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# Effects of the mainstream turbulence intensity and slot injection angle on the endwall cooling and phantom cooling of the vane suction side surface

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## ABSTRACT

In order to obtain better performance, gas turbines always operate with high inlet temperature. This contributes to a high level of thermal load on the first stage vane endwall. To ensure safe operation of a gas turbine within a proper temperature range, the cooling performance of the vane endwall must be further investigated. In the present study, effects of the mainstream turbulence and upstream coolant flow direction on the endwall cooling and vane suction side surface phantom cooling were numerically investigated. Three-dimensional (3D) Reynolds-averaged Navier–Stokes (RANS) equations combined with shear stress transport (SST) $k-\omega$ turbulence model were solved to conduct the numerical simulations on basis of the validated turbulence model. The calculated results indicate that both the adiabatic cooling effectiveness on the endwall and the phantom cooling effectiveness on the vane suction side surface are significantly influenced by slot injection angle. For $\alpha = -30^\circ$, the coolant injection is driven towards the vane suction side, which contributes to the lowest adiabatic cooling effectiveness level on the pressure side endwall and the highest phantom cooling effectiveness level on the vane suction side surface. With the increase of the slot injection angle, the adiabatic cooling effectiveness level on the pressure side endwall is enhanced significantly. In contrast, the phantom cooling (when the vane suction side is cooled by coolant originating from the endwall) of the vane suction side surface is reduced significantly. This is because a large slot injection angle leads to a large coolant momentum towards the pressure side. Moreover, the case with a smaller slot injection angle obtains a slightly higher area-averaged adiabatic cooling effectiveness level around the leading edge due to a relatively larger portion of coolant being confined near the leading edge. In addition, the inlet turbulence intensity has a small impact on the overall endwall cooling and the phantom cooling of the vane suction side surface compared to the slot injection angle.

## 1. Introduction

The soar of the energy demand all over the world and strict regulations on decreasing NOx emission have become great challenges to gas turbine designers. Meanwhile, gas turbines as the indispensable power equipment are designed to operate at an extremely high level of inlet temperature to achieve higher thermal efficiency. However, in order to reduce the NOx emission from the combustor, a flat pattern temperature distribution is generated. As a result, the hot gas will not be confined to midspan region, but can extend all the way to the endwalls. Hence, the first stage vane endwall joint to the combustor outlet is one of the critical regions requiring special thermal protection [1]. For gas turbines, the interfaces between the turbine and the combustor are inevitable because the gas turbine is assembled with different units, hence these interfaces provide relatively higher-pressure coolant injection supplied by the compressor to prevent the mainstream hot gas ingestion. The inlet boundary layer separates from the endwall at the upstream area of the vane leading edge, which forms a horseshoe vortex and changes the trajectory of the coolant. Consequently, a large portion of the coolant is drawn into the mainstream. Therefore, advanced cooling techniques are required to address the issue of low cooling effectiveness level and high thermal load of the region along the pressure side.

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## Nomenclature

| | |
|---|---|
| $d$ | diameter of film hole |
| $h$ | height of vane |
| $k$ | turbulent kinetic energy |
| $\dot{m}$ | mass flowrate |
| $T$ | temperature |
| $T_\infty$ | mainstream temperature |
| $T_{aw}$ | adiabatic wall temperature |
| $T_c$ | coolant temperature |
| $V$ | velocity |
| $u_\tau$ | friction velocity |
| $v$ | fluctuating velocity |
| $x$ | lateral coordinate |
| $X$ | non-dimensional lateral coordinate $X = \frac{x}{d}$ |
| $y$ | vertical coordinate |
| $Y$ | non-dimensional vertical coordinate $Y = \frac{y}{d}$ |
| $z$ | streamwise coordinate |
| $Z$ | non-dimensional streamwise coordinate $Z = \frac{z}{d}$ |
| $y^+$ | dimensionless wall-normal height of first cell at wall |

*Greek*

| | |
|---|---|
| $\alpha$ | slot injection angle |
| $\theta$ | non-dimensional temperature $\theta = (T - T_c)/(T_\infty - T_c)$ |
| $\rho$ | density |
| $\eta$ | adiabatic film cooling effectiveness |
| $\bar{\eta}$ | laterally averaged film cooling effectiveness |
| $\bar{\bar{\eta}}$ | area-averaged film cooling effectiveness |
| $\tau$ | shear stress |
| $\mu$ | dynamic viscosity |

