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Coherent structures in the wake behind a trailing edge cutback

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ABSTRACT

An experimental study was performed to investigate the influence of coolant ejection on the aerodynamic characteristics of the unsteady wake behind a trailing edge cutback. A high-resolution planar particle image velocimetry (PIV) system was emlpoyed to conduct detailed flowfield measurements at a Reynolds number of $Re_h = 2000$. The time-averaged velocity fields, the distributions of reverse-flow intermitteny and velocity defects were comparatively studied, and contours of streamwise Reynolds stress and shear stress were examined to disclose the influence of coolant ejection on wake aerodynamic performance. Proper orthogonal decomposition (POD) ananlysis was applied to the velocity flowfileds to disclose the evolution of coherent structures and the mixing process between the cooling stream and mainstream. Large scale coherent structures shed from both the lip and lower plates were identified in low-order modes, indicating that these are the most energtic structures in the wake. Moreover, a "strip" structure was found in the unpaired third eigemode for lower blowing cases (VR = 0.5 and 0.75). By POD filtering with first six eigenmodes, the flapping motion of the separated shear layer from the upper shear layer of the lower plate was observed. Coherent strucutres were identified from the contours of swirling strength. It is speculated that the "strip" structure and the flapping of the seprarated shear layer is resuled from vortex merging, i.e., the merging of two clockwise-rotating vortical structures shed from the upper shear layers of the lip and lower plates.

1. Introduction

Thermodynamic analysis of gas turbines shows that the thermal efficiency and power output of a gas turbine greatly rely on the higher turbine inlet temperature [1,2]. Advanced high-performance gas turbines are operated at peak temperatures that are well beyond the maximum allowable melting temperature of the blade material, and turbine inlet temperatures even in excess of 2000 K [3,4] have been reported in recent developments. The turbine blades are therefore subjected to severe heat loads and require extensive internal and external cooling in order to operate at reliable conditions. Analyses of temperature distributions show peak temperatures at both the leading and trailing edge of a turbine blade [5–7]. The implementation of trailing edge cooling is particularly difficult due to structural and aerodynamical constraints. The thickness of the trailing edge is expected to be as thin as possible to minimize aerodynamical loss, which would certainly exacerbate the difficult circumstances for trailing edge cooling from heat transfer considerations. Advanced trailing edge cooling designs feature a cutback on the pressure side of the blade trailing edge and cooling air extracted from upstream compressor stages is continuously ejected through a breakout slot onto the exterior cutback surface, forming an insulating film to prevent hot mainstream gas from impinging onto the wall of the suction side, as shown schematically in Fig. 1.

In fact, the internal or external structures in the trailing edge section are very complicated in order to improve the film-cooling effectiveness. Numerous efforts have been devoted to the investigation of geometrical effects on film cooling performance, e.g. variations in the rib- or pin-fin-array, slot-to-lip ratio, cutback lip thickness or shape, and ejection angle of cooling stream [4,8–12]. Taslim et al. [8] experimentally studied the effects of slot geometries on film-cooling effectiveness. Four different slot lip thickness-to-height ratios and three different slot width-to-height ratios were tested over a blowing ratio (coolant-to-mainstream mass flux ratio) range of 0–1.3. The results showed that the cooling effectiveness is highly sensitive to slot-to-lip ratio, but not significantly sensitive to either slot width-to-height ratio or density ratio. Martini et al. [9] conducted a comprehensive experimental study to investigate film cooling performance downstream of various trailing edge cooling slots. The film cooling effectiveness was found to be significantly affected by internal slot design and the relatively thick lip, which may give rise to vortex shedding. Flow instabilities generated in the wake of the lip might be involved in the relatively fast decay of film cooling effectiveness along the trailing edge cutback. Large-scale unsteadiness was proposed to play an important role for the mixing between the hot and cold gas streams [13,14].

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Nomenclature

h	slot height
l_c	length of recirculation zone
n	order of eignemode
$\bar{u}$	time-averaged streamwise velocity
v'	transverse fluctuating velocity
M	blowing ratio
Re_h	Reynolds number based on the slot height
U_c	velocity of the coolant
U_g	velocity of the hot gas
U_0	free stream velocity
VR	velocity ratio
$\langle u'u' \rangle / U_0^2$	normalized streamwise Reynolds stress
$\langle u'v' \rangle / U_0^2$	normalized Reynolds shear stress
λ_n	eigenvalue
λ_{ci}	swirling strength
γ_t	reverse-flow intermittency

Barigozzi et al. [15] experimentally investigated the unsteady mixing process taking place between the coolant and main flow downstream of the cutback, up to the trailing edge. Large scale coherent structures were observed, which presence was still evident up to the trailing edge. The shape and rotation direction of the coherent structures changed with injection conditions, as a function of coolant to mainstream velocity ratio, strongly influencing the thermal protection capability; however, the Strouhal number almost remained unchanged. Results of highly resolved LES of trailing edge cutback film cooling reported by Schneider et al. [5] showed that the blowing ratio has a clearly visible effect on the mean flow and the kind of coherent structures that were formed behind the lip of the cutback. The cooling effectiveness was highly related to the change in type and strength of the dominant coherent structures. These structures dominated the mixing between the hot and cool gas and the heat transfer. Coherent structures periodically shed from the blunt cutback lip were also observed in a standard RANS modeling of trailing edge cutback cooling [16]. As the blowing ratio increased in a certain range, these structures caused a counter-intuitive decrease of the adiabatic film cooling effectiveness, which was also observed in previous results [5].

