Heat Transfer Characteristics on Blade Tip with Unsteady Wake

Minho Bang, Seok Min Choi, Jun Su Park, Hokyu Moon, Hyung Hee Cho

Abstract**—** Present study investigates the effect of unsteady wakes on heat transfer in blade tip. Heat/mass transfer was measured in blade tip region depending on a variety of strouhal number by naphthalene sublimation technique. Naphthalene sublimation technique measures heat transfer using a heat/mass transfer analogy. Experiments are performed in linear cascade which is composed of five turbine blades and rotating rods. Strouhal number of inlet flow are changed ranging from 0 to 0.22. Reynolds number is 100,000 based on 11.4 m/s of outlet flow and axial chord length. Three different squealer tip geometries such as base squealer tip, vertical rib squealer tip, and camber line squealer tip are used to study how unsteady wakes affect heat transfer on a blade tip. Depending on squealer tip geometry, different flow patterns occur on a blade tip. Also, unsteady wakes cause reduced tip leakage flow and turbulent flow. As a result, as strouhal number increases, heat/mass transfer coefficients decrease due to the reduced leakage flow. As strouhal number increases, heat/mass transfer coefficients on a blade tip increase in vertical rib squealer tip.

Keywords**—**Gas turbine, blade tip, heat transfer, unsteady wakes.

I. Introduction

GAS turbine is one of the reliable and efficient thermal power systems due to its high efficiency and specific work. In order to maximize efficiency and output of the gas turbine, operating temperature in gas turbine is exposed to extremely high temperature condition.

Due to the high operating temperature, thermal damages in turbine blade occur frequently. Especially, gas turbine blade tip is one of parts that are vulnerable to thermal damages in turbine blade. This is because tip leakage flow has negative influences on the rotors. There should be clearance between shroud and rotating rotors. Therefore, strong tip leakage flow pass by the tip clearance making blade loading loss and causing thermal damage on blade tip. Furthermore, inlet flow condition in stator is different from inlet flow condition in rotor. Unsteady wakes derived by the relative motion of stator and rotor make different inlet condition in rotor. Unsteady wakes from trailing edge of stator has an effect on heat transfer coefficients distribution of blade ranging from endwall to tip.

A lot of researchers investigated heat transfer coefficient distribution in blade tip region considering various design variables. Bunker [1] and Sunden [2] reviewed a variety of papers about blade tip. They reported general knowledge concerning turbine blade tip heat transfer and flow characteristics ranging from fundamental things to current papers. Chyu et al. [3] experimentally investigated convective heat transfer at the grooved blade tip. They conducted various heat transfer experiments varying depth-to-width ratios and tip gap-to width ratios It is reported that average heat transfer in overall blade tip region decreases as cavity depth increases. Also, viewing from a standpoint considering heat transfer design, it is not recommendable to make overly deep cavity. Cho et al. [4] investigated local heat/mass transfer on the shroud according to the blade tip clearance. It is reported that the heat/mass transfer characteristics on the shroud changed a lot with various blade tip clearances. Rhee and Cho [5] experimentally measured local heat/mass transfer characteristics on the near tip region and tip, shroud with rotating turbine blade. Many heat/mass transfer measurements are conducted with various rotational speed ranging from 154.5 rpm to 384.2 rpm. Heat/mass transfer in off design conditions has different distributions of heat/mass transfer coefficients due to changed tip gap flow and incidence angle. Moreover, Rhee and Cho [6] experimentally measured heat /mass transfer distribution on tip, shroud, and blade surface with various vane/blade relative positions. Heat/mass transfer on the tip, shroud and blade surfaces are largely influenced due to the blockage effect by relative blade positions. There are also many researches about heat transfer characteristics in turbine blade using various squealer tip configurations. Kwak and Han [7] investigated heat transfer measurements on the squealer tip and tip near region using transient liquid crystals technique. It is reported that the heat transfer coefficients on the tip and shroud are reduced in turbine blade applied squealer tip. Azad et al [8] experimentally measured heat transfer coefficients on various squealer tip geometries ranging from one-sided squealer geometries to two-sided squealer geometries. They concluded that a single squealer tip has lower heat transfer coefficients than a double squealer tip. Saxena et al. [9], [10] investigated the effects of squealer tip geometries and unsteady wake on heat transfer in blade tip using hue-based liquid crystal measurement technique. However, it is difficult to clearly compare heat transfer distribution on various blade tip configurations.

