Numerical investigation of the blade tip with slot film cooling hole

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ABSTRACT
In the present study, film cooling effectiveness and flow characteristics on tip floor and rim surfaces of the blade tip having slot film cooling hole were investigated using numerical simulation. In a base film cooling hole case, coolant from film cooling hole could not be ejected evenly in tip cavity due to the mixing with tip leakage flow, resulting in low film cooling effectiveness on tip floor and rim surfaces. Slot cooling hole was installed on pressure side/suction side of the rim in order to improve uneven coolant ejection in tip cavity. From pressure side slot cooling hole case, coolant was ejected near the pressure side of the rim resulting in high film cooling effectiveness. Film cooling effectiveness near the suction side of the rim was low due to strong reattachment from tip leakage flow. It was shown that coolant from pressure side slot cooling hole had a weak influence on the flow patterns near suction side of the rim. From suction side slot cooling hole case, coolant was ejected near the suction side of the rim resulting in high film cooling effectiveness on overall tip regions. This was because coolant from suction side slot cooling hole prevented tip leakage flow from reattaching at the suction side rim region and making secondary flow in tip cavity. It was seen that coolant from suction side slot cooling hole had a strong effect on the flow patterns in tip cavity. Therefore, film cooling effectiveness on tip floor and rim surfaces were significantly enhanced in the blade tip equipped with slot cooling hole on the rim.

NOMENCLATURE
T Temperature (K)  
ρ Density (kg/m³)

v Velocity (m/s)  
Re Reynolds number  
η Adiabatic film cooling effectiveness  
M Blowing ratio  
c Coolant part  
∞ Mainstream part

INTRODUCTION
As the demand for power has been increasing all over the world, the efficiency of a gas turbine has been required to be increasing continuously. Because the efficiency and power output of a gas turbine is a strong function of the turbine rotor inlet temperature. Thus, turbine blades are exposed to extremely high temperature, which exceeds their melting temperature. Therefore, it is a significant problem in thermal design of gas turbine blade to apply various cooling techniques on turbine blade ranging from internal cooling to external cooling. Moreover, there occurred a strong flow called tip leakage flow induced by pressure difference between pressure and suction side of a turbine blade. This strong flow resulted in severe thermal load on the blade tip. Therefore, many previous researchers have investigated a lot of experiments and numerical simulations in order to analyse heat transfer characteristics on blade tip. Bunker et al. [1] and Sunden et al. [2] reviewed fundamental studies of gas turbine blade tip heat transfer and reported various blade tip cooling techniques considering tip clearance and rim height. Jin and Goldstein [3-4] investigated heat transfer characteristics on flat blade tip using a naphthalene sublimation method. Under various flow conditions ranging from Reynolds number to turbulence intensity, they measured local heat/mass transfer coefficients.
on flat blade tip. Rhee and Cho [5-6] measured local heat/mass transfer coefficients near the tip and shroud under rotating blade conditions.

Furthermore, in order to reduce thermal load on blade tip and aerodynamics loss from tip leakage flow, a lot of studies regarding various squealer tip configurations and film cooling techniques have been investigated. Kwak and Han [7-8] investigated heat transfer characteristics on squealer tip using experimental method. Mhetras et al. [9] measured squealer rim walls and squealer cavity floor of blade tip using a pressure sensitive paint. They showed that film cooling effectiveness were significantly influenced by shape and location of film cooling holes. Christophel et al. [10-11] measured adiabatic film cooling effectiveness and heat transfer coefficients on blade tip equipped with pressure side film cooling holes. They reported that in case of blade tip equipped with pressure side film cooling hole, a small tip gap had a better cooling performance compared to a large tip gap.

Although film cooling hole have been applied on blade tip in various types such as pressure side holes and tip floor holes, durability of the blade tip is not thoroughly satisfied under high thermal load condition. Therefore, in the present study, we suggested slot film cooling hole on squealer rim wall of blade tip in order to give a better cooling performance. Using numerical simulation, flow and heat transfer characteristics on blade tip equipped with slot film cooling hole were investigated.

**NUMERICAL SET UP**

Numerical simulations were performed to analyse flow characteristics and film cooling effectiveness on blade tip region using ANSYS CFX 17.2. From Fig.1, various types of film cooling holes are installed on blade tip region ranging from tip floor to rim wall; Figure 1(a) is a base film cooling hole case; Figure 1(b) is a pressure side slot film cooling hole; Figure 1(c) is a suction side slot cooling hole. In order to maintain averaged blowing ratio 1 of all cases, same film cooling hole area is applied to all three cases. Numerical simulations were carried out under experimental condition of the linear cascade. Detailed boundary conditions of numerical simulations were shown in Fig. 2. Inlet condition was set at 10.4 m/s in accordance with blade inlet angle and Reynolds number (Re) is 150,000 based on inlet velocity and blade axial chord length. Outlet condition was set at 1 atm in accordance with experimental condition. Blade surfaces were set adiabatic condition and side walls were set as a periodic condition according to experimental condition. Coolant inlet...
was set to 0.33 m/s for all three cases in order to keep averaged blowing ratio maintained as 1. Density ratio was maintained as 1 by using same air property at main flow and secondary flow. Figure 2(b) shows a grid independence test in a numerical simulation. It was seen that area averaged film cooling effectiveness on blade tip region was converged over 11 million of elements and averaged $y^+$ on blade tip region is below 1. With about 11 million of elements, numerical simulations for all cases were carried out. Also, a transitional shear stress transport turbulence model was used to analyse flow patterns in blade tip region accurately, where, after flow acceleration, laminar-to-turbulent transition occurred.

