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Effect of the wake on the heat transfer of a turbine blade endwall according to relative position of the cylindrical rod

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A R T I C L E I N F O

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A B S T R A C T

In a turbine passage, the wake, which affects the heat transfer of a turbine blade, occurs periodically due to rotation of the blade. We analyzed the effect of wake on the endwall of the turbine blade according to the relative position of the turbine blade and the vane in a stationary condition. The naphthalene sublimation method was used to measure the heat transfer and detached eddy simulation (DES) was used to analyze flow characteristics. The wake from the vane was simulated by using a cylindrical rod upstream of the blade. The cylindrical rod was placed in four which positions that were aligned leading edge-to-leading edge. The pressure and Q criterion distributions varied according to the position of the upstream wake. As the position of the upstream wake changed, the point at which the passage vortex and wake met varied. Wake and passage vortex met at $x/C_x = 0.2$ in position 1 and at $x/C_x = 0.55$ in position 2. After the wake and passage vortex had met, the secondary flow scattered. Therefore, the local and averaged heat transfer varied due to flow characteristics. Thus designers of film cooling holes on endwalls should consider these effects to ensure appropriate cooling performance.

1. Introduction

Turbine inlet temperature has increased with the improved efficiency and power of gas turbines. Furthermore, the dry lean premixed combustion method is now widely used for reducing NOx emission. Thus, the endwalls of turbine blades are now exposed to higher thermal loads. For this reason, the heat transfer characteristics of the endwall surface of a gas turbine blade have received attention from gas turbine heat transfer researchers.

Lagnston, L. S. [1–3], Wang, H. P. [4] and Radomsky [5] et al. analyzed the flow characteristics in a turbine passage. They observed that secondary vortices, such as horseshoe, passage and corner vortices, are induced in a turbine passage. Furthermore, Graziani, R. A. [6], Goldstein, R. J. [7], Kang, M. [8], Dunn [9], Simon, T. W., [10], and Povey, T. [11] et al. analyzed not only the flow characteristics, but also the heat transfer distribution, of the endwall. They reported that an induced horseshoe vortex increased heat transfer at the leading edge. Additionally, a passage vortex caused a locally non-uniform heat transfer distribution on the endwall. Chyu, M. K. [12] reviewed these articles to understand those the effects of these phenomena on the endwall.

The information cited above is helpful for turbine cooling designers who are designing film cooling holes for the endwall of a turbine blade. Many different types of film cooling holes have been adopted for use in endwalls and blade. Goldstein, R. J. [13], Takeishi, K. [14], Friedrichs, S. [15,16], Nicklas, M. [17], Acharya, S. [18] and Li, X. [19] et al. conducted experiments on the effects of film cooling holes on the endwall. They explored flow characteristics near the endwall with film cooling holes at various locations. They also analyzed the heat transfer and film cooling effectiveness of endwalls with film cooling holes. Thole. K.A. [20], Cardwell, N.D. [21], Hada, S. [22] and Chowdhury, N.H. [23] et al. focused on the effect of the mid-passage gap on the endwall and found that this gap significantly affected the cooling of the endwall. Therefore, misalignment is a critical issue in endwall design. Charbonnier, D. [24], Du, K. [25,26] and Zhu, P. [27] et al. analyzed the effect of purge flow occurring in front of a turbine blade: purge flow significantly affected secondary flow in the turbine passage. Inlet boundary conditions should be considered with respect to the effect of purge flow. Colban et al. [28] conducted experiments on the effect of a fan-shaped hole in the endwall. They found that jet lift-off from the pressure side was reduced, in turn increasing the film cooling effectiveness. Yao, Y. et al. [29] studied the converging film cooling holes by numerical simulation. They concluded that console shape suppressed the penetration to the main flow. Sundaram, N. and Thole, K. A. [30]

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Nomenclature

C	blade chord length (m)
C_p	pressure coefficient
C_x	blade axial chord length (m)
d	rod diameter (m)
D_{naph}	mass diffusion coefficient of naphthalene vapor in air ($m^2 s^{-1}$)
f	frequency of turbine blade (s^{-1})
f_d	period of wake from cylindrical rod (s^{-1})
h_m	mass transfer coefficient ($m s^{-1}$)
$\dot{m}$	local naphthalene mass transfer rate per unit area ($kg m^{-2} s^{-1}$)
Nu	Nusselt number
P	pitch of the blade
Pr	Prandtl number
p_t	Total pressure at inlet ($kg m^{-1} s^{-2}$)
p_i	Local static pressure ($kg m^{-1} s^{-2}$)
Q	Q-criterion $\left(Q = \frac{1}{2}(\|\Omega_{ij}\|^2 - \|S_{ij}\|^2)\right)$
Re	Reynolds number
Sc	Schmidt number
Sh	Sherwood number
St	Strouhal number
S_{ij}	strain tensor
U	inlet flow velocity ($m s^{-1}$)
V_x	axial velocity ($m s^{-1}$)

