International Communications in Heat and Mass Transfer 97 (2018) 125–135

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Effects of unsteady wakes on heat transfer of blade tip and shroud

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ARTICLE INFO

Keywords:
Gas turbine
Heat transfer
Unsteady wake
Blade tip
Shroud

ABSTRACT

An experimental study has been conducted to investigate the heat-transfer characteristics of blade tips and shrouds with and without unsteady wakes. Depending on the presence of unsteady wakes, the local heat/mass-transfer coefficients of the tip and shroud were measured using the naphthalene sublimation method. Wakes from unsteady blades were modeled as wakes generated from moving cylindrical rod bundles. Test conditions were set to a Reynolds number of 100,000, based on an inlet velocity of 11.4 m/s and the axial chord length. The Strouhal number was varied from 0 to 0.22. For the case without unsteady wakes ($St = 0$), high heat/mass-transfer coefficients appeared in regions where various flow patterns, such as flow reattachment, swirling flow, and vortices, occurred. Unsteady wakes ($St = 0.22$) made high turbulence intensity of the tip leakage flow, and flow patterns ranging from flow reattachment to tip leakage vortex in the tip and shroud were changed and dispersed in the presence of unsteady wakes, thus changing the heat/mass-transfer distributions in these areas. Due to the high thermal load on the tip and shroud under unsteady wake conditions, more detailed cooling designs must be considered, ranging from film cooling holes to the installation of additional structures on the blade tip, especially in the leading edge region and mid-region I of the tip, and the mid-region I and trailing edge region of the shroud.

1. Introduction

Because the efficiency and power output of gas turbines are proportional to the turbine inlet temperature, operating temperatures in gas turbines have increased continuously. However, due to these high-temperature conditions, the thermal loads on gas turbine blades have also increased, and thermal damage to turbine blades occurs frequently, especially to the blade tip and shroud. The main cause of damage to the blade tip and shroud is the tip-leakage flow that passes via the tip clearance from the pressure side to the suction side of the turbine blade. It is difficult to apply cooling techniques such as film cooling or impingement jets to the blade tip and shroud effectively, because of their confined spaces and complex flow patterns, which result from tip-leakage flow, flow reattachment, and swirling flow. Thus, it is important to gain a deep and detailed understanding of the heat-transfer characteristics of the blade tip and shroud to apply appropriate cooling techniques to these components.

Many investigations of the heat-transfer characteristics of the blade tip and shroud have been reported, considering various design parameters ranging from tip clearance to tip geometries, to determine the detailed heat-transfer characteristics. Bunker et al. [1] and Sunden et al. [2] reviewed studies of gas-turbine blade-tip heat transfer and cooling techniques and provided design guidelines for blade tips considering various design parameters, such as tip clearance, rim height, and cooling techniques. Mayle and Metzger [3] investigated the heat-transfer characteristics of a rectangular cavity-shaped blade tip, considering the relative motion between the blade and the stationary shroud. They reported that the relative motion between the tip and shroud had a weak influence on overall heat transfer from the blade tip. Chyu et al. [4, 5] and Metzger et al. [6] studied the heat transfer fundamentals in the tip region of a rectangular cavity-shaped blade. Using tip cavity geometry, they observed that the cavity geometry was a dominant factor in the local heat/mass transfer distribution. Cho et al. [7] measured local heat/mass-transfer characteristics experimentally using a stationary shroud while varying the tip clearance. They observed that as tip clearance increased, the local heat/mass-transfer characteristics of the shroud changed significantly. Jin and Goldstein [8, 9] measured local heat/mass transfer experimentally on the flat tip of a blade in a linear cascade, while changing the tip clearance (0.86–0.9% of the chord), Reynolds number (400,000–700,000), and turbulence intensity of the main stream (0.2% and 12%).

Moreover, many studies have addressed not only the heat-transfer characteristics of flat tips but also those of squealer tips to reduce stage aerodynamic loss and thermal load at the tip. Azad et al. [10]

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https://doi.org/10.1016/j.icheatmasstransfer.2018.07.005

Nomenclature

C	Chord length $[m]$
C_x	Axial chord length $[m]$
C_p	Static pressure coefficient
D_{naph}	Mass diffusion coefficient of naphthalene vapor in air
t_{rim}	Rim height $[m]$
h_m	Local mass transfer coefficient
Nu	Nusselt number ($Nu = hC_x/k_c$)
$\dot{m}$	Naphthalene mass flux per unit area $[kg/\ m^2 s]$
P	Pitch $[m]$
P_∞	Mainstream static pressure at cascade inlet
Pr	Prandtl number
Sc	Schmidt number
R	Ideal gas constant $[J/kg \cdot K]$
Re	Reynolds number ($Re = U_\infty C_x/\nu$)
St	Strouhal number ($St = 2\pi fd/U$)
S	Span [m]
Sh	Sherwood number ($Sh = h_m C_x/\ D_{naph}$)
$\overline{Sh}$	Pitch-wise averaged Sherwood number
T_∞	Mainstream temperature $[K]$
T_w	Naphthalene surface temperature $[K]$
U	Mainstream velocity of cascade inlet $[m/s]$
d	Rod diameter $[m]$
f	Rod passing frequency
t	Tip clearance $[m]$
$\delta\tau$	Runtime $[s]$
δz	Sublimation depth of naphthalene surface $[m]$
ρ	Density of air
ρ_s	Density of solid naphthalene $[kg/m^3]$
$\rho_{v,\ w}$	Vapor density of naphthalene on the surface $[kg/m^3]$
$\rho_{v,\ \infty}$	Vapor density of naphthalene in the mainstream $[kg/m^3]$
α_1	Blade inlet angle [°]
α_2	Blade outlet angle [°]

