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# Influence of different film cooling arrangements on endwall cooling

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ABSTRACT

The complex large scale coherent vortex systems which originate and develop through the endwall passage have strong interaction with the film cooling flows near the endwall. Two full coverage film cooling arrangements on a typical flat vane endwall were investigated experimentally. The influence of coolant mass flow rate and density ratio on each configuration was studied. Detailed measurements of adiabatic film cooling effectiveness distribution were conducted using PSP technique. The characteristics of different film cooling arrangements were analyzed. As the coolant mass flow rate rises, the film cooling coverage becomes better for both configurations. The influence of density ratio on film cooling distribution is quite complex. The results indicate that the configuration with iso-pressure line distributed film cooling has a more uniform distribution of film cooling effectiveness while the configuration with axial distributed film cooling has a better coverage mainly downstream of the passage.



## 1. Introduction

As the energy demand of the whole world rises, gas turbine has become an indispensable power-equipment in many fields because of its high efficiency and low emission. To further increase the output and efficiency of modern gas turbine, the turbine inlet temperature and single-stage load are increased which results in a higher thermal load and more three-dimensional aerodynamic loss [1]. In order to reduce $NO_x$ emissions and other pollutants generated during combustion, premixed combustor is preferred [2,3]. The employment of premixed combustor will change the combustor exit temperature profile from a parabola to a more uniform one [3]. Hot spot may occur from 10% to 90% vane span. These will directly affect the cooling of the first stage vane especially the endwall region.

The secondary flow structures make the flow field near the endwall highly three-dimensional. The vortices originate from the leading edge horseshoe vortex migrate and develop through the entire passage [4]. The early researches on endwall mainly focused on the flow field structures, aerodynamic and heat transfer characteristics when it was unnecessary to cool the endwall [5–7]. Afterwards discrete film holes were applied to the endwall cooling. Quite a few investigations found that the complex flow field in the near endwall region has a significant effect on the endwall film cooling and most of them showed negative effect of endwall secondary flow. Takeishi et al. [8] studied the influence of secondary flows in the passage on endwall film cooling and found that the endwall film cooling jets were deflected from the pressure side to the suction side. Thomas et al. [9] conducted experimental and numerical investigation of 1st stage vane endwall film cooling and found that due to the complex vortex and effect of pressure gradient, the areas close to leading edge and pressure side as well as the region around trailing edge were difficult to be cooled. Wright et al. [10] showed that the vortices formed upstream of the blade cascade would greatly reduce the endwall film cooling effectiveness. Based on a systematic study of endwall film cooling, Friedrichs et al. [11–13] proposed several distinct regions requiring individual cooling hole placements because of the influence of complex flow field near endwall and optimized the endwall film cooling depending on the flow pattern near the endwall. However the secondary flow is not always harmful to endwall cooling. Experimental results from Zhang et al. [14] and Zhang et al. [15] showed that the secondary flow and horseshoe vortex could carry the film cooling discharged from showerhead and pressure side to cover the endwall.

Meanwhile, the film cooling jets also affect the flow field and development of vortex near the endwall. Many experimental and numerical works have investigated the influence of film injection on the endwall cooling in front of the leading edge [16–18]. Recently with aid of non-intrusive measurement techniques, more parameters are studied. Zhang et al. [19] measured the surface distribution of film cooling effectiveness by using PSP technique. The results indicated the existence of a strong interference between the cooling jets and the endwall secondary flows. PSP technique was also used by Wright et al. [20] to study the film

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**Nomenclature**

| | |
|---|---|
| $C$ | gas concentration [–] |
| $C_{ax}$ | axial chord length [m] |
| $C_d$ | discharge coefficient [–] |
| $D$ | hole diameter [m] |
| $D.R$ | density ratio [–] |
| $k$ | constant [–] |
| $L$ | hole length [m] |
| $M$ | blowing ratio [–] |
| $Ma$ | mach number [–] |
| $M_{air}$ | molar mass of air [g/mol] |
| $M_c$ | molar mass of coolant [g/mol] |
| $M_\infty$ | molar mass of mainstream [g/mol] |
| $P$ | pressure [Pa] |
| $p$ | pitch length [m] |
| $R$ | gas constant for air [J/kg K] |
| $Re$ | Reynolds number [–] |
| $S$ | vane span [m] |
| $T$ | temperature [K] |
| $U$ | velocity [m/s] |
| $X, Y, Z$ | coordinates [m] |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | inclined angle [°] |
| $\beta$ | compound angle [°] |
| $\eta$ | film effectiveness [–] |
| $\rho$ | Density [kg m$^{-3}$] |

