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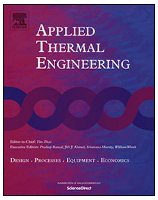

Research Paper

Influence of mainstream turbulence on turbine blade platform cooling from simulated swirl purge flow

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HIGHLIGHTS

- Performing engine – cascade analogy for the investigations of platform and suction surface cooling.
- Elevated mainstream turbulence intensity improves cooling performance.
- Rotation effect deviates coolant trajectories and decreases cooling effectiveness.

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ABSTRACT

The paper presents the combined effect of mainstream turbulence intensity and swirl ratio on the cooling performance of turbine blade platform and suction surface. Pressure sensitive paint (PSP) mass transfer technique provides detailed cooling effectiveness distribution on platform and suction surface. Experiments have been completed in a low speed wind tunnel facility with a five blade linear cascade. The inlet Reynolds number based on the chord length is 250,000. Coolant to mainstream density ratio maintains at 1.5 to match engine conditions. Detailed mainstream turbulence intensities for test are Tu (%) = 0.72, 3.1, 6, 8.2, and 13. Swirl ratios (S) of 1 presents without rotation effect but 0.4 simulates high relative motion between rotor and coolant to represent rotation effect. Coolant to mainstream mass flow rate ratios are MFR (%) = 0.5, 1.0 and 1.5. Results show that elevated mainstream turbulence intensity increases cooling effectiveness in general. Best cooling performance is observed for high mainstream turbulence intensity of 13% cases no matter with or without rotation effect. Rotation effect reduces coolant capability at higher MFR of 1% and 1.5% cases for tested mainstream turbulence intensities.

1. Introduction

For higher thermal efficiency and specific power of modern gas turbines, increasing turbine inlet temperature becomes necessary. While turbine inlet temperature is far beyond the yielding point of the structural components, advanced turbine cooling technologies become imperative from Han et al. [1]. Due to larger area of the platform and endwall directly exposed to hot mainstream gas, it needs to effectively cool these regions. Leakage flow from the gap between combustor exit and nozzle inlet can be used for endwall cooling. Purge flow from the gap between stator and rotor is used for platform cooling. However, the strong secondary vortexes developed ahead and within the flow passages dominate coolant trajectories. More effective cooling schemes can be proposed by better understanding and being in control of these secondary vortexes. Two informative review articles [2,3] summarized critical findings for endwall and platform cooling.

In gas turbine engine flow field, the first-stage vanes behind the exit of the combustor usually experience high turbulence ranging from Tu = 7% to 20%. In general, elevated turbulence level promotes earlier boundary layer transition, and increases heat transfer and aerodynamic loss. Effect of the mainstream turbulence intensity on heat transfer of the turbine blade surfaces was investigated by Zhang et al. [4] with Tu = 0.7~17% in a low speed wind tunnel and Nix et al. [5] around Tu = 10~12% in a transonic turbine cascade. They both concluded elevated mainstream turbulence intensity increased heat transfer coefficient.

Mainstream turbulence intensity effect (Tu) on flat surfaces was discussed in [6–11]. Saumweber et al. [6] reported elevated Tu from 3.6% to 11% reduced film cooling effectiveness on the flat plate up to 30% for shaped holes. Chen et al. [7] studied Tu = 0.5% and 6% on the flat plate film cooling from low to engine-like density ratios. Increasing Tu reduced film cooling effectiveness for fan-shaped holes but increased effectiveness slightly for cylindrical holes at higher blowing ratios. Colban et al. [8] investigated Tu = 1.2% and 8.9% on

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endwall film cooling using cylindrical and fan-shaped holes. They reached the similar conclusion as [7] for both holes. Wright et al. [9] studied Tu = 0.75% and 13.4% on platform cooling by ejecting purge flow as coolant in front of the blade leading edge. They mentioned that elevated turbulence weakened the passage vortex to improve platform cooling. It was indicated by Thole et al. [10] that high mainstream turbulence can flatten out the endwall inlet boundary layer profile. This implied that horseshoe vortex near leading edge and associated passage vortex can be suppressed by high mainstream turbulence.

Rotation effect is one of the critical parameters on platform cooling. However, it is much more challenging to conduct measurements in a rotating platform to study rotation effect on platform cooling performance. Instead, three research groups [11–13] simulated rotation effect on platform cooling in a stationary cascade. They created swirl purge flows resulting from relative motion between rotating rotor-platform and stationary purge flow. Swirl purge flow (served as coolant) has a tangential velocity component to simulate the effect induced by rotation. Barigozzi et al. [11] compared purge flow without rotation effect and swirl purge flow with rotation effect on platform cooling at Tu = 0.6%. Stinson et al. [12] used two swirl inclined angles to simulate rotation effect on platform cooling at Tu = 6%. Li et al. [13] performed a more comprehensive study of swirl ratio effect (S = 0.4, 0.6, 0.8, and 1) on platform and suction surface cooling at Tu = 0.72%. These three studies reached the same conclusion that rotation effect simulated by swirl purge flow had a negative effect on cooling effectiveness. Strength of the horseshoe vortex and passage vortex was enhanced by purge swirl vortex induced by rotation. Stronger vortex near leading edge and inside flow passages is mixed with more coolant and decreased coolant capability on platform.