investigated the heat-transfer characteristics at the tip and shroud using various squealer tip geometries. They measured the heat-transfer coefficients of the blade tip surface using transient liquid crystal techniques, and used various squealer tip geometries, including both single and double squealer tips, to show that among the six geometries tested, a single squealer along the midchord of the blade produced the lowest heat transfer on the blade tip surface. Kang et al. [11] and Seo et al. [12] investigated heat/mass transfer characteristics on the plane tip equipped with a full coverage winglet in a turbine cascade. They reported that the tip surface with a full coverage winglet is exposed to a much less severe thermal load than a plane tip surface with no winglet. However, a protruding full coverage winglet experiences a more severe thermal load than that of a plane tip surface with no winglet. Lee et al. [13] and Seo et al. [14] focused on heat/mass transfer characteristics on a squealer tip equipped with a full coverage winglet in a turbine cascade. They concluded that for the cavity squealer tip with a full coverage winglet, the average heat/mass transfer rate of the cavity floor is lower than that on the winglet top surface, regardless of tip clearance. Kwak and Han [15] measured heat-transfer coefficients experimentally on a squealer tip and in nearby tip regions using a transient liquid crystal technique. They showed that the heat-transfer coefficients of the squealer tip were higher than those of nearby tip regions, such as the pressure side, suction side, and shroud, due to the complex flow patterns at the squealer tip. Park et al. [16] focused on the heat-transfer coefficients and film cooling effectiveness at the tip and inner rim, using a squealer rim. They reported that both side rims had higher heat-transfer coefficients than the tip surface and suggested appropriate cooling systems with film-cooling holes that could reduce thermal loads on a squealer tip.

To model actual operating conditions, it is essential to consider the various flow conditions of the cascade, such as rotation conditions, vane/blade relative positions, and unsteady wakes. Rhee and Cho [17, 18] investigated the heat/mass-transfer characteristics in regions near the tip and shroud using rotating blades equipped with flat tips in an annular cascade. They measured the heat/mass-transfer coefficients in regions near the tip and shroud, changing the rotational speed of the blade from 154.5 to 384 rpm, and reported that the heat/mass-transfer characteristics changed with the incidence angle of the incoming flow. Rhee and Cho [19, 20] investigated the effects of the relative positions of the vane/blade on the heat-transfer characteristics of the tip, shroud, and blade surface. They concluded that heat/mass-transfer characteristics changed significantly due to a blockage effect resulting from the relative positions of the vane/blade. Han et al. [21] measured heat-transfer coefficients on blade surfaces experimentally, considering unsteady wakes. They observed variation in the heat-transfer characteristics of the blade surface depending on the Strouhal number, which considers the rotating rod speed, rod number, rod diameter, and mainstream velocity. Park et al. [22, 23] and Choi et al. [24] investigated the heat/mass-transfer characteristics of endwall and blade surfaces in the presence of an unsteady wake. They reported that the overall heat transfer of the end wall surface and pressure side of the blade increased as the Strouhal number increased; weakening of the passage vortex occurred due to unsteady wakes. Liu et al. [25, 26] measured velocity, surface pressure, and heat transfer in a linear

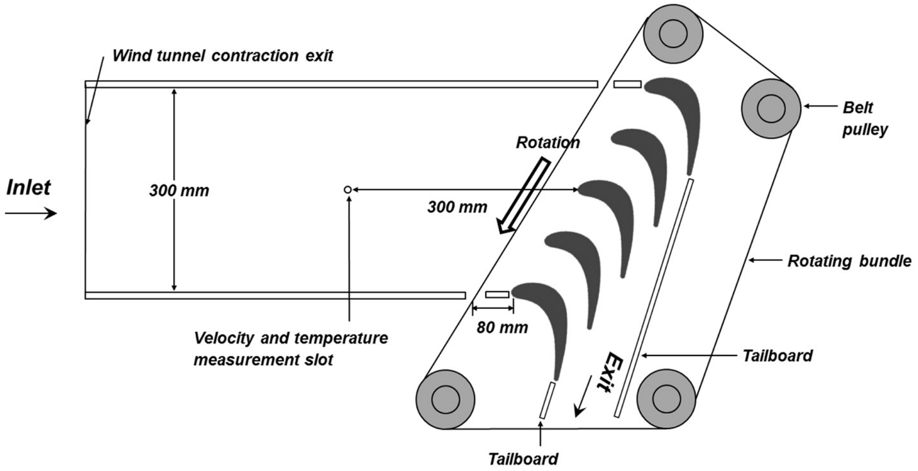

Fig. 1. Schematic view of experimental apparatus.