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The effect of effusion holes inclination angle on the adiabatic film cooling effectiveness in a three-sector gas turbine combustor rig with a realistic swirling flow

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ABSTRACT

The introduction of Lean Burn concept as basic Low-NO_x scheme for future aero-engines is heavily affecting the aero-thermal design of combustors. A great amount of air is admitted through the injection system with relevant swirl components, producing very complex flow structures (recirculations, vortex breakdown) for flame stabilization. As a consequence a reduced quantity of air is available for liner cooling, pushing the adoption of high effectiveness cooling schemes. Effusion cooling represents one of the first choices due to its low weight and a relatively easy manufacturability. Liner metal temperature is kept low by the combined protective effect of coolant film, heat removal inside holes and an improved cold-side convection. In lean burn systems the evolution of film protection can be heavily influenced by the swirl flow interaction with combustor walls.

The subject of this work is to investigate the effects of the realistic flow field of a lean burn injector on the adiabatic film cooling effectiveness on an effusion cooled combustor liner. A dedicated three-sector rig was designed with the aim of measuring film effectiveness with Pressure Sensitive Paint technique. Three effusion cooling geometries with different inclination angles were tested at various levels of pressure drops across the perforation, resulting in different blowing ratio values. It was also taken into consideration several flow rate levels of starter film realized by spent dome cooling air, injected through a dedicated plain slot. The analysis of film effectiveness measurements were supported by flow field investigation in the near wall region carried out by means of Particle Image Velocimetry.

Results pointed out the relevant impact of combustor flow field on the adiabatic film cooling effectiveness as well as a significant role of the inclination angle, recommending a careful revision of standard design practices based on one dimensional flow assumption and suggesting possible holes arrangement optimization.

1. Introduction

In modern gas turbine combustors the process of flame stabilization and anchoring is widely based on the use of swirling flows. Combustion air is delivered as swirling jets in single or multiple configurations. The objective is to promote the so-called vortex breakdown process, which is the base flow structure of swirl stabilized flames. With this type of flow, wide low speed regions are produced by the onset of inner and outer recirculations, supporting local flame anchoring. Recirculating flows allow to have a continuous supply of high temperature gases to incoming fresh mixture, while the strong velocity gradients and flow unsteadiness greatly enhance free stream turbulence which improves the overall reaction and mixing rates. This type of flame stabilization process has become more and more common and exasperated with the widespread use of lean flames for reduction of NO_x emissions, firstly adopted in heavy duty gas turbines [1], and more recently considered also for aero-engine combustors to fulfil the future emissions standards [2].

A common characteristics of lean burn gas turbine combustors is

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Nomenclature

Acronyms

CCD	Charged Coupled Device
Cd	Discharge coefficient $[-]$
CR	Corner Recirculation
IR	Inner Recirculation
NO_x	Nitrogen Oxides
PERM	Partial Evaporation and Rapid Mixing
PIV	Particle Image Velocimetry
PMMA	Poly-Methyl Methacrylate
PSP	Pressure Sensitive Paint

Greek symbols

α	Injection angle $[deg]$
η	Film Cooling Effectiveness
σ	Perforation porosity $[-]$
θ	Tangential direction in swirler flow $[-]$

Latin symbols

BR	Blowing Ratio $[-]$
DR	Density Ratio $[-]$
Re	Reynolds number $[-]$
S_N	Swirl Number $[-]$
$\dot{m}$	Mass flow $[kg/s]$
A	Area $[m^2]$
C	Mass fraction $[-]$
D	Diameter $[m]$
d	Holes diameter $[m]$
G	Momentum flux $[kg/m/s^2]$
P	Static pressure $[Pa]$
S	Hole pitch $[m]$
T	Temperature $[K]$
V	Velocity $[m/s]$
W	Slot coolant consumption $[-]$
x	Stream-wise, axial direction $[m]$
y	Span-wise, lateral direction $[m]$
z	Orthogonal to test plate direction $[m]$

Subscripts

ad	adiabatic
aw	adiabatic wall
cool	cooling flow
eff	effusion flow
h	hydraulic
in	inlet
main	mainstream
max	maximum
out	outlet
slot	slot cooling system
sw	swirler
w	wall
x	axial direction
y	lateral direction
z	orthogonal to test plate direction

the great amount of air delivered by the fuel-air injection system, that can reach $70-75\%$ of total combustor air. This means a strong reduction of air available for liner wall cooling, forcing to the introduction of high effectiveness cooling schemes. Among different possible solutions, effusion cooling (or full coverage film cooling) certainly represents one of the most promising technology. It is based on the injection of cooling air through a dense pattern of small diameter holes drilled on the liner. The purpose is to generate an high effectiveness layer of coolant on the liner surface, avoiding its direct exposure to hot gases, and to provide heat removal by forced convection inside each hole. An additional positive contribution to overall cooling effectiveness may come to an increased convective heat transfer on the cold-side of the liner due to the suction effect of coolant flow near the rim of each effusion holes. Thanks to the relative simple manufacturing process involved and a reduced impact on combustor weight, effusion is one the first options, especially in aero-engine applications. A recent review on effusion cooling concept with a discussion about the basics related to hole spacing and coolant-hot-gas interaction can be found in Krewinkel [3], where some perspectives about the application of effusion cooling to turbine blade cooling are also reported. More specific assessments regarding the application of effusion cooling to combustor liner with fundamental analysis about the relative weight of the three main contributions to overall cooling effectiveness can be found in Martiny et al. [4] and more recently in Gerendás et al. [5] and Andreini et al. [6].

The engineering problem of applying effusion to combustor liner cooling, together with all related physical aspects, has been widely analysed over the last 40 years, with several contributions available in the open literature. In particular most part of the studies have usually been aimed at investigating the role of the various flow and geometric parameters on the film cooling effectiveness, generally with simplified configurations (flat plates with uniform mainstream flow). One of the first contribution is due to Kasagi et al. [7] where the overall cooling effectiveness of full coverage film cooling plates was measured at different blowing ratios with liquid crystals technique. The focus was put on the role of thermal properties of the plate material. Among the pioneering studies it is worth to cite the contributions by Andrews and coworkers [8–10] where the effects on film effectiveness of several parameters, as the number of holes, length and arrangement, were investigated. In their study, Martiny et al. [11] evaluated row by row adiabatic film effectiveness (via Infra-Red thermography) and performed flow visualizations (by means of Schlieren photography) on a full coverage film cooling plate with highly inclined holes (17°) at different blowing ratios (0.5–4.0). It was observed that, even with high blowing ratio and therefore with full penetration of jets, an appreciable cooling benefit can be measured in terms of adiabatic film effectiveness. This is due to a reduction of gas temperature in the mixing region contributing to keep near wall temperature low even without the presence of a coherent film: this is expected to be the process in actual combustor where high blowing ratios are commonly observed.

An extensive parametric study was later realized by Gustafsson and Johansson [12] where overall cooling effectiveness was tested with Infra-Red thermography. A large database was obtained varying several flow and geometric parameters, nevertheless results in terms of overall cooling effectiveness do not permit to accurately separate the effects on adiabatic film effectiveness and heat transfer. In the contribution by Harrington et al. [13] the effect of an increasing free stream turbulence on the adiabatic film effectiveness was analysed for normal injection holes. A reduction of film coverage is observed when turbulence increases, but the impact is largely reduced with blowing ratios approaching 1.0.