*Subscripts*

| | |
|---|---|
| $aw$ | adiabatic wall |
| $c$ | coolant |
| $m, \infty$ | mainstream |
| $r$ | recovery |
| $s$ | static |
| $t$ | total/stagnation |

*Acronyms*

| | |
|---|---|
| AAEV | algebraic anisotropic eddy viscosity |
| AASF | algebraic anisotropic scalar flux ratio |
| CFD | computational fluid dynamics |
| MFR | mass flow ratio |
| PS | pressure side |
| PSP | pressure sensitive paint |
| PIV | particle image velocimetry |
| SS | suction side |

cooling effectiveness distributions on a blade platform with both purge flow and discrete film holes. Takeishi et al. [21] investigated the influence of film cooling jet on leading edge horseshoe vortex employing LIF, PIV techniques. They concluded that enough amount of coolant or reasonable combination of distance and blowing ratio could efficiently reduce the vortex intensity. However, the horseshoe was enhanced if the inclined angle was too large or blowing ratio was not high enough. Thrift and Thole [22] studied the effect of trench flow injection angle upstream of leading edge on the endwall cooling. The results showed the influence of blowing ratio and injection angle on endwall heat transfer and the formation of horseshoe vortex.

A certain number of studies were carried out to investigate the performance of full coverage endwall film cooling. Barigozzi et al. [23] studied the effects of a fan-shaped hole endwall cooling geometry on the performance of a nozzle vane cascade. The results indicated that the passage vortex and the 3D effects were weakened at high injection rates leading to a strong reduction of the endwall cross flow. Knost and Thole [24,25] conducted measurements of two endwall film cooling arrangements combined with cooling from a flush slot that simulates leakage flow between the combustor and turbine sections. They found that the momentum flux ratio had a significant impact on cooling performance. Andrei et al. [26] performed PSP measurement of film cooling effectiveness on a real engine vane. They found good adiabatic effectiveness downstream the location of throat because of the superposition of film cooling. However due to the secondary flow, the fillets were not well protected.

In this paper, two typical full coverage film cooling arrangements of endwall were investigated experimentally at different coolant mass flow ratios and density ratios. Detailed measurements of adiabatic film cooling effectiveness distribution of the endwall were performed. The influence of the coolant mass flow ratio and density ratio on the distribution of endwall film cooling was studied. The characteristics of different film cooling arrangements were analyzed.

## 2. Experimental facilities

The cooling characteristics of endwall configurations with different film cooling arrangements were experimentally investigated in a linear vane cascade. The test rig for the endwall film cooling measurements was described in detail in the previous works [27]. The vane cascade was installed in an open loop wind tunnel driven by a radial compressor which simulated the mainstream of the cascade, in Fig. 1. The main flow field was rectified to a homogeneous flow field before entering the cascade. Both the temperature and pressure were measured upstream of the vane leading edge.

A displacement air compressor or high-pressure gas tank provided the coolant gas to the endwall which made an independent system. The coolant massflow rate was controlled and measured by electric mass flowmeters. The temperature of the coolant was set and determined by a heat exchanger prior to entering the test section. The heat exchanger maintained the coolant at a certain temperature within a difference of 0.5 °C to that of the mainstream as required by the pressure sensitive paint technique which is described in the next part. The coolant temperature inserted in the coolant plenum was measured by a thermocouple below the endwall.

The linear vane cascade consisted of four vanes and three passages between them, Fig. 2. The airfoil of the vane was from an F-class turbine. As optic measurement techniques were applied in the experiment, the frame of the cascade section was made of transparent plexiglass. The ordinate origin is set on the endwall at the stagnation point of the vane. $X$ coordinate is parallel to the axial direction and $Y$ coordinate is pointing from pressure side to suction side. $Z$ coordinate is parallel to the spanwise direction. All the following discussions are based on this coordinate system. The endwall configuration for study was fixed in the middle passage of the cascade. The pressure distributions at the midspan of the vanes and on the endwall surface were measured by static pressure taps and pressure sensors before all experiments.