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Heat transfer and film cooling effectiveness on the squealer tip of a turbine blade

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ABSTRACT

Detailed heat/mass transfer coefficients and film-cooling effectiveness were measured on the tip and inner rim surfaces of a blade with a squealer rim. The test blade was a two-dimensional version of a modern first-stage gas turbine rotor blade with a squealer rim. The experimental apparatus was equipped with a linear cascade of three blades, and the axial chord length (C_x) was 237 mm with a turning angle of 126°, the mainstream Reynolds number based on the axial chord and inlet velocity was 1.5×10^5. In addition, three different types of blade tip surfaces were equipped with a single row of film-cooling holes along the camber line, near the pressure and suction-side rim. The blowing ratio was fixed at 1.5. High heat transfer rates were observed near the leading edge on the tip surface due to reattached flow. Furthermore, heat transfer on both inner side surfaces was higher than that on the tip surface. High film cooling effectiveness was observed in the middle region ($0.1 < X/C_x < 0.6$) due to stagnation of the film cooling. Ultimately, a proper cooling system is suggested to reduce the thermal load and enhance the film cooling effectiveness in the squealer tip.

1. Introduction

The inlet temperature of turbine engines has been steadily increasing with the development of new engine. Turbine blades experience severe thermal stress and fatigue as a result of exposure to high-temperature gases. In particular, the tips of gas turbine rotor blades are subjected to large thermal loads, resulting in damage to the blade tips. Such thermal loads arise due to tip leakage flow through the gap between the rotating blade tip and the stationary shroud. The hot leakage flow accelerates due to large pressure differences that exist between the pressure and suction-sides of the blade, resulting in a thin boundary layer and high heat-transfer rates. This flow across the blade tip is also undesirable in terms of efficiency because it increases turbine power losses. Consequently, squealer-type tips are employed to reduce leakage flow. The presence of a rim and groove increase the flow resistance of the leakage flow, resulting in a decreased leakage flow rate. However, thermal loads and stresses are concentrated at the edge of the rotor blade tip and thus, cracking and breakage can occur in this region. Therefore, it is important to understand the flow and heat transfer characteristics of the squealer tip cavity.

Morphis and Bindon [1] have contributed to the general understanding of tip-gap flow patterns. In particular, they conducted pressure and flow field measurements on an axial turbine blade tip in a linear cascade under low-speed conditions and suggested tip leakage flow characteristics. Metzger et al. [2] and Chyu et al. [3] investigated heat transfer phenomena for rectangular grooved tip models. The researcher performed experiments using cavities with various depth-to-width and tip gap-to-width ratios, and incorporated the effect of relative motion by introducing a moving shroud surface over the grooved tip model. From the obtained results, it was suggested that heat transfer upstream of the cavity was greatly reduced. When compared to a rectangular flat tip, the heat transfer coefficient was higher at the downstream end of the cavity due to flow reattachment inside the cavity. Cho et al. [4] experimentally measured the local heat/mass transfer characteristics on a shroud with various blade tip clearances. The results showed that the heat/mass transfer characteristics changed significantly with respect to the gap distance between the tip of the turbine blade and the shroud. Rhee and Cho [5,6] also studied the local heat/mass transfer

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characteristics on a blade tip and shroud using a low-speed turbine annular cascade. The heat/mass transfer coefficients on the blade tip were about 1.7 times higher than those on the blade surface and shroud. Furthermore, the heat/mass transfer on the blade tip for the rotating chase was about 10% lower than that for the stationary case due to reduced leakage flow with the relative motion. The effect of rotation reduces tip leakage flow into the tip cavity. Heat transfer on the squealer tip surface is also slightly affected by the tip leakage flow in the rotational condition comparing with the stationary condition. Therefore, the stationary case will show characteristics of tip leakage flow for various conditions and is considered one of the extreme conditions.

Rhee and Cho [7,8] also investigated local heat/mass transfer characteristics on the near-tip surfaces of stationary and rotating blades for various relative blade positions. The effect of blade position, which causes a different interaction to occur between the vane and blade, was found to change the incoming flow condition. As a result, significantly different patterns were observed on the blade surface, especially near the blade tip, due to variations in the tip leakage flow. Kwak [9] experimentally studied the effect of tip clearance on the heat transfer characteristics of the blade tip surface. The authors measured the heat transfer on a flat tip using a transient liquid-crystal technique and compared the findings to those obtained for a squealer tip. The experimental results showed that heat transfer on the squealer tip was lower than that on the flat tip. Papa et al. [10] used the naphthalene sublimation method to measure the heat transfer coefficients on a squealer tip with a winglet-type rim on the pressure-side, and compared the results to those obtained with a general squealer tip. Azad et al. [11] investigated heat transfer and flow on squealer tips by varying the tip clearance and turbulence intensity. The heat transfer coefficients on the pressure-side rim and in the trailing edge region increased with a rise in the turbulence intensity. However, no significant difference in the local heat transfer coefficient was observed inside the cavity or on the suction-side rim as the turbulence intensity was varied. Park et al. [12,13] measured detailed heat/mass transfer coefficients on the blade tip of a squealer rim by changing the rim height and tip clearance. As the tip clearance raised, heat/mass transfer on the tip surface also increased due to the increased amount of tip leakage flow. On the other hand, as the rim height was increased, heat/mass transfer on the tip surface was reduced due to the increased flow resistance in the cavity.

