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Research Paper

Effusion cooling characteristics of a model combustor liner at non-reacting/reacting flow conditions

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HIGHLIGHTS

- Temperature distribution on the test combustor liner is detected by infrared thermography.
- Effusion cooling performance shows great difference at non-reacting and reacting conditions.
- Liner cooling optimization should be designed with considering combustion.

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ABSTRACT

Detailed effusion cooling feature on both inner and outer liner of a scaled annular combustor equipped with three axial swirlers has been investigated experimentally under both non-reacting and reacting flow conditions. The main flow is electrically heated for non-reacting cases, while methane-air premixed combustion is performed for the reacting conditions. Temperature distribution on the target bended plates with 7 rows of cooling holes in an in-line layout is captured by infrared thermography, and the overall cooling effectiveness is analyzed. Effects of nominal coolant to mainstream flowrate ratio and equivalence ratio are evaluated respectively. Non-reacting results show that the macro rotational flow generated by the swirl flows interacts with cooling film, leading to circumferentially non-symmetric cooling protection on both liners. At reacting conditions, stagnation of the high temperature flame impinging on the liner wall locates at X/D range of 0.4–0.5, which has not been observed in non-reacting experiments. Outer liner obtains better cooling protection than inner liner when reaction is activated. The effect of equivalence ratio is surveyed at $\Phi = 0.7$, 0.8, 0.9, 1.0 and 1.1. This work highlights the significance of combustion in evaluating the effusion cooling performance on the real annular combustor liners, providing more accurate prediction compared to the conventional non-reacting methods.

1. Introduction

Lean-burn combustion mode is generally adopted in modern gas turbine combustors for the reason that the legislation regarding to NOx emissions nowadays is getting more and more strict, which means more air will be imported to the combustor for reaction and thus air for cooling the combustor liner reduces greatly. To solve the problem, some advanced liner cooling methods are proposed and put into practical application. Among all these methods, effusion cooling, also called as full coverage film cooling, is one of the most efficient [1], especially in cooling air consumption. Because of its advantages, some aircraft engines and industrial gas turbines have applied it separately or combined with other methods [2] for the combustor liner cooling.

Krewinkel [3] reviewed plenty of fundamental work done on the flat plate effusion cooling and pointed out that momentum of cooling jets from the multitude of discrete holes is low, which is helpful to attach film on the cooled surface, and a large amount of heat is taken away through cooling air convectively flowing in the numerous small holes. Leger et al. [4] experimentally investigated the effect of the aero-thermal condition on the multi-hole cooling characteristics by IR thermography to simulate different thermal load on the combustor liner at different zones, and suggested the way of optimization through adjusting geometrical parameters of the effusion holes layout. More recently, CHT/CFD simulation method was used to evaluate the impact of the hole density on cooling effectiveness through varying the hole diameter by Andrews et al. [5]. Another experiment work done by Huang et al. [6] also focused on the effect of hole diameter (d = 0.5 mm

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Nomenclature

d	cooling holes diameter, mm
T	temperature, K
V	volume flow rate, m^3/h
M	blow ratio
D	outlet nozzle diameter, mm
X	streamwise distance, mm
S	circumferential distance, mm

Greek symbols

η	cooling effectiveness
λ	flow rate ratio
Φ	equivalence ratio
$\bar{\eta}$	streamwise or circumferentially averaged cooling effectiveness
$\bar{\bar{\eta}}$	area averaged cooling effectiveness

Subscripts

H	hot gas or air
C	coolant
W	liner wall surface
Main	mainstream

Acronyms

IR	infrared radiation
CHT	conjugate heat transfer
CFD	computational fluid dynamics
PIV	particle image velocimetry
PSP	pressure sensitive paint
TLC	thermochromic liquid crystal

and 1 mm) at 90° injection angle, their results indicated that the cooling effectiveness of the effusion cooling with densely arrangements could be close to that of porous plate so called transpiration cooling. Besides, Goldstein and Stone [7] and Koc et al. [8] reported the effusion cooling performance on the curved surface.

