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Computational Analysis and Optimization of Blowing Ratio for Effective Film Cooling of a Gas Turbine Blade

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Abstract: Film cooling is vital to gas Turbine blades so as to protect them from the high temperatures and thermal stresses caused due to the flow of hot combustion gases on the surface of the blade. This study focuses on the efficient computation of film-cooling flows. Initially Computational analysis was done on a flat Plate with holes inclined at 35^0 to the surface plate. The results obtained were verified and compared to previous experimental measurements. Further, Film cooling effectiveness of a gas turbine blade was studied by using a row of inclined holes at 30^0 to the surface of the blade. The density ratio of the Coolant (i.e. air) to mainstream was varied from 1.2 to 2.0 while the velocity ratio was varied from 0.208 to 0.83. The surface temperature of the blade was measured with the help of Ansys CFX 14.5 where temperatures were obtained along the jet centreline and across other locations of the blade. A point along the centreline has been taken where the jet remains attached to the surface of the blade and temperatures were recorded while varying the density & velocity ratios. The results obtained were modelled and Regression Analysis was performed to find the contribution of the above parameters on the effectiveness of film cooling. An equation has been derived and decoded to find the optimum value of blowing Ratio for maximum effectiveness at the selected point on the surface of the blade.
Keywords – Turbine blade, density ratio, velocity ratio, blowing ratio and film cooling effectiveness

I. Introduction

Film cooling has long been established as one of the main mechanisms used to maintain the temperature of gas-turbine blades down to safe operating levels. Pressures to improve engine efficiency continuously drive engine temperatures to higher levels, which leads to the need for more effective blade-cooling systems. Film cooling depends primarily on the coolant-to-hot mainstream pressure ratio, temperature ratio, and the film cooling hole location, configuration, and distribution on a film-cooled blade. The coolant-to-mainstream pressure ratio can be related to the coolant-to-mainstream mass flux ratio,M (blowing ratio), while the coolant-to-mainstream temperature ratio can be related to the coolant-to-mainstream density ratio.

In a typical gas turbine the blowing ratios vary from 0.5 to 2.0 and the density ratios vary from 2 to 1.5. In general higher the pressure ratio, the better the film cooling protection at a given temperature ratio, while the lower the temperature ratio, the better the film-cooling protection at a given pressure ratio. However, a too high pressure ratio may reduce the film cooling protection because of jet penetration into the mainstream. Therefore, it is important to optimize the amount of coolant for airfoil film cooling under engine operating conditions..Film cooling has been studied extensively, both numerically and experimentally. Studies on the subject are generally divided into two subjects: flow characteristics and heat transfer characteristics.

The first in a series of research reports from the University of Minnesota began with Goldstein et al. (1968) in the paper " Film Cooling with Injection through Holes : Adiabatic Wall Temperature Downstream of a Circular Hole" reporting the effectiveness results from a circular hole. This was followed by a study of Goldstein et al. (1970) - "Film cooling Following Injection through Inclined Circular Tubes". A Study of the accompanying heat transfer coefficient distributions for the Minnesota effectiveness data was reported by Eriksen and Goldstein (1970).Pedersen et al. (1977) in the paper "Film Cooling with Large Density Differences between the Mainstream and Secondary Fluid Measured by the Heat-Mass Transfer Analogy" presented the first open-literature study of the effects of density ratio on film cooling. Their primary test surface geometry utilized holes angled 35^{0}from the surface, directed in the downstream direction, with three diameter hole spacing, but with holes half the diameter of the previous Minnesota single-row studies. Their data showed that beyond about 10 hole diameters, the centerline effectiveness maximizes for a V.R of about 0.5 – 0.6, over a D.R range from 0.8 – 4.0. Goldstein et al. (1974) in the paper "Effects of Hole Geometry and Density on Three-Dimensional Film Cooling" present a limited amount of effectiveness data with D.R variation to show that higher film-cooling effectiveness can be achieved at larger blowing ratio when D.R is greater than Unity. Ito et al. (1978) in the paper "Film Cooling of a Gas Turbine Blade" reported the effect of curvature on effectiveness with D.R varied from 0.75 to 2.0, with a surface geometry of 35^0 holes spaced three diameters apart, and with M varied from 0.2 to 3.0.Foster and Lampard (1980) in the paper "The Flow and Film Cooling Effectiveness Following Injection through a Row of Holes" acquired both effectiveness and concentration profile data, and primarily studied the influence of injection angle (35^0, 55^0 and 90^0) and row spacing (1.25-3.0 d) on effectiveness for a range of M from 0.5-2.5.

Forth et al.(1985) in the paper " The effect of Density Ratio on the Film Cooling of a Flat Plate" carried out a study of D.R effects on film cooling from a single 30^0 row

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of holes with three-diameter hole spacing. This research was similar in content to that reported by Forth and Jones (1988) in the paper "Scaling Parameters in Film Cooling". Both studies showed that there exist two regimes of Injection: weak injection describing film-cooling flow that emerges and stays attached to the surface; and strong injection describing film-cooling flows with high enough momentum to lift from the surface and penetrate into the mainstream. The momentum flux parameter was found to scale the weak injection data, whereas velocity Ratio scaled the strong injection data.Dittmar et al (2002) in the paper "Assessment of Various Film Cooling configurations using shaped and compound angled holes based on large scale experiments" reported that shaped holes provide better coverage at higher blowing ratios by resisting jet penetration into the mainstream. Berhe et al. (1999) in the paper "Curvature Effects on Discrete-Hole Film Cooling" conducted a numerical study to investigate the effect of surface curvature on cooling effectiveness. For the low blowing ratios considered, the convex surface resulted in a higher cooling effectiveness than both the flat and concave surfaces. For the convex case, the coolant jet is pressed to the surface by a strong cross-stream pressure gradient. On the Concave Surface, the mixing between the coolant jet and the mainstream is strong, so the cooling effectiveness degrades. Eslam et al (2012) in the paper "Effect of Shaped-Hole on Film Cooling Effectiveness of a Gas Turbine Blade" conducted analysis on holes at stream wise angles of 30, 60 and 90^0 with 3 blowing ratios 0.45,1 and 2.0. It was concluded that the maximum centerline effectiveness with blowing ratio occurs at stream wise angle 30^0 jets on concave, convex and flat plate surface.