In the present study, heat/mass transfer of a turbine blade tip in linear cascade varying squealer tip geometries and unsteady wakes. Detailed heat/mass transfer distribution on the blade tip are measured using naphthalene sublimation method. The objectives of the research are: (1) to find out flow patterns in

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various tip geometries; (2) to measure local heat/mass transfer coefficients on blade tip depending on tip geometries and unsteady wakes.

II. Experimental Setup

Fig. 1 shows overall experimental apparatus. The linear cascade is the same as the experimental apparatus [11]. Each blade span is 196.2 mm and tip clearance is 3.8 mm (2.8% of axial chord length). Pitch of blades is 135.5 mm and blade turning angle is 119°. Experiments are conducted on third blade tip and periodicity of blades is satisfied through adjustable guide plates. Flow velocity is set to 11.4m/s at the end of blades and controlled by changing blower frequency inverter. Reynold is 100,000 based on exit velocity and axial chord length.

During experiments, temperature of the air should be kept constant. This is because naphthalene vapor pressure is very sensitive to room temperature [12]. 1℃ variation of room temperature makes 10% variation of naphthalene vapor pressure.

Unsteady wakes from trailing edge of vane/blade could be modeled as wakes from passing rod bundle. Pitch of rod is 80 mm, and rod diameter is 5 mm. Rod bundle is rotated by two belts tied with pulleys. By controlling the rpm of pulleys, rod passing frequency is changed ranging from 19.6Hz to 78.5Hz. Also, rod passing strouhal number is varied ranging from 0 to 0.22 and defined as (1):

$$St = \frac{2\pi f d}{U} \quad (1)$$

Heat/mass transfer coefficients are measured by naphthalene sublimation method. Naphthalene sublimation method calculates heat transfer coefficients using heat and mass transfer analogy. During naphthalene sublimation method, wall conduction and radiation errors are eliminated. The local naphthalene sublimation depth was measured through linear variable differential transformer and automated positioning table.

The mass transfer coefficient is defined as (2):

$$h_m = \frac{\dot{m}}{\rho_{v,w} - \rho_{v,\infty}} = \frac{\rho_S(\Delta z/\Delta t)}{\rho_{v,w} - \rho_{v,\infty}} \quad (2)$$

Sherwood number which is a non-dimensional form of mass transfer coefficient is expressed as (3):

$$Sh = \frac{h_m C}{D_{naph}} \quad (3)$$

Using heat/mass transfer analogy, Nusselt number which is a non-dimensional form of heat transfer coefficient is expressed as (4):