Except bunch of studies taking only effusion cooled plates as objects, Scrittore et al. [9,10] measured thermal and flow field in a scaled effusion cooled combustor simulator with the uniform main flow to explain how film flow developed and influenced cooling performance, and effect of dilution holes on the cooling effectiveness was investigated particularly. On this combustor, Kianpour et al. [11] conducted CFD computation to study the thermal and flow field characterization for variable cooling hole configurations. However, the truth is that swirling flow is generated by the injectors to stabilize the flame mostly in the state-of-the-art lean burn combustors, and this intense swirling flow brings about typical vortex breakdown, leading to strong interaction with the effusion cooling flows on the wall. This complex 3D flow field in the combustor should not be negligible to predict the thermal protection on the liner correctly. Patil et al. [12,13] performed both experiments and simulations to reveal the convective heat transfer coefficient under the representative swirl flow produced by the axial swirler in can and annular combustors. It was shown that peak heat transfer coefficient location on the liner was where swirl flow impinged, and this location could move upstream or downstream with the variation of the swirling strength. Ramirez et al. [14] replaced axial swirlers with radical swirlers and conducted the heat transfer as well as flow field measurements in the same annular combustor as Patil's. Carmack et al. [15] thoroughly compared the difference on the heat transfer coefficient measured by IR camera and flow field visualized by PIV for radical and axial swirlers in Patil's can combustor.

To author's knowledge, investigation of effusion cooling performance under realistic swirl flow in the combustor has been only recently performed, firstly by Wurm et al. [16–18]. They developed a three-nozzle planar combustor test rig with PIV system for flow field and IR thermography for temperature field measurements. They reported that swirl flow would interact with the near wall film flow, altering local blow ratio and cooling effectiveness. A dimensionless parameter cooling efficiency was recommended to analyze impact on cooling performance of injector geometry. Research group from the University of Florence also did a great amount work on this topic experimentally and numerically. Andreini et al. [19,20] carried out flow and heat transfer measurements in a three sector scaled planar combustor equipped with PERM injectors using PIV, TLC and PSP techniques. They also pointed out that expanding swirling flow impinges on the liner wall, causing strong interaction with the wall and effusion jets there. A macro recirculation flow structure would be formed due to three injected swirl flows, which resulted in the effectiveness non-uniform distribution in the lateral direction. Furthermore, a new CFD approach [21] was presented to replace effusion cooling hole with local sources and sinks modeling for both fluid and thermal motion through the hole, which can save considerable computational cost. And this methodology was then validated to be effective in an annular combustor simulation under reacting flow conditions [22].

From the literature reviewed above, it is found that few experiments are done at reacting conditions, but in fact the flame pattern and heat release corresponding to the combustion is extremely important for evaluating cooling protection on the liner. Lefebevre [23] analyzed heat transfer process on a liner unit including radiation. Durox et al. [24] studied different flame patterns in an annular combustor, indicating that V-type and M-type flame shapes would occurs simultaneously due to the interaction of adjacent injectors, and these two types of flame would produce different heat load on the liner wall.

The objective of this work is to explore the effect of reaction on effusion cooling through making comparisons between non-reacting and reacting conditions. This study captures temperature distribution on the target plate with effusion holes by the infrared thermography, revealing the effusion cooling feature on the liner of a scaled annular combustor equipped with three axial swirlers. Overall effusion cooling effectiveness for in-line layout is analyzed at different coolant to mainstream flowrate ratio cases. For the combustion condition, influence of the equivalence ratio on cooling performance is also investigated. It is hoped that the present work could be a beneficial extension of prevalent non-reacting studies on combustor effusion cooling.

2. Experimental setup

2.1. Experimental apparatus

A scaled three sector annular combustor with effusion cooling plates equipped on both outer and inner liners is constructed and tested at non-reacting as well as reacting flow conditions. The whole experimental system, depicted in Fig. 1, consists of mainstream supply system, fuel system, cooling system, infrared (IR) temperature measurement system and the test section. For