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Effect of an unsteady wake on the external heat transfer of 2nd stage rotor

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ABSTRACT

A rotor blade is affected by the unsteady wake from the stator in the previous stage. An unsteady wake causes differences in the flow and heat transfer distribution on the external surface of the rotor blade. Therefore, the effect of unsteady wake should be studied for optimal design of blade cooling. To investigate the effect of an unsteady wake, this study measured the local heat transfer distribution over the entire external blade surface using the naphthalene sublimation method. Several rods moved across the inlet of the cascade to make the unsteady wake and the Strouhal number was varied from 0.0 to 0.3. The heat transfer on the entire pressure-side surface in an unsteady wake increases due to the high turbulence. The unsteady wake flow disturbs the developing passage vortex and tip leakage flow. As a result, the heat transfer near the endwall and tip surfaces in the unsteady wake case is lower than that in the steady case.

1. Introduction

Vortices and highly turbulent flows have large effects on the heat transfer of the external surfaces of a turbine blade. Therefore, many studies have examined the heat transfer and flow characteristics of blade external surfaces. As shown in Fig. 1, different vortices and turbulent flow influence different surfaces of a turbine blade, such as impinging flow on the leading edge, transient flows on the suction-side surface, and passage vortex on the endwall surface. The characteristics of these vortices around turbine blade have been reported by Langston [1,2], Sieverding [3], and Dunn [4]. These papers summarized the previous studies of aerodynamic and convective heat transfer on external blade surfaces. And they have made contributions to improve understanding of flow and heat transfer phenomena on the turbine blade.

Detailed information on the heat transfer of external blade surfaces is required to design proper cooling schemes and to determine appropriate boundary conditions for numerical calculations. Therefore, many studies have aimed to develop measuring techniques to obtain detailed heat transfer distributions under various operating conditions. Blair [5] measured the heat transfer on blades under a large-scale annular cascade for various Reynolds numbers, surface roughnesses, and inclination angles. Giel et al. [6] studied the effect of the incidence angle on the blade surfaces in a transonic linear cascade. Rhee and Cho [7,8] investigated the effect of the incidence angle of a rotating turbine blade in a low-speed wind tunnel. These studies found considerable variation in the heat transfer coefficient in the near-tip region.

The interaction between the rotor and stator results in an unsteady wake flow in the main inlet flow of rotor passages. The unsteady wake increased the turbulence intensity of the flow in the rotor passage rather than the flow in the stator passage. Therefore, the effect of an unsteady wake flow should be considered when studying the flow and heat transfer of the rotor. Hodson et al. [9,10] predicted the unsteady wake flow in a rotor passage using computational fluid dynamics and measured it in experiments. They found that the characteristics of passage wakes in the rotor passage dominated the free–stream unsteadiness. Liu and Rodi [11] also measured the velocity of an unsteady wake flow in a linear cascade. They investigated the mechanism of flow transition caused by passing wakes and found a relationship between the starting point of the transition and the wake-passing frequency.

Some studies have investigated the effect of unsteady wakes on the heat transfer of a rotor surface. Han et al. [12] measured temperature at 36 points on the blade surface and calculated the averaged heat transfer distribution on a rotor surface to investigate the effect of an unsteady wake. Liu and Rodi [13] studied the heat transfer and pressure characteristics on a blade surface with an

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Nomenclature

C_{ax}	blade axial chord length (m)	SP	blade span (m)
D	rod diameter (m)	Sc	Schmidt number (ν/D_{naph})
D_{naph}	mass diffusion coefficient of naphthalene vapor in air (m^2/s)	Sh	Sherwood number, Eq. (3)
f	rod-passing frequency (Hz)	Δt	runtime (s)
h	heat transfer coefficient (W/m^2 K)	U	inlet flow velocity (m/s)
h_m	mass transfer coefficient, Eq. (2)	x	coordinate in blade chord direction
k	conductivity of air (W/m K)	y	coordinate traverse to the blade chord direction
$\dot{m}$	local naphthalene mass transfer rate per unit area (kg/m^2 s)	z	coordinate in spanwise direction of cascade
Nu	Nusselt number (hC_{ax}/k)	α	thermal diffusivity (m^2/s)
P	pitch of blade (m)	ν	momentum diffusivity (m^2/s)
P_{bar}	pitch of road (m)	δ	boundary layer thickness (m)
Pr	Prandtl number (ν/α)	ρ_s	density of solid naphthalene (kg/m^3)
S	Strouhal number/Eq. (1)	$\rho_{v,w}$	vapor density of naphthalene on the surface (kg/m^3)
s	span direction	$\rho_{v,\infty}$	vapor density of naphthalene in the mainstream (kg/m^3)