Greek symbols

δt	run time (s)
δz	sublimation depth of naphthalene surface (m)
ρ_s	density of solid naphthalene on the surface ($kg m^{-3}$)
$\rho_{v,\ w}$	vapor density of naphthalene on the surface ($kg m^{-3}$)
$\rho_{v,\ \infty}$	vapor density of naphthalene in the mainstream ($kg m^{-3}$)
φ	flow coefficient
$\Delta z/\Delta t$	naphthalene sublimation rate ($m s^{-1}$)
Δt	time step
Δx	streamwise direction grid size
Ω_{ij}	rotation tensor

explored the effect of bump and trench modifications on film cooling holes in the endwall. They concluded that arranging trenches and bumps in a row increased film cooling effectiveness at the endwall. Chung, H. et al. [31] measured the heat transfer of vane and endwall with misaligned combustor-turbine interface. They found out that vortex generated by step caused higher thermal load on vane near the endwall. Jiang, Y. et al. [32] investigated the effect of coolant chamber configurations with swirling film cooling. They found out that swirling coolant has higher film cooling effectiveness in blowing ration $M = 1.0$ and 1.5. Yusop, N. M. et al. [33] conducted conjugate analysis with film cooling of new multi-layer convex surface. They concluded that array of compound hole on convex surface were helpful for turbine cooling. Yu, Z. L. et al. [34] compared the various film cooling hole angles in double chamber model. They found out that enhancing hole inclination and injection orientation is helpful for turbine cooling.

According to the experimental and numerical research, film cooling holes should be positioned accurately on the endwall. However, a wake effect is induced in the turbine passage by the stator and the rotor. This wake effect also changes the flow conditions in the turbine passage, contributing to heat transfer at the endwall. Suzen, Y.B. [35], Lei, Q. [36], Ibrahim, M.B. [37] and Lin, D. [38] et al. analyzed the effect of upstream wake in the turbine passage. They showed that flow conditions changed periodically due to the rotation of the turbine rotors. Thus, they then analyzed the loss mechanisms in turbine passage due to upstream wake. Hwang, S. et al. [39] measured conjugate heat transfer under upstream wake conditions. They found that the thermal load on the turbine blade changed periodically due to the rotation of the blade. Park, J. S. [40] and Choi, S. M. [41] et al. measured heat transfer distribution on the endwall with an upstream wake, showing that the upstream wake produces a uniform heat transfer distribution on the endwall. Nikparto, A. et al. [42] investigated the film cooling effectiveness of blades in the presence of a wake effect. They concluded that unstable wake changes the flow conditions on the pressure and suction sides. Guo, L. et al. [43] conducted a numerical simulation of the heat transfer of a blade with an unsteady flow. They observed that the increased turbulence contributed to greater heat transfer at the suction surface.

Many previous researchers have observed that the local heat transfer distributions of endwalls are greatly affected by the upstream wake. Exposure to a periodic wake effect induces pressure and temperature deviations at the endwall. This effect is expressed as the Strouhal number, which is defined as [44]:

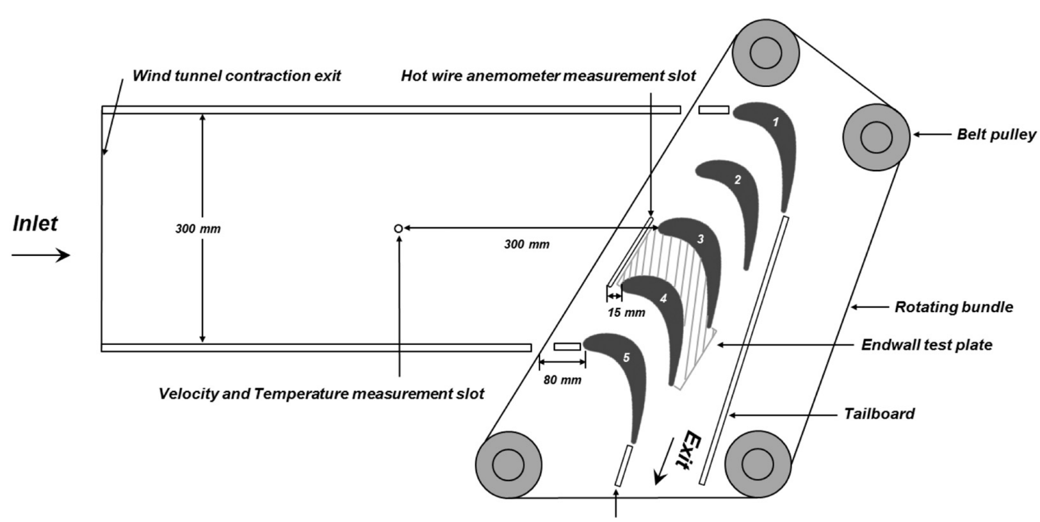

Fig. 1. Five blade linear cascade with cylindrical rod [41].