The current study investigates the combined effect of mainstream turbulence intensity (Tu) and swirl ratio (S) or rotation effect on platform cooling and blade suction surface phantom cooling. From a previous study [13], effectiveness consistently changed while varying swirl ratio from 0.4 to 1. It is reasonable to choose the two most representative swirl ratios to study the combined effect. Swirl ratio of 0.4 simulates the most pronounced rotation effect and 1 represents without rotation effect. These two swirl ratios combine with five mainstream turbulence intensities (Tu = 0.72, 3.1, 6, 8.2, and 13%) for test. Three typical coolants to mainstream mass flow rate ratios (MFR) for the study are 0.5, 1, and 1.5%. Current design adapts axisymmetric contour of a dolphin nose to suppress horseshoe vortex in front of the blade leading edge row. Pressure sensitive paint (PSP) mass transfer technique is workable to measure small level of the phantom cooling effectiveness, seen from Li et al. [14]. Furthermore, PSP has demonstrated good capability of measuring effectiveness on the curve surfaces such as high turning turbine blade surfaces [14] and full-scale turbine vanes in an annular cascade [15]. Therefore, PSP is selected to show detailed high resolution conduction free contours of platform cooling and suction surface phantom cooling.

2. Experimental setups and procedure

2.1. Simulation of swirl purge flow

Because of the relative motion between rotor and stator in the real gas turbine engines, i.e. stationary endwall and rotating platform, purge flow (coolant) from the seal gap between rotor and stator contains certain amount of the swirl motion toward rotor platform. Velocity triangle analysis shows engine-cascade analogy in Fig. 1. Swirl ratio of S = 1 represents no relative motion between rotor and coolant but S = 0.4 simulates 60% of the relative motion or 60% of the coolant with motion. For S = 0.4 case, rotation induces a tangential velocity V_r to generate a purge swirl vortex inside purge cavity before coolant swirls up into mainstream. It should be noted that injection angle of 30° with respect to S = 0.4 is a conceptual number to represent simulated large degree of the relative motion between rotor and coolant in current study. Each swirl ratio has its own nondimensional engine representative velocity ratios of VR^* and VR^{**} in Table 1 provided by solar turbines to match industrial engine conditions. VR^* is the ratio of circumferential (tangential) velocity component to cascade inlet velocity. VR^{**} is the ratio of actual injection velocity to cascade inlet velocity. Hole diameter (D), hole spacing (P_e/D) are designed based on VR^{**}.

Test section designed for simulating swirl purge flow is shown in Fig. 2 (a). Swirl purge flow or purge flow injects from a long

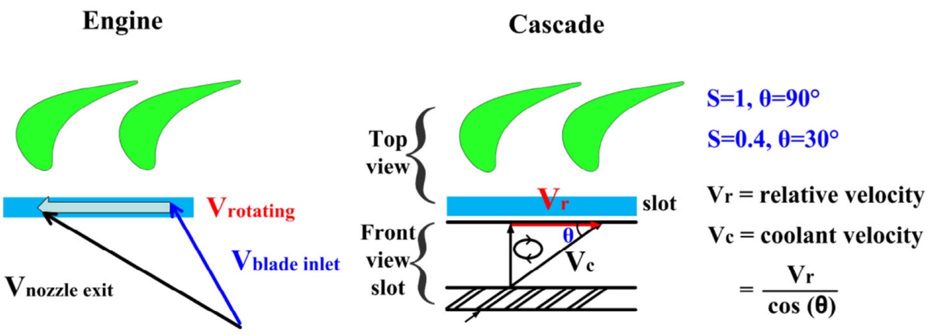

Fig. 1. Velocity triangle analysis.

Table 1
Specifications of current tested cases.

Swirl ratio S	Injection angle θ (degree)	Coolant to mainstream mass flow rate MFR (%)	Hole diameter D (cm)	Hole spacing P_e/D	VR^*	VR^{**}	Mainstream turbulence intensity Tu (%)
0.4	30	0.5	0.45	3.75	0.87	0.99	0.72% (no grid) [13]
		1	0.63	2.65			3.1%, 6%, 8.2%
		1.5	0.77	2.17			(fine grid)
1	90	0.5	0.71	2.56	0	0.40	13% (coarse grid)
		1	1.00	1.87			
		1.5	1.22	1.48			

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