$$\frac{Nu}{Sh} = \left(\frac{Pr}{Sc}\right)^{0.4} \quad (4)$$

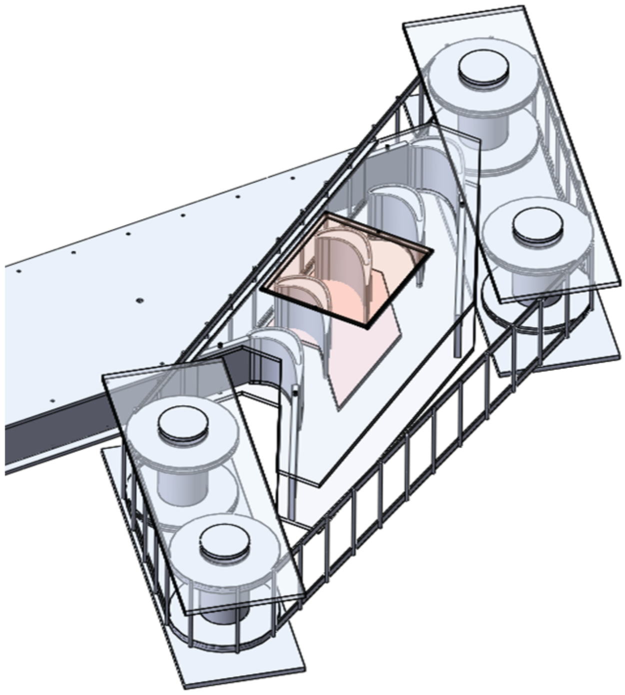


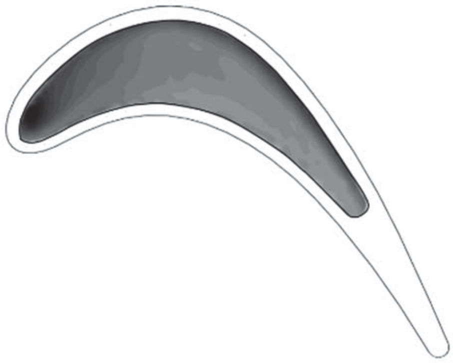
Fig. 1 Linear cascade experimental apparatus [11]

III. Results

Fig. 2 shows Sherwood number distribution on blade tip surface depending on strouhal number. Fig. 2 (a) is the case that unsteady wake effect is not considered. It clearly shows that the leading edge and the region along the suction side rim have a higher heat transfer coefficient. This is because after tip leakage flow was separated from the pressure side rim, leakage flow reattached the tip surface and formed a swirling flow along the suction side rim. Due to the flow patterns, high heat/mass transfer coefficients appear. Fig. 2 (b) is the case that unsteady wake is considered. Strouhal number is set as 0.22 and makes difference in inlet flow condition. There is lower heat/mass transfer distribution than steady case. Unsteady wake effect makes high turbulence intensity of inlet flow and protects tip leakage flow from getting into the tip clearance. Therefore, compared to the steady case, lower heat/mass transfer distribution appears.

Fig. 3 represents the area-averaged Sherwood number on tip surface. Similar to the result from Fig. 2, the case that unsteady wake effect is considered has lower area-averaged heat/mass transfer coefficients. The case that strouhal number is 0.22 is 19.8% lower heat transfer that the steady case. This is because unsteady wake effect makes tip leakage flow reduced. Despite of high turbulence intensity of inlet flow, reduced leakage flow makes momentum in flow patterns such as flow reattachment and swirling flow weakened.

(a)



(b)

