Aerospace Science and Technology ••• (••••) •••–•••

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

# Studies on effusion cooling: Impact of geometric parameters on cooling effectiveness and coolant consumption

Vishal Venkatesh [a], J. Sriraam [a], Vignesh D. Bala [a], K. Subash [a], Kishore V. Ratna [b], A.R. Srikrishnan [a,*], Balajee Ramakrishnananda [a], Batchu Suresh [c]

[a] *Department of Aerospace Engineering, Amrita School of Engineering, Coimbatore, Amrita Vishwa Vidyapeetham, Amrita University, India*
[b] *Department of Mechanical Engineering, Amrita School of Engineering, Coimbatore, Amrita Vishwa Vidyapeetham, Amrita University, India*
[c] *Gas Turbine Research Establishment, Bengaluru, India*

ARTICLE INFO

*Article history:*
Received 3 July 2017
Received in revised form 23 November 2017
Accepted 25 December 2017
Available online xxxx

*Keywords:*
Effusion cooling
Conjugate heat transfer
Coolant consumption

ABSTRACT

This study is focused on the impact of certain important geometric parameters on cooling effectiveness and coolant consumption for effusion cooling of aircraft combustor liner. The three dimensional turbulent flow field in a domain representing the combustor with several rows of effusion coolant injection is considered for the analysis. The geometric parameters considered are: angle of injection of the coolant, axial and transverse pitch of the injection holes, hole spacing and hole diameter. Also, based on the analysis of the temperature field within the chamber, a novel concept of '*variable hole diameter*' has been introduced to reduce coolant consumption. A symmetric 3D computational model including the combustion chamber, coolant chamber and the effusion plate was used for the study. Conjugate heat transfer was modeled between the effusion-cooled wall and the two chambers. A detailed mass flow rate analysis has been performed for the various cases in order to study the impact of parameters on coolant consumption. The proposed approach of using an effusion plate with variable hole diameters is found to be effective in reducing the net coolant consumption significantly while maintaining a given level of cooling effectiveness.

## 1. Introduction

In view of the consistent demand for improving the efficiency and power output of modern day aircraft engines, it is imperative to maintain significantly high levels of temperature and pressure within the combustor [1,2]. An adverse consequence of such extreme operating conditions is that the temperature values approach and sometimes exceed the allowable material limits [3,4]. This necessitates the deployment of an effective cooling scheme to protect the components exposed to the hot-stream of combustion gases. Convection cooling, Regenerative cooling, film cooling, effusion cooling, impingement cooling, transpiration cooling and heat-pipe cooling are some of the methods used for thermal protection [5]. *Effusion cooling* is an advanced cooling concept for aircraft engine combustors [2] where, cold air is injected through small subsequent rows of cooling holes in the chamber wall thereby providing a film of cooler fluid acting as a barrier between the wall material and the hot gases [5,6]. When air from a conventional film cooling slot moves downstream, its temperature gradually increases due to entertainment of surrounding hot gases. In the case of effusion cooling, the continuous injection of cold air into the film enables it to maintain the cooling effectiveness further downstream [7,8]. Although transpiration cooling is regarded as the best in terms of cooling effectiveness [8–11], structural weaknesses associated with this method is of major concern.

From the perspective of the overall performance of the aircraft engine it is important to minimize the mass of the coolant stream utilized purely for combustor cooling [12], bypassed from the thrust production cycle. Also, the approach of increasing the temperature and pressure levels within the combustor increases the Nitric Oxide (NOx) emissions. The solution to this problem is lean combustion. This in turn results in the requirement of utilizing a significantly high mass flow rate of air in the primary zone and it will be at the expense of the coolant available for liner cooling [2]. Hence, it is critical to optimize coolant consumption and this has to be factored into the design of the cooling system. This necessitates improvement in cooling effectiveness for a given mass flow rate of the coolant.

Geometric parameters like hole-size, hole-spacing and inclination and operating conditions like blowing ratio and temperature

---

[*] Corresponding author.
*E-mail address:* ar_srikrishnan@cb.amrita.edu (A.R. Srikrishnan).

https://doi.org/10.1016/j.ast.2017.12.044
1270-9638/© 2018 Published by Elsevier Masson SAS.

Please cite this article in press as: V. Venkatesh et al., Studies on effusion cooling: Impact of geometric parameters on cooling effectiveness and coolant consumption, Aerosp. Sci. Technol. (2018), https://doi.org/10.1016/j.ast.2017.12.044

**Nomenclature**

| | |
|---|---|
| $\eta$ | Cooling effectiveness |
| $\alpha$ | Hole inclination (or) angle of injection |
| $d$ | Hole diameter |
| $p/d$ | Pitch-wise hole spacing |
| $s/d$ | Stream-wise hole spacing |
| $x/d$ | Position on the wall |
| $T_c$ | Coolant temperature |
| $T_w$ | Wall temperature |
| $T_\infty$ | Mainstream or hot-stream temperature |
| $U$ | Main stream velocity |
| $u$ | Longitudinal velocity component ($x$-component) |
| $\rho_c$ | Coolant density |
| $\rho_\infty$ | Mainstream density |
| BR | Blowing Ratio |
| CHT | Conjugate Heat Transfer |
| TKE | Turbulent Kinetic Energy |
| Pr | Prandtl number |

ratio influence effusion cooling performance. Several studies have analyzed the impact of the geometry and the operating conditions on the efficacy of the cooling system. Andrews et al. [13] have experimentally studied the influence of hole size on discrete hole film cooling. The overall effectiveness increased from approximately 0.54 to 0.63 for the range of hole diameters considered in their study. Studies of Andrews et al. [14], show that the increase in number of holes of coolant injection favorably influences cooling effectiveness. Also, a simultaneous reduction in the hole diameter lead to a substantial increase in $\eta$, as the coolant effusing from smaller holes induces less mixing. Similar results were also observed in the experimental investigations of Johansson et al. [6], and Gustafsson et al. [4].

