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Effect of film cooling on the aerodynamic performance of an airfoil

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A B S T R A C T

The effect of film cooling on the aerodynamic performance of turbine blades is becoming increasingly important as the gas turbine operating temperature is being increased in order to increase the performance. The current paper investigates the effect of blowing ratio on the aerodynamic losses of a symmetric airfoil by pressure measurements and Particle Image Velocimetry (PIV). The test model features 4 rows of holes located on the suction side at 5%, 10%, 15% and 50% of the chord length. The Reynolds number based on the airfoil chord is 1.2×10^5. Experiments are performed by varying the location of air injection, the angle of attack, and the mainstream velocity. The coolant air is injected at ambient temperature and the blowing ratio is varied from 0 to 1.91. It is observed that the losses due to film cooling increase with blowing ratio of 0 to 0.48, and the wake is shifted towards the suction side. Conversely, the aerodynamic losses decrease when the blowing ratio is increased further from 0.64 to 1.91. This trend has been observed for all the experimental configurations. The effect of blowing ratio on flow separation is investigated with the time-averaged velocity fields obtained from PIV measurements. It is observed that low blowing ratios, the separation point shifts upstream and at high blowing ratios the ejected coolant energizes the flow and delays separation. The pressure field around the airfoil is reconstructed from the integration of the Poisson equation based on the PIV velocity fields. The experimental results can be used for validation of numerical models for predicting losses due to film cooling.

1. Introduction

Gas turbine manufacturers are committed to increasing the fuel efficiency of their engines by increasing the operating pressure and temperature. However, the materials used for turbine blades are severely limited in their maximum allowable temperature due to durability and structural problems such as creep, corrosion, oxidation and fatigue (Cohen et al., 1987; Boyce, 2002). The first stage of the high pressure turbine (HPT) is subjected to the most severe combination of stresses and temperature and is generally the limiting component of the engine (Boyce, 2002). Therefore, the HPT blades and nozzle guide vanes (NGV) are generally equipped with sophisticated cooling systems and thermal barrier coatings to maintain an acceptable temperature distribution on the airfoil. Air is extracted from last stages of the high pressure compressor (HPC) and is injected in the HPT for cooling the blades and vanes internally, and is subsequently ejected out through film cooling holes, trailing edge and blade tip. Several rows of film cooling holes are used to form a protective layer of air to act as a thermal barrier between the hot gases and the airfoil surface. Although this has been proven as an effective way to reduce the airfoil surface temperature, the ejected air might modify the aerodynamic characteristics of the flow around the turbine airfoil. With operating temperatures steadily increasing, it is important to account for the effects of film cooling on the blade/vane aerodynamic characteristics. Denton (1993) defined losses in terms of entropy generation due to viscous effects in boundary layers, mixing processes, shock waves, and heat transfer. His analysis showed that understanding the various physical mechanisms and quantifying accurately the rate of entropy creation due to these losses are not straightforward.

Several experimental investigations have been performed in the past to estimate the influence of film cooling on entropy increase. Jackson et al. (2000) tested a symmetric airfoil in a transonic non-turning test section. A single row of holes was placed on the suction side at 49% of the chord length from the leading edge. Both conical diffused holes and round cylindrical holes were tested. Pressure measurements were performed at one chord length downstream of the trailing edge at Mach numbers from 0.4 to 1.24. Losses were evaluated by normalized local total pressure

Abbreviations: CCD, Charge Coupled Device; FOV, Field of View; HPC, High Pressure Compressor; HPT, High Pressure Turbine; IAL, Integrated Aerodynamic Losses; KE, Kinetic Energy; PIV, Particle Image Velocimetry; NGV, Nozzle Guide Vane.

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Nomenclature

BR	blowing ratio = $\frac{\rho_c V_c}{\rho_\infty V_\infty}$
C_D	discharge coefficient
C_p	local total pressure loss coefficient
C_{pr}	pressure coefficient
c	airfoil chord
$f_\#$	f-stop
I	Momentum flux ratio = $\frac{\rho_c V_c^2}{\rho_\infty V_\infty^2}$
l	acquisition length
M	Mach number
N	number of image pairs
$\dot{m}$	mass flow rate
P	pressure
R	air gas constant
T	temperature
V	velocity

Greek symbols

α	angle of attack
δ_{PIV}	uncertainty in Particle Image Velocimetry
δt	time delay between PIV laser pulses
γ	heat capacity ratio
λ	area-averaged loss coefficient
ν	kinematic viscosity of air
Ω	total pressure loss coefficient
ρ	density

Subscripts

0	total quantity
1	upstream measuring location
2	downstream measuring location
∞	main-stream
c	coolant
s	isentropic
V	velocity
x	x-component
y	y-component

coefficients, normalized exit Mach number, and kinetic energy distributions. Their results indicate that aerodynamic losses increase with the Mach number ratio between the coolant and the mainstream. Integrated Aerodynamic Losses (IAL) were determined by integrating the total pressure difference between an upstream and a downstream location. It was found that integrated aerodynamic losses increased with the blowing ratio (BR). A strong dependency of the mixing losses on hole geometry was observed. Shock losses were isolated and proved to be lower than the mixing losses.

