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CFD analysis of combustion liner with different geometry holes for effusion film cooling

The advanced gas turbine is designed to operate at higher temperature to increase thermal efficiency. Since the gas temperature exceed the allowable material temperature, so cooling techniques of turbine components are more important.

Effusion film cooling is an external and highly sophisticated cooling technology, which protects the liner by injecting the secondary cooler fluid at particular locations over the liner surface exposed to the higher gas temperatures. The injected fluid forms as a thin layer (film) on the liner surface and protects the liner surface from higher gas temperatures. In elliptical geometry of holes in plate for effusion cooling is studied for the samples made of adiabatic and conductivity material. To increase the life of combustion chamber it is essential to know the amount of cooling air to be used for cooling of the liner.

For effusion film cooling, geometry of the hole is one of the key parameters which influences the coolant mass flow rate and it spread over the liner surface thus affecting the cooling effectiveness. The commercially available FloEFD software is used for calculating the surface temperature and effusion cooling effectiveness distribution throughout the sample plate and result values are in good agreement and this has given confidence to usage of the commercial software FloEFD for predicting the film effectiveness. After result validation finally concluded that span wise elliptical hole (Config-2) have more effectiveness than circular holes.

Keywords: Gas turbine; effusion cooling; combustion liner; FloEFD; CFD.

1.0 Introduction

Temperature of the inside gas turbine combustion chamber is 1800 K to 2000 K which is too high for engineering material. In order to reduce wall temperature and improve the reliability of the combustion chamber, the wall was protected from hot gas by various cooling technologies. The effusion cooling is widely used because of its simplicity.

In this methods cold air was injected through small holes in the chamber wall which creates cooler film fluid which will act as a barrier between wall material and hot gases. The overall efficiency of a gas turbine highly depends on the effectiveness of film cooling. Some of the researches have been conducted by various researches over the last decades. In the other side numerical simulations became way to accelerate the design of gas turbine engines and to optimize their performance due to usage advanced computational fluid dynamics (CFD) software. We come to know that effusion film cooling performance will influenced by aero-thermal conditions as well as by the geometrical design of the film cooled plate surface. Mostly literatures are based on effect of geometrical characteristics such as coolant hole diameter, hole angle, hole arrangement etc.

Bruno et al. [1] have studied the flow measurement in film cooling flows with adiabatic and high conductivity material with circular and elliptical effusion hole configuration. They modelled for different length to cross-section and studied under for changing input values by increasing number of arrays so finally it was concluded no difference have been found when comparing with two different arrays. A Andreini et al [2] have studied about circular array and shaped holes with angle of inclination by 17° and in which two plates are used one having circular and other one had shaped holes with elliptical cross-section. They were performed for conjugate simulations for circular holes geometry in order to quantify heat transfer effects and directly compared to experimental effectiveness data. Reaz Hasan et al [3] invest the effectiveness of effusion film cooling on and adiabatic flat plate with cylindrical hole of 30° inclination are used for supplying cold air to hot flow and film cooling effectiveness is calculated for a continuous array of cooling rows. So finally it is concluded that strong relationship between velocity ratio and adiabatic film cooling effectiveness are achieved. M Martiny et al [4] have given a mathematical model used to describe the coupled heat transfer in effusion-cooled combustor walls is used and this model is validated with

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experimentally determined exit temperature. This studied shows the isolated effects of the different dimensionless quantities on the cooling effectives.

The aim of this work is evaluation of adiabatic and overall effectiveness on the plate,which are representative of many effssion-cooling combustor liner walls. The analysis is carried out for two diffrent effusion configurations have been chosen one with normal ellipse and other is the 90p roration of the normal ellipse configuration. Analysis is carried out for elleptical holes machined at an angle of 30p by using CFD anlysis soltware FloEFD and which was not carried by any researchesers so far. The angle of cut for holes was selectected with the help of literature, a few reserchers optimiesd their anlysis of effussion cooling for circular holes using CFD. The research is focusing on the validation, optimization and comparison of experimental results by using FloEFD analysis CFD tool, which gives the confidence to use this software (FloEFD).

2.0 Validation of experimental results

Validation is carried out for the experimental work of Felix, J et al [3] for circular hole of 2.4mm diameter and compared to analytical results of FloEFD. The same boundary conditions and porosity on liner flat plate are used for analysis as used in experiments. The aim of this validation is to compare the adiabatic and overall effectiveness over a flat plate of a specific cooling geometry. This allows the complete control of two separate flows of the main stream and the coolant by considering temperature and pressure. The two separated flow will pass through valves and they passed through the test plate. Flat plate surface was divided into 254 equal points to collect surface temperature in various locations.