Based on an experimental study Liu et al. [15] concluded that the cooling effectiveness of densely arranged cooling holes of diameter 0.5 mm could be nearly the same as that of transpiration cooling with sintered porous flat plates. The experimental study of Goodro et al. [16], showed a drop in the effectiveness with increased spacing. The authors also observed increased heat-transfer coefficients in stream-wise direction for the denser array of holes. Experimental studies by Martinaz-Botas et al. [17] were carried for inclination angles of 30°, 60° and 90° with zero pressure gradients. The results show that the $\eta$ is maximum for a hole inclination of 30°. Similar studies were performed by Andrews et al. [18] on full coverage effusion cooling with inclined holes for angles of 30° and 90° and it was found that, an array of inclined cooling holes gives better performance than normal holes.

Studies on operating conditions like blowing ratio and temperature ratio have shown that their impact on effectiveness is mostly coupled. The effectiveness is found to increases with increase in temperature ratio and this effect is more pronounced at higher velocity ratios [4]. The experimental study of Scrittore et al. [19] investigated the development of cooling films over 20 rows of holes, for two different blowing ratios: 3.2 and 5.0. In their study the turbulence levels did not have significant impact on adiabatic effectiveness. However, in general it is considered that high level of turbulence significantly decreases adiabatic effectiveness [7] due to the concomitant increase in mixing.

Several numerical studies also have focused on the influence of geometry on effusion cooling performance [20–22]. Numerical investigations were carried out on the performance of anisotropic and $k$–$\varepsilon$ turbulence models by Facchini et al. [23]. The simulation results deviated from experimental local temperature field but the laterally averaged temperature distribution was in good agreement with the experiments.

It is important to include conjugate heat transfer (CHT) analysis in computational studies of effusion cooling, as the basic mechanism of heat transfer in effusion cooling is threefold: conduction across the walls, convection within the coolant holes and convection through the protective layer over the wall. Relatively few numerical studies have included CHT analysis [20,21,23–28]. The coolant flow is established due to the pressure difference between the combustion and coolant chambers, in real effusion cooling systems. The coolant chamber is part of the domain for the investigations that include CHT analysis.

The present study sets off from the above background. In view of the importance of minimizing coolant requirement, the study focuses on analyzing the impact of selected geometric parameters on overall effectiveness and coolant consumption for an effusion cooled chamber. The analysis thus addresses the coupling between mass flow rate, geometry and cooling effectiveness. The study incorporates conjugate heat transfer analysis and explores means to minimize the coolant requirement for a given level of cooling performance. In open literature quantitative information available on the impact of geometry on coolant consumption is scanty. Advancing further from the current level of information available in open literature, the present study attempts to address the following:

1. Parametric variation of geometry with concurrent analysis of coolant mass flow for each configuration. The geometric parameters include angle of injection, transverse pitch, stream-wise pitch and hole diameter.
2. Incorporating conjugate heat transfer to the analysis there by facilitating the modeling of more realistic inlet conditions for the coolant supply. The study thus incorporates conduction as well as convection. As stated above CHT studies on effusion cooling are limited.
3. Examining the differential impact of geometry parameters like angle of injection on cooling at the upstream and the downstream regions of the cooled plate. To the best of the authors' knowledge previous studies have not addressed this aspect.
4. Exploring the possibility of reducing coolant requirement by varying the mass flow along the plate. An important aspect in effusion cooling is the continuous injection of coolant. This helps maintain the effectiveness at downstream locations at an acceptable level. However, coolant holes downstream inject cold air into a film which is already at a lower temperature (compared to the main-stream) propagating along the wall as a single layer. Thus in order to cool the wall at downstream locations the same flow rate of coolant employed upstream may not be required. Based on this possibility, a novel concept of deploying *variable hole diameter* along effusion cooled plate for reducing the coolant consumption has been introduced and preliminary analysis for different cases have been performed.

## 2. Computational methodology and validation

The study considers a three-dimensional domain of a "*combustion chamber*" with an effusion cooled wall and a coolant chamber. The geometry is based on the experimental configurations of Scrittore et al. [19] (Fig. 1). For the validation study, the bottom plate was modeled with a hole diameter ($d$) of 5.7 mm and an inclination of 30°. The dimensions of the combustion chamber are $250d \times 4.9d \times 50d$ and the dimensions of the coolant chamber are

Please cite this article in press as: V. Venkatesh et al., Studies on effusion cooling: Impact of geometric parameters on cooling effectiveness and coolant consumption, Aerosp. Sci. Technol. (2018), https://doi.org/10.1016/j.ast.2017.12.044