*Subscripts*

| | |
|---|---|
| aw | adiabatic wall condition |
| c | coolant conditions |
| in | inlet condition |
| rms | root-mean-square |
| $\infty$ | mainstream conditions |
| $w$ | wall condition |

Many studies concerning the flow and cooling mechanism of the leakage flow between the combustor and the turbine stage have been conducted. A comprehensive review of widely used platform heat transfer and cooling technologies can be found from Han et al. [2], Chyu [3], Simon and Piggush [4]. Blair [5] was the first to indicate that upstream film coolant injection reduced heat transfer and it also had an impact on the passage flow. He also conducted an experiment by using a smooth configuration with a trip wire to measure the variation of the boundary layer. His results indicated that the upstream slot and coolant injection both promoted transition within the boundary layer. The experiment by Burd et al. [6] investigated the cooling mechanism of the coolant leakage from the upstream slot. The results showed that the upstream slot coolant leakage achieved an overall 6% higher cooling effectiveness level relative to the case without the upstream slot coolant leakage. Based on an experiment, Pasinato et al. [7], Nicklas et al. [8] and Knost et al. [9] showed that upstream slot coolant was ejected non-uniformly and driven towards the suction side of the passage and the upstream slot leakage. Therefore, the coolant was easily lifted off the endwall surface and then drawn into the passage vortex flow. This resulted in a large uncooled region around the vane pressure side.

A detailed review by Bunker [10] indicated that the configuration of film holes was of significance for improving the cooling effectiveness. The experiment by Gritsch et al. [11] investigated the effect of different fan-shaped holes in terms of the film cooling effectiveness and heat transfer coefficients. The results showed that the cooling effectiveness and heat transfer of a fan-shaped hole diffused in both lateral and streamwise orientation were superior to a conventional film hole which only diffused laterally, particularly at a high blowing ratio.

For purpose of a high cooling effectiveness level, the upstream slot was implemented to enhance the cooling performance of the endwall. The experiment by Cardwell et al. [12] suggested that the hot regions can be significantly reduced by decreasing the width of the upstream slot. This contributed to the coolant spreading uniformly due to the high momentum of the coolant injection. Moreover, Cardwell et al. [13] conducted experiments to investigate the influence of the endwall alignment on the endwall film cooling performance. They concluded that the endwall alignment enhanced the cooling effectiveness significantly when the pressure side endwall was higher than the suction side endwall. To obtain better cooling performance, some researchers put forward new cooling configurations. Thrift and Thole [14] investigated the influence of flow injection angle on a leading-edge horseshoe vortex. They found that high momentum injection increased the endwall heat transfer at each slot angle. In addition, Saumweber et al. [15] indicated that free-stream turbulence has a significant effect on heat transfer coefficients, especially for the shaped holes.

To obtain better cooling performance, some researchers put forward new cooling configurations. Based on the flow structure near the leading edge-endwall junction, Milidonis et al. [16] proposed the slot injection and their experiments indicated that a higher film cooling effectiveness was achieved around the blade-endwall corner junction due to the assistance by leading edge endwall vortex flow. Moreover, Du and Li [17] proposed a novel upstream slot configuration. The simulated results showed that the filleted upstream slot obtained superior film cooling performance of the endwall surface in comparison with the conventional slot configuration. In addition, a numerical study by Du et al. [18] concerning the effect of the leading edge injection slot stated that the film cooling effectiveness of the leading edge-endwall junction was significantly enhanced by introducing the leading edge injection slot.

In the endwall cooling system, a part of coolant inevitably mixes with mainstream, some of lifted coolant will be driven by the passage vortex towards the vane suction side surface. As a result, the vane suction side surface can be cooled by this portion of the coolant. This cooling mechanism is called phantom cooling, which has been discussed and investigated for several decades in the gas turbine industry. Although many researchers have discussed it, only a few really have conducted investigation concerning the performance of phantom cooling. Two papers by Roback and Dring [19,20] presented phantom cooling measurements of a one and half stage rotating turbine stage by using a gas chromatography method. Zhang et al. [21] expanded the phantom cooling definition and conducted experiments to investigate the effects of the vane showerhead injection angle and film compound angle on nozzle endwall phantom cooling. The results indicated that phantom cooling on the endwall by the SS film injections was found to be insignificant, but phantom cooling on the endwall by the pressure side airfoil film injections significantly enhanced the endwall phantom cooling but was a strong function of the mass flow rate. Experiments by Zhang and Yuan [22] investigated the phantom cooling on the suction side blade surface by the endwall film cooling.