3.0 Project methodology

In this effusion cooling technique the testing plate consists of an array of some specific distance called span wise pitch and stream wise pitch. This method of cooling is the very powerful way to fulfillment of combustion liners requirement. By using different shape of the holes a thin layer of coolant is maintained on the combustor liner to isolate the component from the hot gases. The most interesting aspect is the significant effect of wall cooling due to the heat removed by the passage of coolant inside the holes. In these configuration holes are distributed uniformly over the whole surface, the aim of these configuration is to numerical evaluation calculation of adiabatic effectiveness on both the configuration plates.

These two configurations geometry having the same porosity and the same slanted injection of 30° both configurations having different shaped elliptical holes projecting a circular imprint on the plate. Two geometry of different orientation were studied with a steady-state CFD analysis of holes staggered array. Table 1 shows the different parameters used for configuration-1 and configuration-2. This method of cooling is the very powerful way to fulfillment of combustion liners requirement. By using different shape of the holes a thin layer of coolant is maintained on the combustor liner to isolate the component from the hot gases. The most interesting aspect is the significant effect of wall cooling due to the heat removed by the passage of coolant inside the holes. In this type of configuration the holes are distributed uniformly over the whole surface, Table 1 shows the different parameters used for configuration-1 and configuration-2.

TABLE 1: DESIGN PARAMETERS OF CONFIGURATION 1 AND 2

Design parameters	Configuration-1	Configuration-2
Major Axis	1.92 mm	0.75 mm
Minor axis	0.75 mm	1.92 mm
Porosity	2.99 %	2.99 %
Angle of inclination	30°	30°
Effective diameter	1.97 mm	1.97 mm
Total no of holes	77	77
Conductivity (W/m-K)	0.3	0.3
Specific heat (J/kg K)	1700	1700
Thickness mm	0.96	0.96
Density (kg/m3)	1020	1020
p/b	6	6
s/a	12	12

3.1 GEOMETRY CONFIGURATION

Fig.1 shows the arrangement of the hole on the effusion plate, in which pitch from one hole to another hole was defined with respect to flow of the mainstream gas. From the below 3D sketch first hole location was located at 50mm, 50mm. Major axis of the elliptical was considered along with parallel to flow direction of main stream. This type of arrangement of hole called it as configuration 1.

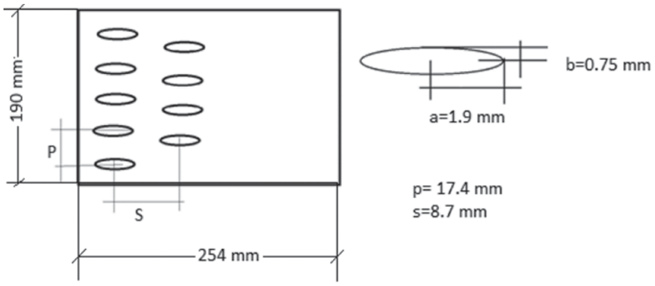


Fig.1 Line diagram of configuration 2

P- Span wise pitch in mm

S- Stream wise pitch in mm

Similarly Fig.2 gives the detail of holes configuration-2 in which major axis was perpendicular to the main stream flow.

3.2 COMPUTATIONAL DOMAIN MODEL

The flow domain studied in this report is shown in Fig.3. For both configurations hot gas is passing through main

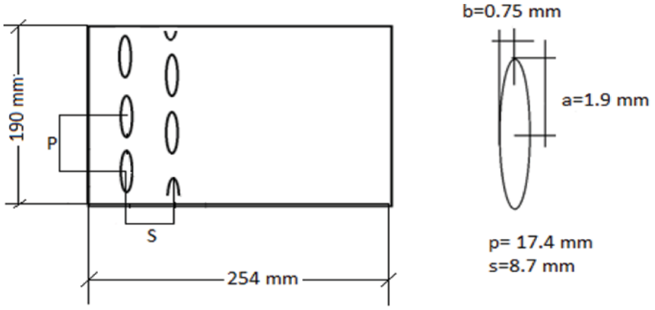


Fig.2: Line diagram of configuration-2

stream inlet duct and similarly coolant will pass through the coolant cylinder. This phenomenon occurs due to difference in pressure. The diameter of the hole is ‘d’ which is equal to effective diameter of 1.97 mm, the width of the inlet is choosen as one span-wise hole-to-hole pitch p/d as shown in Figs.1 and 2. Cooling holes were considered for parametric evaluation of adiabatic effectiveness against the continuous array. Solid works 3d software was used for creating model. Adiabatic flat plate is located in between mainstream flow and coolant flow by considering cut out at main stream duct.