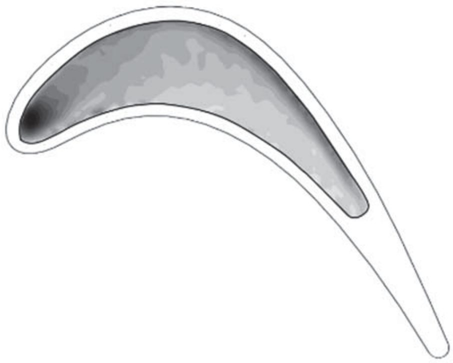


Fig. 2 Sherwood number distribution on blade tip surface:(a) St=0, (b) St=0.22

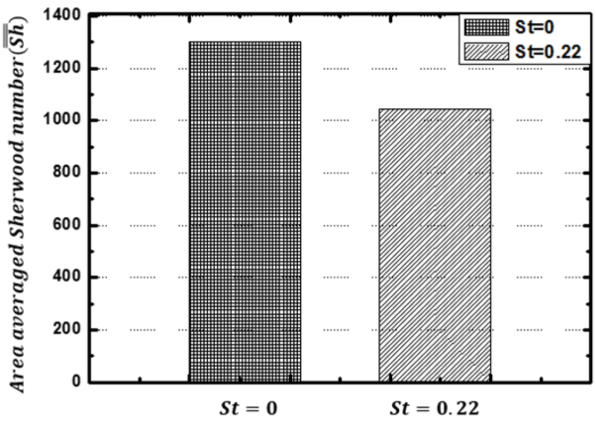


Fig. 3 Area-averaged Sherwood number in tip surface varying Strouhal number

IV. Conclusion

This study measured detailed heat/mass transfer characteristics on blade tip surface varying strouhal number 22 to investigate the effect of unsteady wake on blade tip region. Experiments are performed in linear cascade which is composed of five turbine blades and rotating rods, and Strouhal number that is independent variable in the present investigation is changed from 0 to 0.22 depending on changing rod passing frequency. Results showed that there is a difference in heat/mass transfer coefficient distribution with increasing Strouhal number. To be more specific, in the case that strouhal number is 0.22, heat/mass transfer distribution on the blade tip surface has a different aspect compared to steady case. As strouhal number increases, sherwood number in blade tip region monotonically decreases. Compared quantitatively to steady case, the case that strouhal number is 0.22 has 19.8% lower area-averaged Sherwood number. This is because tip leakage flow is reduced due to the unsteady wake effect and this makes lower heat/mass transfer on the tip surface. Therefore, this results should be considered in turbine blade cooling design.

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References

[1] R. S. Bunker, "A Review of Turbine Blade Tip Heat Transfer," Annals of the New York Academy of Sciences, Vol 934, pp.64-79, 2001.

[2] B. Sunden and G. Xie, "Gas Turbine Blade Tip Heat Transfer and Cooling: A Literature Survey," Heat Transfer Engineering, Vol 31, pp.527-554, 2010.

[3] M. K. Chyu, H. K. Moon, and D. E. Metzger, Heat Transfer in the Tip Region of Grooved Turbine Blades, Journal of Turbomachinery, Vol 2, pp131-138, 1989.

[4] H. H. Cho, D. Rhee, and J. H. Choi, "Heat/Mass Transfer Characteristics on Turbine Shroud with Blade Tip Clearance," Annals of The New York Academy of Sciences, Vol. 934, pp. 281-288, 2001.

[5] D. Rhee and H. H. Cho, "Local Heat/Mass Transfer characteristics on a Rotating Blade with Flat Tip in Low-Speed Annular Cascade-Part I: Near-Tip Surface", ASME J. of Turbomachinery, Vol. 128, No. 1, pp. 96-109, 2006.

[6] D. Rhee and H. H. Cho, "Effect of Vane/Blade Relative Position on Heat Transfer Characteristics in a Stationary Turbine Blade: Part 1- Tip and Shroud," International Journal of Thermal Sciences, Vol. 47, pp. 1528 – 1543, 2008.

[7] J. S. Kwak and J. C. Han, "Heat-Transfer Coefficients of a Turbine Blade-Tip and Near-Tip Regions,", Vol. 17, pp. 297-303, 2003.

[8] G. S. Azad, J. C. Han and R. J. Boyle, "Heat Transfer and Flow on the Squealer Tip of a Gas Turbine Blade," Journal of Turbomachinery, Vol. 122, pp. 725-732, 2000.

[9] V. Saxena, H. Nasir and S. V. Ekkad, "Effect of Blade Tip Geometry on Tip Flow and Heat Transfer for a Blade in a Low-Speed Cascade," Journal of Turbomachinery, Vol. 126, pp. 130–138, 2004.

[10] V. Saxena and S. V. Ekkad, "Effect of Squealer Geometry on Tip Flow and Heat Transfer for a Turbine Blade in a Low Speed Cascade," Journal of Heat Transfer, Vol. 126, pp. 546-553, 2004.
[11] S. M. Choi, J. S. Park, H. Chung, B. M. Chang, and H. H. Cho, "Effect of Unsteady Wakes on Local Heat Transfer of 1st Stage Blade Endwall," Proceedings of ASME Turbo Expo 2015, pp. V05BT13A024, 2015.
[12] R. J. Goldstein and H. H. Cho, "A Review of Mass Transfer Measurements Using Naphthalene Sublimation," Experimental Thermal and Fluid Science, Vol. 10, pp. 416-434, 1995.

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