unsteady wake. These studies showed that the heat transfer increased with the wake frequency and that an unsteady wake promoted an earlier and broader boundary layer transition, inducing high heat transfer on the suction surface of the blade. Zhang and Han [14], Du et al. [15], and Rhee and Cho [16] also investigated the effect of the upstream wake on the blade surface heat transfer and reported that the upstream wake increased the heat transfer coefficient in the mid-span of the blade. Therefore, it is difficult to estimate the effect of unsteady wake on the tip and endwall regions using previous studies. Park et al. [17] measured the detailed heat transfer distribution on the endwall surface with an unsteady wake and discovered a change in the passage vortex with unsteady wake flow. The passage vortex became weak with an unsteady wake flow and it did not influence the broad area on the endwall surface.

The heat transfer distribution on the external surface of a rotor has different characteristics due to the unsteady wake flow. Blade surface is exposed to locally different thermal load due to various secondary vortices as shown in Fig. 1. Therefore, the precise information of local heat transfer distribution on rotor blade is required to turbomachinery cooling designers. However, it is difficult to measure local heat transfer distribution on entire rotor blade with wakes. Many experimental methods, such as IR camera, TLC and PSP have the limitation for measuring local heat transfer due to the interference of wake generator facility. Some previous researchers measured local heat transfer by thermocouples at only mid surface of turbine blade. Therefore, the turbine cooling designer have the limited data. However, the local heat transfer data were required to design high performance blades recently.

The main objective of this study was to investigate the local heat transfer distribution on the entire external surface of a rotor under an unsteady wake flow. The naphthalene sublimation method was used to measure the detailed local heat/mass transfer coefficient. In addition, the Strouhal number was changed from 0.0 to 0.3 to investigate the effect of an unsteady wake. Detailed local heat/mass transfer data will help to understand the effects of unsteady wakes on the external surface of a rotor. Results of this study can also be used for design guidelines for the rotor cooling systems. The data will be useful for verifying turbulence models in numerical calculations and for estimating the temperature and thermal stresses on the external surface of a rotor.

2. Experimental apparatus and data reduction

2.1. Experimental apparatus and conditions

Fig. 2 [17] shows the overall layout of the experimental apparatus. The tests were performed in a low-speed wind tunnel with a 300 × 200-mm cross-section using a five passage linear cascade.

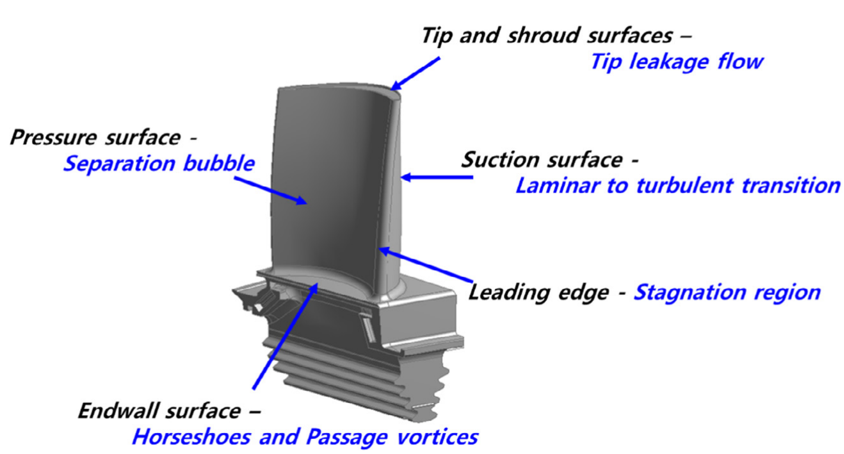

Fig. 1. Various vortices near the blade external surface.