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Structure analysis of adiabatic film cooling effectiveness in the near field of a single inclined jet: Measurement using fast-response pressure-sensitive paint

Ali Rahimi Khojasteh [a,b], Shao Fei Wang [a,b], Di Peng [a,b], Savas Yavuzkurt [c], Yingzheng Liu [a,b,*]

[a] Key Lab of Education Ministry for Power Machinery and Engineering, School of Mechanical Engineering, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai 200240, China
[b] Gas Turbine Research Institute, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai 200240, China
[c] Department of Mechanical and Nuclear Engineering, Pennsylvania State University, University Park, PA, United States

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ABSTRACT

In the present study, the film cooling effectiveness in the near field (x/D < 4) of a single inclined film-cooling jet was measured using fast-response pressure sensitive paint (fast-PSP) and a low-frame-rate CCD camera. Previous experimental data demonstrated considerable variation in this region, and good agreement was established beyond it (x/D > 4). The blowing ratios M = 0.5 and 1.0 were used. The coolant fluid was nitrogen and the air was the mainstream fluid, and both were kept at the same temperature. A fast-PSP measurement technique was used to determine the variations of the film cooling effectiveness with time. The contours of the time-averaged film cooling effectiveness demonstrated that the coolant spread on the surface throughout the near-hole region at M = 0.5, while at M = 1.0, the coolant jet detached from the surface immediately behind the hole and reattached downstream around 1.5 D behind the hole's trailing edge. The spatial distribution of the film cooling effectiveness fluctuations and its cross-correlation pattern convincingly reflected the substantial influence of the energetic unsteady flow structures in the jet and cross-flow interaction. Subsequently, the Proper Orthogonal Decomposition (POD) method was used to identify the coherent parts of the film cooling effectiveness, which are regarded as the signatures of the convective large-scale vortical structures above the wall. At M = 0.5, the near-hole region was subjected to the dominant influence of the counter-rotating vortex pair (CRVP), characterized by the first two POD modes, which contained up to 40% of the fluctuation energy. Two signatures of large-scale symmetric structures were identified with similar energy levels. The second two POD modes corresponding to the horseshoe vortex near the leading edge of the hole were identified and contained around 10% of the fluctuation energy. Phase-dependent variations of the large-scale convective signatures in relation to the quasi-periodic CRVP and horseshoe vortex were separately detected. At M = 1.0, the signatures of the CRVP and the horseshoe vortex were also seen in the POD modes, though they were relatively difficult to distinguish.

1. Introduction

In modern aero-engines and power gas turbines, the gas temperature at the turbine inlet is well beyond the melting temperature of nickel-based super alloys. The film cooling technique has been extensively used to protect the hot sections from excessive heat. The continuous coverage of the surface by the coolant fluid behind the film cooling holes is thus critically important. However, the sudden decrease in film cooling effectiveness immediately behind the hole typically results in local overheating and damage to the blade [1,2]. As the coolant issues from the hole, the fluid enters the mainstream, giving rise to highly three-dimensional mixing phenomena for high blowing ratios. In the jet-crossflow interaction, the superimposed energetic vortical structures overwhelmingly dominate the spatial and temporal variations of the coolant coverage on the surface in the near-hole region. Therefore, a thorough understanding of the film cooling dynamics near an injection hole is highly desirable.

The adiabatic film cooling effectiveness is a dimensionless and normalized form of the adiabatic wall temperature T_{aw}, which is defined as

* Corresponding author at: Key Lab of Education Ministry for Power Machinery and Engineering, School of Mechanical Engineering, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai 200240, China.

E-mail address: yzliu@sjtu.edu.cn (Y. Liu).

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Nomenclature

a_i	mode coefficients of POD
C	oxygen concentrations
C_{aw}	oxygen concentrations of air/coolant very near the wall
C_∞	oxygen concentrations of mainstream
D	hole diameter [mm]
DR	density ratio (ρ_c/ρ_∞)
I	intensity of light recorded by CCD camera
I_{Air}	intensity of air
I_b	intensity of background
I_{N2}	intensity of nitrogen
I_{ref}	intensity of reference
L/D	hole length-to-diameter ratio
M	blowing ratio $(\rho_c U_c/\rho_\infty U_\infty)$
n	mode number of POD
$P_{O_2,Air}$	partial pressure of oxygen with air as coolant
$P_{O_2,coolant}$	partial pressure of oxygen
$P_{O_2,N2}$	partial pressure of oxygen with nitrogen as coolant
$P_{O_2,ref}$	reference pressure
R	temporal correlation matrix
$R_{\eta\eta}$	correlation function
Re	Reynolds number
T_∞	mainstream temperature [K]
T_{aw}	adiabatic wall temperature [K]
T_c	coolant temperature[K]
U_c	coolant velocity [m/s]
U_∞	mainstream velocity [m/s]
x	streamwise coordinates [mm]
y	wall normal coordinate [mm]
z	lateral coordinate [mm]
X, Y, Z	Cartesian coordinates