**DATA REDUCTION**

In the present study, film cooling effectiveness was used to compare cooling performance of each cases. Generally, film cooling effectiveness is defined as the equation (1):

$$\eta = \frac{T_\infty - T_{aw}}{T_\infty - T_c}$$

(1)

where $T_\infty$ is the mainstream temperature, $T_c$ is the coolant temperature at the coolant inlet, and $T_{aw}$ is the adiabatic wall temperature. Film cooling effectiveness is mainly affected by the adiabatic wall temperature, which does not consider conduction in blade wall. The blowing ratio was used to calculate the mass flux ratio of mainstream and film cooling hole. Generally, blowing ratio is defined as the equation (2):

$$M = \frac{\rho_c v_c}{\rho_\infty v_\infty}$$

(2)

where $\rho_c$ is the coolant density, $\rho_\infty$ is the mainstream density, $v_c$ is the coolant velocity at the film cooling hole, and $v_\infty$ is the mainstream velocity at inlet.

**RESULTS AND DISCUSSION**

Figure 3 shows streamlines and temperature contour in the blade tip with film cooling coolant. Figure 3(a), it was seen that strong coolant jet was ejected from hole in the leading edge region of blade tip and relatively weak coolant jet was ejected through holes in the pressure side and trailing edge region of blade tip. In the leading edge region, there were strong flow reattachment from tip leakage flow passing by tip clearance and a vortex developed from boundary layer of inner rim wall. The boundary layer of inner rim wall was separated due to adverse pressure gradient from inner rim wall. These flow patterns such as flow reattachment and a vortex developed from boundary layer of inner rim wall. Therefore, coolant jet from hole in the leading edge region of blade tip had no significant effect on the leading edge of tip region. This coolant jet strongly ejected toward shroud and covered hole downstream region. After leading edge region, coolant and hot gas from tip leakage flow were mixed up along the tip cavity. From Fig. 3(b), coolant jet was ejected from slot of pressure side rim and had a great influence on tip cavity. In the leading edge region, a vortex from boundary layer separation was mixed up with the coolant jet, resulting in high film cooling effectiveness. Due to the influence of a vortex, coolant from pressure side rim flowed along the pressure side rim, which resulted in high film cooling effectiveness. It was seen that and the mixing of coolant and hot gas developed along the tip cavity. As shown in Fig. 3(c), coolant jet from slot of suction side rim made various flow patterns in the tip cavity. It was seen that coolant jet had an influence on a vortex from inner rim boundary layer separation and flow reattachment along the suction side rim. The mixing of coolant and hot gas occurred and was developed along the tip cavity.

Figure 4 indicated film cooling effectiveness distribution of pressure side rim, suction side rim, and tip floor. According to the flow characteristics on blade tip region, film cooling effectiveness were diversely changed. Figure 4(a) showed film cooling effectiveness distribution in base film cooling hole case. There were low film cooling effectiveness regions near leading edge region of pressure side rim, suction side rim, and tip floor. This was because of flow reattachment from tip leakage flow. Because of the coolant jet from hole in the leading edge region, high film cooling effectiveness on rim walls and tip floor occurred. In the mid region of the blade tip, it was shown that as the mixing of coolant and hot gas dominated mid region of the
blade tip, film cooling effectiveness distributions were uniform. In the trailing edge region of the blade tip, it was seen that high film cooling effectiveness occurred due to coolant from the holes in the trailing edge region. From Fig. 4(b), there were film cooling effectiveness distributions of pressure side slot cooling hole case. Along the suction side rim, there was a low film cooling effectiveness due to flow reattachment and swirling flow from tip leakage flow. Approaching from leading edge region to trailing edge region, a vortex formed by inner rim boundary layer separation and coolant had a major influence on tip floor, causing high cooling performance. In the pressure side rim, high cooling performance appeared because of coolant jet from slot cooling hole. In the suction side rim, low film cooling effectiveness appeared due to flow reattachment along the suction side rim. Also, there were high film cooling effectiveness distribution on some regions, resulting from the influence of coolant. As shown in Fig. 4(c), there were film cooling effectiveness distributions for suction side slot film cooling hole case. In the tip floor, strong flow reattachment made low film cooling effectiveness on the leading edge region of tip floor. Generally, there occurred high film cooling effectiveness on tip floor. In pressure side rim, the region where swirling flow dominated had low film cooling effectiveness. In suction side rim, it was seen that low film cooling effectiveness appeared upper part of slot film cooling hole. This was because tip leakage flow influenced on upper part of slot film cooling hole by reattaching the region.

CONCLUSION

The investigation was carried out to study the effects of slot film cooling hole in the blade tip using numerical method. In order to compare the effects of slot film cooling hole, various geometries from pressure side slot film cooling hole to suction side slot film cooling hole were applied. It was shown that suction side slot film cooling hole had a great cooling performance compared to the other cases. However, it is needed to do more parametric studies in order for optimum slot film cooling hole design of the blade tip.

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