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ORIGINAL ARTICLE

# Film cooling effects on the tip flow characteristics of a gas turbine blade

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**Abstract** An experimental investigation of the tip flow characteristics between a gas turbine blade tip and the shroud was conducted by a pressure-test system and a particle image velocimetry (PIV) system. A three-times scaled profile of the GE-E3 blade with five film cooling holes was used as specimen. The effects on flow characteristics by the rim width and the groove depth of the squealer tip were revealed. The rim widths were (a) 0.9%, (b) 2.1%, and (c) 3.0% of the axial chord, and the groove depths were (a) 2.8%, (b) 4.8%, and (c) 10% of the blade span. Several pressure taps on the top plate above the blades were connected to pressure gauges. By a CCD camera the PIV system recorded the velocity field around the leading edge zone including the five cooling holes. The flow distributions both in the tip clearance and in the passage were revealed, and the influence of the inlet velocity was determined. In this work, the tip flow characteristics with and without film cooling were investigated. The effects of different global blowing ratios of $M=0.5$, 1.0, 1.3 and 2.5 were established. It was found that decreasing the rim width resulted in a lower mass flow rate of the leakage flow, and the pressure distributions from the leading edge to the trailing edge showed a linearly increasing trend. It was also found that if the inlet velocity was less than 1.5 m/s, the flow field in the passage far away from the suction side appeared as a stagnation zone.


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**Nomenclature**

| | |
|---|---|
| $C$ | axial chord length (unit: m) |
| $d$ | cavity depth (unit: m) |
| $H$ | blade span (unit: m) |
| $M$ | blowing ratio $M=\rho_c V_c/\rho_i V_i$ |
| $P$ | pressure (unit: Pa) |
| $r$ | rim width (unit: m) |
| $V$ | flow velocity (unit: m/s) |
| $Vor$ | vorticity |
| $X$ | $x$-axial distance (unit: m) |

*Greek letters*

| | |
|---|---|
| $\alpha$ | inlet angle (unit: deg) |
| $\beta$ | thermal conductivity exit angle (unit: deg) |
| $\theta$ | shear stress inclined wall angle (unit: deg) |
| $\rho$ | angular frequency density (unit: kg/m$^3$) |

*Subscripts*

| | |
|---|---|
| c | secondary flow (coolant, or film cooling air) |
| i | inlet mainstream (freestream, or incoming flow) |
| t | total value |

*Abbreviations*

| | |
|---|---|
| BS | blade passage section |
| OS | outlet section |
| PS | pressure side |
| SS | suction side |
| SSZ | suction-side stagnation zone |
| US | upstream section |
| VP | vortex pairs |

## 1. Introduction

The increase of the inlet temperature of gas turbines has resulted in a higher heat load on turbine components. Blade tips are directly exposed to the leakage flow and a large thermal load, leading to difficulties in cooling. A complex flow prevails at the tip gap between the rotating blade tip and the stationary shroud. The leakage flow with a high velocity will impinge on the blade tip. As the hot gas leaks through the tip clearance from the pressure side to the suction side, the blade tips also may be broken because the thin boundary layer and the associated high heat transfer coefficient. A squealer is essentially a recessed cavity on the blade tip. The squealer tip as a labyrinth seal structure increases the flow resistance, which effectively reduces both the leakage flow and the tip heat transfer. Film cooling is most widely used in cooling systems of gas turbine blades. The coolant from discrete film cooling holes also reduces the tip leakage flow and the tip heat transfer.

To find solutions for obtaining low heat transfer in the blade zone, many investigations have been conducted. Metzger et al. [1] and Chyu et al. [2] concluded from experiments that there is an optimal value of the depth to width ratio for a given pressure difference across the gap. They found that although the heat transfer rate on the cavity floor is lower than that on a flat tip, the additional heat transfer area resulted in higher heat transfer. Heyes et al. [3] found that by using a suction side rim blade tip, the leakage flow was reduced more than by a flat tip. A single point measurement on the cavity bottom was carried out by Yang and Diller [4] to report local heat transfer coefficients on a squealer tip. Kim et al. [5] summarized the results of Metzger‘s important experimental work, i.e., the heat transfer and film cooling effectiveness for a rectangular tip model. Bunker and Bailey [6,7] experimentally investigated the heat transfer coefficient and the leakage flow with wooden strips glued to the tip surface. Dunn and Haldeman [8] experimentally investigated time-averaged heat flux data for a recessed tip on the platform of a transonic turbine blade. Bunker and Bailey [9] experimentally investigated the effect of rim height and oxidation on the tip heat transfer, and they found that a higher rim produced lower heat transfer coefficients. Azad et al. [10] investigated the effect of rim geometry arrangement on the tip heat transfer and found that the suction side rim provided the lowest heat transfer coefficient. Papa et al. [11] experimentally studied average and local mass transfer coefficients on the tip blade using the naphthalene sublimation technique. Kwak et al. [12] experimentally studied effects of the rim height and the tip gap clearance on the tip heat transfer coefficients. They found that higher rims reduce the heat transfer coefficients on the blade tip and shroud, but there was a weaker influence on both the pressure and suction sides. Mhetras et al. [13] experimentally studied effects of shaped holes on the tip pressure side and coolant jet impingement on the pressure side squealer rim from tip holes, using a pressure sensitive paint (PSP) technique. Mhetras et al. [14] also investigated the film cooling effectiveness from shaped holes on the near tip pressure side and cylindrical holes on the squealer cavity floor by the PSP technique. Wang et al. [15] found the overall cooling effectiveness is correlated as the functions of the Reynolds number of the hot mainstream by surface temperature measurements with an infrared thermal imaging system. O. Hassan and I. Hassan [16,17] investigated the film cooling effectiveness and the heat transfer coefficient of a Micro-Tangential-Jet film cooling scheme on a gas turbine vane using transient thermochromic liquid crustal (TLC) technique. The particle image velocimetry (PIV) plays a more important role in experimental fluid mechanics, including turbine aerodynamics experiments [18,19]. Praisner and Smith [20,21] investigated instantaneous flow field and heat transfer on the endwall by both PIV measurements and liquid crystal thermography (LCT) in a water tunnel. Palafox et al. [22] also investigated the interaction between the tip leakage flow vortex and passage vortex by using particle image