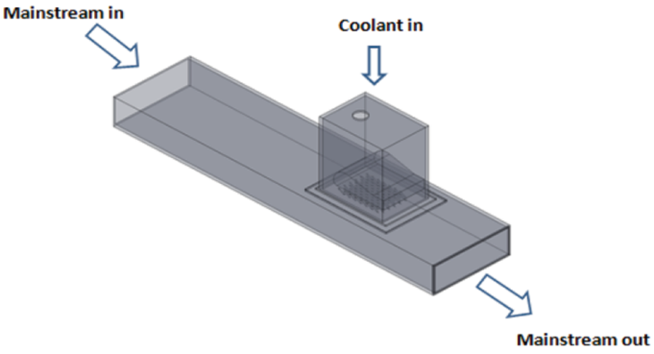


Fig.3: Computational domain

TABLE 2: FLOW PARAMETERS

Flow parameters	
Mainstream inlet pressure in bar	92197.16
Mainstream outlet pressure in bar	91997.7
Mainstream inlet temp in K	369.84
Mainstream out Temp in K	300.00
Coolant pressure inlet in bar	95052.49
Coolant temp inlet in K	305.77

3.3 MATHEMATICAL EQUATION

Film cooling effectiveness is a non-dimensional parameter which is used to define the performance of film cooling, given by equation 1. The steady state heat transfer and flow through the geometry are governed by the laws of conservation of mass, momentum and energy and are well established. The adiabatic film cooling efficiency is given by below equation.

$$\eta = (T_{main} - T_{wall})/(T_{main} - T_{coolant}) \qquad \ldots (1)$$

T_{main} – Main stream temperature (hot gas)

T_{wall} – Adiabatic wall temperature of effusion plate (adiabatic wall)

$T_{coolant}$ – Coolant temperature

3.4 INVESTIGATION GEOMETRY

Effusion cooling arrays have been selected for the present study with circular holes with “Conventional” heat transfer having the same porosity of experimental.

Porosity = (n*(area of circle))/P*S

Where p- Span wise pitch in mm

s- Stream wise pitch in mm

Flat plate comprised various rows of holes. Arranged in a staggered pattern, are representative of the chosen configurations, in this case angle of inclination was taken as 30° to enhanced heat removed by convection in the holes due to the increased area. The below plate dimensions are considered for analysis.

3.5 BOUNDARY CONDITION

The primary inlet of hot gas and secondary inlet of cold air are set to specified velocity according to the particular velocity ratios. The out let of the as shown in the above Fig.3. All the walls of the domain are considered as no-slip and transverse planes were modelled as symmetry. Below parameters are considered as boundary condition for main stream as well as cold air.

3.6 COMPUTATIONAL DETAILS

The entire model for simulation is meshed in FloEFD 17, and the first step is to decide the type of mesh that should be used for the present study. The accuracy of CFD solution depends on the grid generation to reduce grid-induced error and to resolve the flow physics near the boundary layer. The advantages of Cartesian mesh compared to body fitted mesh is that it takes less time to mesh the model, execute the analysis and also minimizes the computational errors. Meshing is one of the critical point for such a computational domain. Reconstruction of the boundary layer on all the walls and the very low injection angle represent a difficulty to work around. In order to decrease the number of elements of the grid and Cartesian mesh was used with different level refinement. Convergence is considered to be achieving given target goals. In this case total mesh size was 9 million.

The mesh grid consideration is that the grid placement of the various Cartesian meshes inside the computational domain needs to capture actual thermal-flow field phenomenon into account. As there are more intense flow fields that change at the impingement cooling flow ducts and the intersection area between the main cross flow and the cooling flow, local refinement is performed on the grid placement in these areas. Fig.4 shows surface grid distribution on the impingement hole plate and the lining wall for elliptic hole with aspect ratio of AR=0.5.