From the aforementioned literatures, it emerges that large scale coherent structures play a significant role in the mixing process between the coolant and main flow, which would then have a great impact on the trailing edge cooling effectiveness. Most of the previous studies [1–5,8–16] focused on the area immediate behind the breakout slot, i.e., from the slot exit to the trailing edge, however few studies have extended to the wake region behind the trailing edge. As a matter of fact, the coherent structures shed from blade trailing edge would be continuously convected downstream and affect the wake consequently. The distributions of the wake aerodynamical parameters (velocity, temperature, turbulent intensity, etc.), which, meanwhile, serves as the incoming flow conditions for the downstream blades, might be significantly changed, and therefore the performance of the downstream blades or stages would be greatly affected.

The main concern of the present study is to shed light on the influence of blowing ratio on flowfileds and coherent structures in the trailing edge cutback wake from an aerodynamic view. Toward this end, a simplified trailing edge cutback model without interior ribs or pin-fins was adopted to eliminate other impact factors except blowing ratio. Particle image velocimetry (PIV) measurements of the wake behind the trailing edge cutback were conducted and time-averaged flowfileds and turbulent statistics were detailedly examined. Proper orthogonal decomposition (POD) analysis was extensively employed to extract and depict the unsteady behavior of the large scale coherent structures.

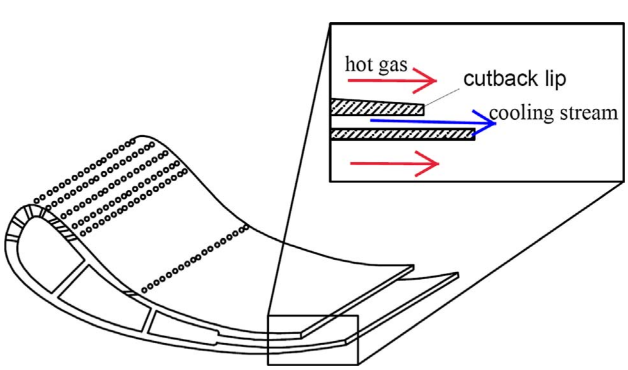

Fig. 1. Schematic of the high pressure turbine blade with trailing edge cutback cooling.

2. Experimental apparatus

2.1. Overview of the wind tunnel

The experiments were performed in the subsonic open-circuit wind tunnel (Fig. 2) located at the Department of Power Engineering, University of Shanghai for Science and Technology. The test section was 300 mm (width) × 400 mm (height) in the cross section and 2000 mm in length. The wind tunnel has a contraction section upstream of the test section and a settling chamber with honeycombs and 4 screens to provide uniform low-turbulence incoming flow. Two-dimensional flow were obtained at the test section, and the spanwise non-uniformity of the mean velocity is less than 1%. The turbulent intensity at the inlet of the test section was found to be less than 0.6% measured by hotwire anemometry. Mainstream flow was driven by a centrifugal blower and a 1.5 kW motor. The free-stream velocity was maintained at $U_0 = 3\,\mathrm{m\,s^{-1}}$, resulting in a Reynolds number based on the slot height $Re_h = 2000$. It is noteworthy that the Reynolds number of the present experiment is relatively lower than engine value due to the limitation of our test facility. It is demonstrated that the Reynolds number is significant to the aerodynamic and heat transfer performance [8,12] of real engine blade, however, as the main consideration of present study is focused on the flow mechanism of a simplified model come from engineering practice, the disparity in Reynolds number is not so critical for present study.

2.2. Trailing edge cutback model

The trailing edge cutback model used in the present study was designed to replicate only the trailing edge portion of a typical high pressure turbine blade with trailing edge cooling. As shown in Fig. 3, the trailing edge cutback model was simplified as a combination of two parallel plates with different lengths. The thicknesses of the lip and lower plates were equal to the height of the slot between the two parallel plates. The interaction between the slot jet flow and main flow is studied, emphasizing more from the point of view of flow mechanism. To this end, some geometrical discrepancies (e.g. the trailing edge corner geometries, the pin-fin structures, and the sloped lip plate, etc.) between the simplified model and the real engine blade are ignored. The head of the test model was machined to be semielliptical in order to avoid flow separation. A well-designed wedge-shaped filter was inserted into the plenum between the two plates for the purpose of obtaining uniform cooling stream exhausted through the slot. Coolant was supplied through the inlets on both sides of the wedge-shaped filter and made a 90-degree turn immediately after it entered the plenum. The cooling stream was directed to the slot exit through the orifices in the filter, which have a diameter of 4 mm. The turbulence intensity of