused ingestion into the slot that ultimately reduces the cooling effectiveness. Cardwell et al. [22] reported that the effectiveness of leakage flow was improved with the backward facing step compared to the forward facing step configurations. However, Zhang and Moon [23] demonstrated that the rows film cooling holes on the downstream of the step showed inferior cooling effectiveness due to the separation bubble behind the step. Overall, the upstream step by platform misalignment induces a flow separation near the endwall boundary layer. As a result, heat transfer on the endwall was augmented by the reattached flow and the cooling coverage from a leakage flow was deteriorated by a flow separation. The situations were similar between the stator vane and rotor blade endwall platforms. Previous studies indicate that the upstream platform configuration has significant effect on fluid flow and heat transfer on the turbine endwall region. Most of them had focused their investigations on only the endwall surface. Though the step-induced flow influences heat transfer on the vane airfoil surfaces as well as the endwall surface (Chen and Goldstein [24]), there are no reported studies regarding heat transfer on the airfoil surface near the endwall under such conditions.

In this study, fluid flow and heat transfer characteristic near the endwall region including the vane airfoil and the endwall surfaces was investigated. Mass transfer technique (naphthalene sublimation method) was utilized to derive detailed heat transfer coefficient on the endwall surface. Flow field measurements and numerical simulations were also performed to understand the results of heat transfer measurement.

2. Problem definition

A misaligned transition between the combustor exit and the nozzle platform results in a backward-facing step at the nozzle entrance. When the gas flows over the backward-facing step, the boundary layer is broken down as the flow separates from the surface and its reconstruction is initiated from the reattachment point. Such undesired phenomena during engine operation may cause a loss in efficiency and heat transfer problems on the nozzle platform. In particular, special attention is required in terms of the heat transfer in the endwall region because the complicated flow makes it harder to predict. This study mainly concerns the heat transfer characteristics on the near endwall of the nozzle vane airfoil under such undesirable design conditions.

To investigate the effects of such discontinuous endwall geometry on heat transfer near the endwall region, three types of inlet configurations were suggested, as presented in Fig. 1: (1) a flat inlet, and (2) a step inlet and large step inlet configurations. The flat inlet is the baseline case for comparison with the other two configurations. The step inlet case has a groove at the endwall of the entrance region, which is shaped like a right-angled triangle. The combustor side endwall and turbine nozzle side endwall have the same height. The large step inlet case has the same groove as the step inlet case, while the combustor side endwall is elevated as much as the groove depth. Consequently, the total step height of the large step inlet case is twice as high as the step inlet case, and is intended to demonstrate a severely misaligned condition. The step is located one-third of the chord length upstream of the vane leading edge. The elevation of the combustor side endwall and the depth of the groove are both one-tenth of the height of the nozzle inlet. Assuming that the influence of the backward-facing step at the nozzle entrance is limited to near the endwall region, the investigation focused on this area, including the pressure and suction side surfaces of the nozzle vane airfoil. The region of interest is indicated in the figure.

3. Experimental setup and data reduction

3.1. Nozzle cascade test section

A schematic of the test section configuration is presented in Fig. 2. There are one full passage and two half passages with two vane airfoils in the test section. Though a larger number of airfoils would give a closer approximation to the ideal condition in a linear cascade experiment, the airfoil number must be limited by the experimental requirements and the feasible dimensions of the facilities. In this experiment, two vane airfoils were utilized to maximize chord length for higher Reynolds numbers. The profiles of the side walls of the test section were determined based on the flow streamline resulting from the Computational Fluid Dynamics (CFD) simulation to satisfy the flow similarity as much as possible. The heat transfer was measured on the full passage located at the center of the test section.

Details of CAD drawings of the test section are presented in the figure. Test section was manufactured using polycarbonate 15 mm thick. Every joint has a rubber seal to prevent pressure leakage. The endwall and vane airfoil specimens for the naphthalene casting were manufactured using