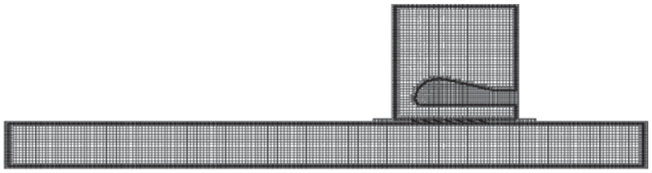


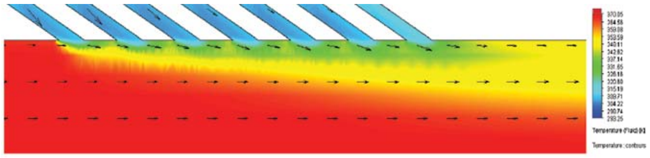
Fig 4: Computational mesh

4.0 Result and discussion

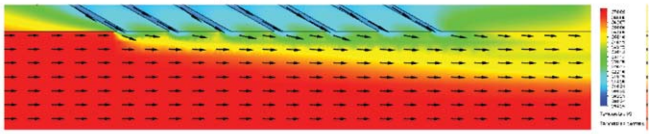
The average adiabatic wall cooling effectiveness is calculated for all the simulations. First hole located at (50mm, 50mm), therefore no heat transfer takes place before the first cooling hole because plate wall is considered as adiabatic and the area before the first hole shows zero effectiveness. The other results that are presented in this paper include temperature contours for different configuration and temperature disturbance within the thermal boundary layers.

4.1 Temperature contours

Fig.5 shows the conventional array bi-dimensional and span wise averaged adiabatic effeceness distributions obtained once the whole post-processing procedure has been fulfilled. Below shows the temperature contour temperature at exit hole where the film thickness will vary by the moment of the coolant passes away from the exit hole. From Fig.5, configuration-2 gives more effectiveness than the configuration-1.



Configuration-1



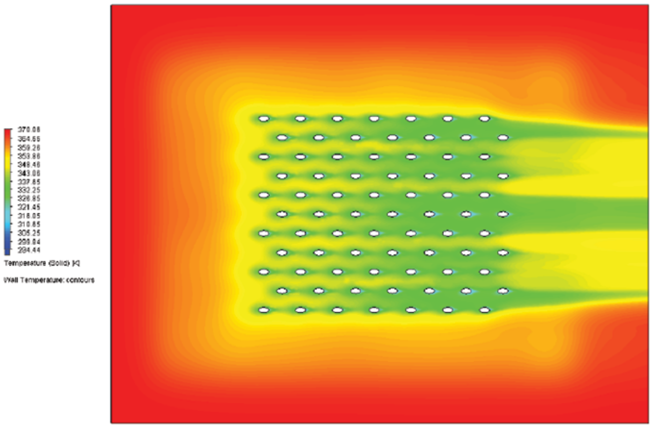
Configuration-2

Fig.5: Temperature contours showing the coolant flow pattern near the hole exit for elliptical hole

Convergence was achieved with the hot gas side heat transfer coefficient augmentation which is captured in the Fig.5.

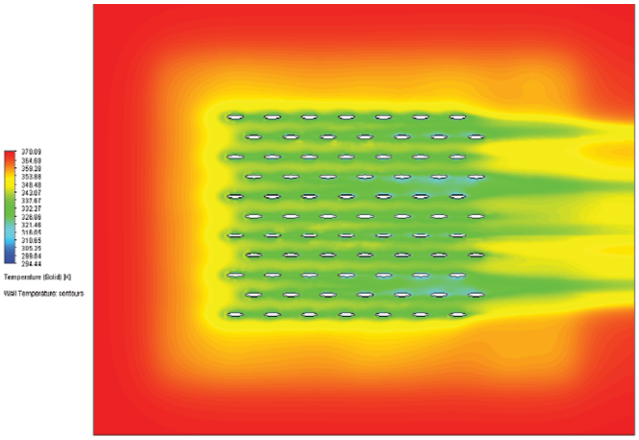
4.2 Wall temperature contours

The contours are obtained at transient and steady state analysis of the top surface of the flat plate is carried out. The colour pallet is used to analyze the variation in temperature at different points on the bottom surface of the flat plate. The temperature counter shown in Figs.6 and 7 represents the surface temperature changes the adiabatic state for a flat plate of thickness 9.6mm, it is observed in all the contours, the temperature of the point near to the hole is lesser temperature in the direction of main stream flow.

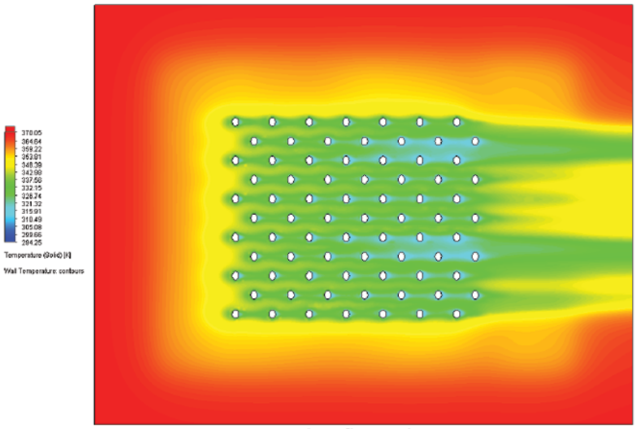


Validation

Fig.6: Temperature contour of a flat plate



Configuration-1



Configuration-2

Fig.7: Non-dimensional temperature contour for flat plate

A flat plate approaches steady state it is seen that the temperature gradient tend to demolish leaving a surface contact of the plate.