Film cooling has become a standard method for protecting gas turbine blades against hot combustion gas. Numerous investigations into film cooling have been conducted so as to understand the underlying mechanism and improve cooling performance [14,15]. However, there are few papers available on blade tip film cooling. Kim [16] and Kim and Metzger [17] measured heat transfer and film cooling effectiveness in the blade tip region using a transient thermal liquid crystal technique with various cooling configurations. Kwak and Han [18] studied the effect of tip clearances and blowing ratios on film cooling effectiveness for a blade tip surface. Ahn et al. [19] also measured film cooling effectiveness and pressure in the blade tip region using pressure-sensitive paint (PSP). Obtained results showed that an increase in the tip clearance and blowing ratio led to more effective film cooling.

An extensive amount of data has been collected for heat transfer on the tip surface. However, for heat transfer on the inner rim surfaces, which are some of the weakest parts of the turbine blade, experimental data are scarce due to difficulties in performing the required measurements. Thus, the main objective of this study is to investigate the detailed heat transfer and film cooling effectiveness distribution on both the tip and inner rim surfaces of a squealer tip using local mass transfer measurements based on the naphthalene sublimation technique. The tip clearance and rim height were varied to evaluate the effect of the shape factor on the squealer tip. In addition, three different types of film cooling arrays were implemented to determine the proper film cooling hole array in the squealer tip.

Detailed local heat/mass transfer data are critical for both an understanding of the tip leakage flow characteristics and the design of film cooling system in the squealer tip. Furthermore, such results are useful for verifying turbulence models in numerical calculations and to estimating both temperature and thermal stress on the blade tip and rim. This manuscript is extension of the work described in ASME (American Society of Mechanical Engineers) Paper No. GT 2010-23203 [20] of the Turbo EXPO 2010 conference.

2. Experimental apparatus

2.1. Wind tunnel and test blade

Measurements were conducted in a stationary blow-down facility with a three-bladed linear cascade. Fig. 1 shows the overall layout of the wind tunnel and secondary injection system. An open-blowing type wind tunnel was connected to the front of the test duct, which had an entrance size of 300 × 198 mm. A turbulence grid was positioned 435 mm from the center blade in the cascade. The bar width and mesh size of the grid were 9 and 52 mm, respectively, leading to a value of 0.684 for the gird porosity. The turbulence intensity when using this grid was approximately 12% at a distance of 150 mm from the leading edge of the center blade, and the velocity of the mainstream was 11.8 m/s, as measured using a pitot tube and a hot-wire anemometer. The inlet boundary layer thickness ($\delta_{0.99}$) on the tip-side endwall measured at a distance of 50 mm upstream from the leading edge of test blade is approximately 8 mm with the turbulence grid. The Reynolds number was fixed at 150,000 based on the axial chord length (C_x). To increase flow periodicity, the adjustable side-walls and tailboards were erected as shown in Figs. 1 and 4(a). Such a setup provided identical flow through the pressure and suction-side passage of the test blade.

Fig. 2 shows the pressure coefficient at the mid-span (53% of spanwise) of the center blade. Ten pressure taps are located on each side from the leading edge to the trailing edge. The solid symbol is without tip clearance and the open symbol is with 3% tip clearance of C_x. The pressure coefficient can be expressed as follows

$$C_p = \frac{P_t - P_s}{\frac{1}{2}\rho U_\infty^2} \quad (1)$$

From the pressure distribution it can be shown, that when a gap exists, the difference between the pressure-side and suction-side becomes smaller than for the case with no gap. Here, aerodynamic losses may be attributed to this tip leakage flow. A more comprehensive discussion of the flow conditions, including the pressure distribution along the blade has been reported by Park et al. [12,13].

In the present study, two different flow conditions were used for the secondary injection flow of film cooling. One was pure air and the other was naphthalene-saturated air. Either pure air or naphthalene-saturated air was injected through the secondary air injection system. The secondary air injection system consisted of a constant temperature reservoir, a heat exchanger, an orifice and a settling chamber with naphthalene powder. Secondary air was supplied to each film cooling hole connected on the back of the test plate by Tygon tubes. The secondary air then passed through the naphthalene powder chamber for the cases of naphthalene-