Ito et al. (1980) performed experiments in a 2-D turning turbine cascade consisting of 6 airfoils. They observed that for both pressure and suction side, a small amount of coolant ejection increased the total pressure losses but the losses diminished at high ejection rates. The total pressure losses across a turbine cascade are affected by the location of injection, the magnitude of injection, and the direction of the coolant flow momentum (Ito et al., 1980).

A turbine vane equipped with film cooling on the suction side was tested in a 2-D cascade by Chappell et al. (2010). The local stagnation pressure losses resulting from film cooling were located mainly in the wake region behind the suction side, as the air was ejected only into the suction surface. Increasing the blowing ratio entailed greater local aerodynamic losses, deficit in the normalized Mach number and kinetic energy contours. They reported that the IAL increased from 4% to 45%, when compared with a blade without film cooling.

Previous experiments isolated the effect of coolant ejection by testing an airfoil with one row of holes. Nevertheless, some investigations have also been performed on fully cooled blades. Osnaghi et al. (1997) carried out measurements on a NGV with film coverage. The authors reported an increase in thermodynamic loss coefficient with BR. They also reported that ejecting air and carbon dioxide resulted in equal losses if the test were carried out at the same global momentum flux ratio.

Results of Mamaev et al. (2015) were obtained from a vane block with film and convective cooling systems. The coolant air was ejected at the leading edge, suction side, pressure side, and the trailing edge. The authors observed that ejection of coolant increased the profile losses, which further rose if the coolant mass flow rate was augmented. Drost and Bolcs (1999) investigated the effects of film cooling by testing a vane with multiple film cooling stations. Their investigation showed that the primary loss coefficient with film cooling was 20–30% higher than for an uncooled blade.

In addition to experimental studies, CFD analyses have been conducted to assess the contribution of film cooling on losses. Walters and Leylek (2000) used the experiments done by Ito et al. (1980) to validate their RANS simulations with three different $k-\varepsilon$ turbulence models, namely: the standard $k-\varepsilon$ model (SKE) (Launder and Spalding, 1974), the RNG $k-\varepsilon$ (RNG) model (Yakhot and Orszag, 1986), and the realizable $k-\varepsilon$ (RKE) model (Shih et al., 1995). Their numerical results matched well with the experimental data. They reported that for suction side ejection, the local total pressure losses increased till a BR of 0.5 and then reduced as the BR was increased further.

Kubo et al. (1998) conducted a CFD investigation using the COBRA code developed by Toshiba R&D Center. It is an implicit, cell centered, finite volume Navier–Stokes code with the standard $k-\varepsilon$ turbulence model. The 2-D slot ejection was simulated to reproduce the effect of a row of discrete holes. Numerical results were compared with total pressure loss profiles obtained by a Pitot probe downstream the trailing edge. They concluded that 2-D CFD models are valid methods to predict total pressure loss as a good agreement was obtained between the experimental and numerical results.

Particle Image Velocimetry (PIV) has been used partially to investigate the effect of film cooling on airfoils. Johnson et al. (2014) tested a plate with cooling holes and identified that high values of density ratio between the cooling jet and the mainstream lead to an attached film, and therefore an improved cooling performance. Raffel and Kost (1998) used PIV on a slotted plate with a nozzle in order to simulate the trailing edge ejection of a transonic turbine blade. They recognized that losses can be reduced by ejecting a small amount of coolant flow out of the trailing edge. Uzol and Camci (2001) examined the aerodynamic losses on a turbine blade with coolant ejection from trailing edge by using PIV. They observed high total pressure loss in the wake region near the trailing edge due to the mixing of the coolant and mainstream flow for 0 to 3% ejection rates. Nevertheless, at high ejection rates, the ejected coolant had enough momentum to fill the wake, which in turn reduced the aerodynamic losses. Hassan (2013) also used PIV to investigate the flow field around a flat plate, and on a real turbine vane with film cooling. However, his research was focused on the thermal performance of the blade and does not provide results on the aerodynamic losses. One of the recent studies on film cooling using PIV was carried out by Eberly and Thole (2014), who produced time-averaged and time-resolved PIV data for a flat plate film-cooling flow at low and high-density ratios. They used a generic film-cooling hole geometry (round, inclined at 30°) with wide lateral spacing (P/D = 6.7) for this study. Their data indicated