Greek symbols

η	film cooling adiabatic effectiveness
$\bar{\eta}_c$	time-averaged film cooling adiabatic effectiveness at centerline
$\bar{\eta}$	time-averaged film cooling adiabatic effectiveness
$\acute{\eta}$	instantaneous fluctuating film cooling adiabatic effectiveness
$\tilde{\eta}$	decomposed fluctuating film cooling adiabatic effectiveness
ρ	density [kg/m^3]
ρ_c	coolant density [kg/m^3]
ρ_∞	mainstream density [kg/m^3]
λ_i	eigenvalues of POD
Λ	diagonal matrix with eigenvalues
φ	phase angle
σ_i	spatial eigenfunction

Abbreviations

CCD	Charge Coupled Device
CRVP	Counter-Rotating Vortex Pair
DMD	Dynamic Mode Decomposition
DR	Density Ratio
IR	Infrared Thermography
PC	Polymer-Ceramic
PIV	Particle Image Velocimetry
POD	Proper Orthogonal Decomposition
PSP	Pressure-Sensitive Paint
RMS	Root Mean Square
TSP	Temperature-Sensitive Paint
UV-LED	Ultra-Violet Light Emitting Diode

$$\eta = \frac{T_\infty - T_{aw}}{T_\infty - T_c} \tag{1}$$

Film effectiveness with a value $\eta = 1.0$ denotes perfect film cooling performance, and $\eta = 0$ indicates the absence of the coolant on the surface. The film cooling effectiveness η decreases rapidly downstream of the hole as the coolant spreads downstream.

Many attempts have been made to determine adiabatic film cooling effectiveness behind a cylindrical hole through a flat plate. Sinha et al. [1] measured the surface temperature at discrete points behind a single inclined hole (35°) using thermocouples. Baldauf et al. [3] used infrared thermography (IR) to measure the influence of density ratio on the adiabatic film cooling effectiveness behind a single inclined hole (30°). Using the temperature-sensitive paint (TSP) technique, Zuniga. [4] identified the gradual decrease in adiabatic film cooling effectiveness far downstream for a row of inclined holes (35°). Direct surface temperature correlations are required to estimate the adiabatic wall temperature and determine the adiabatic film cooling effectiveness. However, the TSP and IR thermography data may not be accurate at the vicinity of the film cooling hole [5], as techniques that measure surface temperature can inherently be subject to errors, due to heat conduction within the bounding material [6]. Heat conduction occurring between the coolant through the hole and the plate can therefore result in inaccurate measurement of adiabatic effectiveness, particularly in the near-hole region [7].

The recent state-of-the-art pressure-sensitive paint (PSP) measurement technique, which solely relies on the oxygen quenching mechanism [8], has been widely applied to determine the adiabatic film cooling effectiveness through mass transfer analogy [9]. Wright et al. [5] compared three measurement techniques (PSP, TSP, and IR) for seven cylindrical compound holes. Both the IR and TSP results demonstrated smooth reduction of the effectiveness in the near field region, while the PSP results showed a sudden drop immediately after the hole with $\sim 20\%$ discrepancy when compared with the TSP and IR results. As claimed by Wright et al. [5], the PSP technique is the best candidate to measure the film cooling effectiveness under true adiabatic conditions, determining detailed information of the jet separation and the reattachment behavior. Time-averaged patterns of film cooling effectiveness with different parameters [10] and configurations [8] were obtained with PSP measurements. Johnson et al. [6] measured the jet-in-crossflow interaction at intensity ratios of DR = 0.9–1.2 and blowing ratios of M = 0.5–1.0 using PSP and particle image velocimetry (PIV). In a scaled parametric study, the time-averaged effectiveness pattern was determined for a large area x/D < 30, which demonstrated a sudden drop in effectiveness immediately behind the hole when M > 0.4. However, no clear observations could be made in the near-hole region, due to inadequate spatial resolution (Table. 1). The comparison conducted by Johnson et al. [6] on a cylindrical hole found the experimental measurements of the adiabatic film cooling effectiveness to be in good agreement far downstream, beyond x/D = 8, but significant disagreement occurred in the near field x/D < 8. The spatial resolution and unknown geometric factors may affect this. Most previous computational efforts related to film cooling have relied heavily on the experimental measurements of adiabatic film cooling effectiveness by Mayhew et al. [11], Seo et al. [12], Sinha et al. [1], and Pedersen et al. [13] for validations. However, these studies showed a considerable discrepancy in the near-hole region ([14,15]).