4.3 Adiabatic effectiveness

Predicted wall temperature distribution on lining wall plate under different location with adiabatic heat transfer is shown

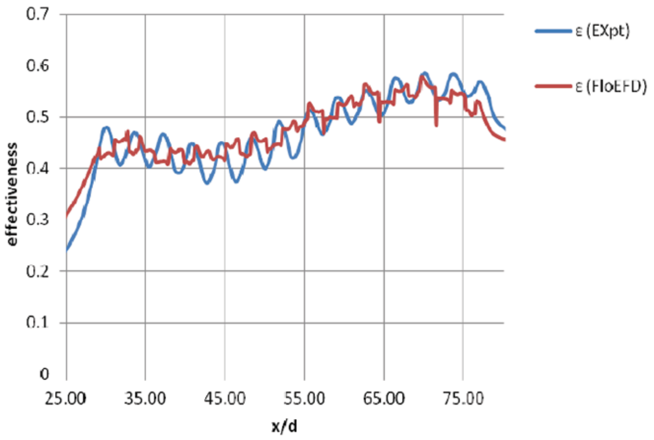


Fig.8: Adiabatic film cooling effectiveness of experimental and FloEFD result

in Fig.7. And also the experimental and analytical values are compared by considering effectiveness. The compression is shown in the Fig.8.

By calculating effectiveness of the circulars and configuration 1 and 2 holes, it is observed that configuration 2 gives the good results shown in Fig.9 also gives compression between conventional and shaped holes, span wise adiabatic effectiveness plotted against x/d. Figs.8 and 9 show the higher effectiveness values are achievable employing the shaped array of configuration 2 than circular holes.

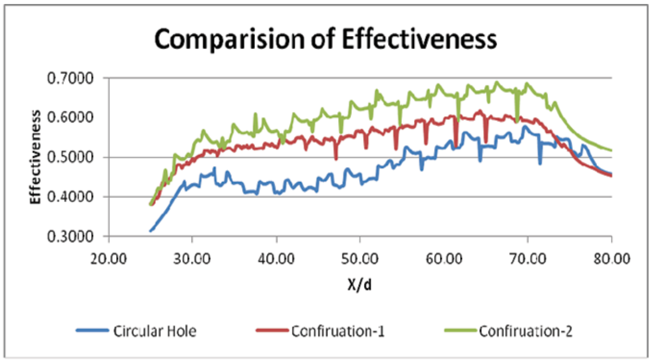


Fig.9: Comparison of adiabatic film cooling effectiveness with different shaped holes

TABLE 3: COMPARISON OF THE EXPERIMENTAL AND NUMERICAL RESULTS

Condition	Coolant mass flow (Kg/Sec)	% Variation	Average Effectiveness	% Variation
Experimental	0.0194	-	0.4686	-
Computational	0.0182	-6.2	0.4768	-1.1

4.4 FILM COOLING EFFECTIVNESS RESULT

Experimental and computational percentage of variation is calculated and shown in Table 3.

5.0 Conclusions

CFD prediction of film cooling effectiveness over the flat plate of the combustion liner using FloEFD 17. This study is carried out to understand the effect of different geometry shapes of holes and staggered array. At an angle 30p the computational domain is discreatized with the Cartesian mesh at 10 million approximately.

- CFD prediction of temperature distribution has a maximum effectiveness in configuration-2.
- Change in the shape of the geometry shows that there is no significant change in film cooling effusions.
- Increase in holes geometry increase the coolant mass flow rate. There is no change in the mainstream mass flow rate.
- For the flat plate with elliptical holes the overall effectiveness increased.
- From Fig.9 comparison of adiabatic film cooling effectiveness with different shaped holes is arrived.
- Film cooling effectivness shows how the coolant protects the surface from the interaction of the mainstream with the surface.

6.0 Acknowledgments

The authors would like to express their sincere thanks to Gas Turbine Research Establishment, DRDO for allowing to do the project at GTRE organization. The authors would also like to express their heartiest thanks to Dr. Batchu Suresh, Sc 'G' and Dr. Basawaraj, Associate Professor whose valuable guidance and constant support have made this project a success.

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