This study aims to contribute to validation process, by employing the widely used commercial flow simulation package Ansys CFX to predict the flow development that results from coolant injection into the flow over a flat surface, from a single row of inclined injection holes, over a range of momentum and density ratios.there by allowing examination of their effects on film cooling effectiveness. The experimental data by A.K.Sinha et al. (1991) are used for validation purposes.

II. CFD Validation & Analysis

Analysis on flat plate: The first stage in the project involved validating the conditions of the solver and seeing to it that it confirms with the experimental values obtained previously. The experimental setup described in "Film Cooling Effectiveness Downstream of a Single Row of holes with Variable Density Ratio" by A.K.Sinha was taken and modeled in PTC Creo.

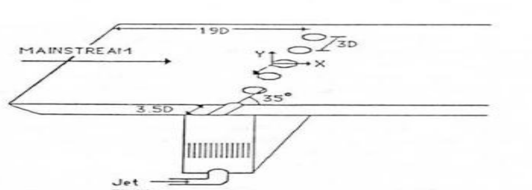

Figure-2.1: Experimental set up of A.K.Sinha et.al

In the test plate, the jet was issued from a row of 7 holes, each 1.27 cm in diameter and spaced 3 diameters apart laterally. Each hole was inclined at 35^0 from the surface and the injecting passage had an L/D of 1.75.

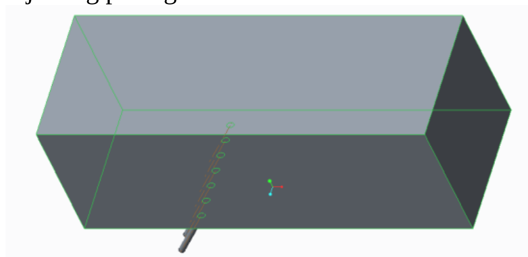

Figure-2.2: CREO Model of flat plate

Initialize the boundary conditions by taking the values from A.K.Sinha et al (1991).

Table-2.1: Boundary Conditions

Condition : A	
Temperature of Mainstream (T∞)	300 K
Temperature of Coolant/Jet (Tc)	250 K
Velocity of Mainstream (V∞)	20 m/s
Velocity of Coolant/Jet (Vc)	16.6 m/s
Condition : B	
Temperature of Mainstream (T∞)	300 K
Temperature of Coolant/Jet (Tc)	257 K
Velocity of Mainstream (V∞)	20 m/s
Velocity of Coolant/Jet (Vc)	12.5 m/s
Other Parameters	
Turbulence – Mainstream	Low (1%)
Turbulence – Coolant Flow	Low (1%)
Pipe Wall	Free Slip +Adiabatic
Test Plate	Free Slip + Adiabatic
Wall	Symmetry

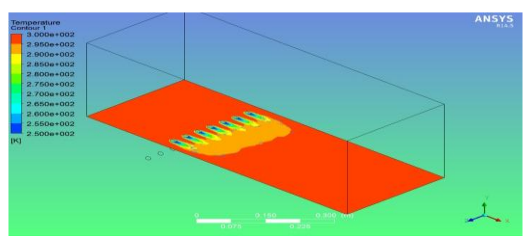

Figure-2.3 :Surface Temperatures for Condition "A" [V.R = 0.83, D.R = 1.2]

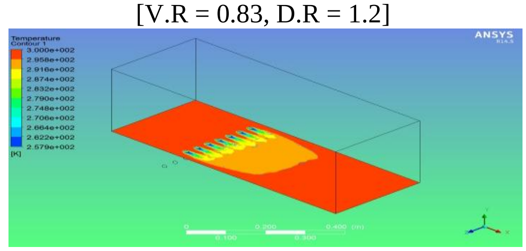

Figure -2.4 : Surface Temperatures for Condition "B"
[V.R = 0.625, D.R = 1.6]

From the Temperature Plot available from CFX, the Centerline Effectiveness was measured using the Formula:

$$\eta = (T_\infty - T_{\text{aw}})/(T_\infty - T_{c,\text{exit}})$$

Where,
(T_∞) =Temperature of Mainstream,
(T_c) =Temperature of Coolant/Jet,
(T_{aw}) = Temperature of adiabatic wall.
The results indicate that at X/D = 5. Hence, it has been decided to conduct analysis at X/D=5.

Analysis on blade: This stage involved conducting an analysis of film cooling on a Aerofoil Shaped Gas Turbine Blade whose coordinates are taken from NASA Technical Paper 1136 – "Effect of cooling hole geometry on Aerodynamic Performance of a Film Cooled Turbine Vane tested with cold air in a Two dimensional Cascade.

The blade was modelled using PTC Creo Parametric using advanced options like "Datum Plane" and "Datum Points" for generation of the curve of the blade. The following points were kept in mind while designing the model: The Cooling hole has constant diameter D and length L.The cooling hole metering section diameter (D) is equal to 5mm.Each of the cooling hole total length (L) and span wise pitch (P) is taken to be three-times the cooling hole metering section diameter; i.e P=L=3D. The cooling fluid is injected to the mainstream at a stream wise angle of 30^0 and a span wise angle of 90^0.

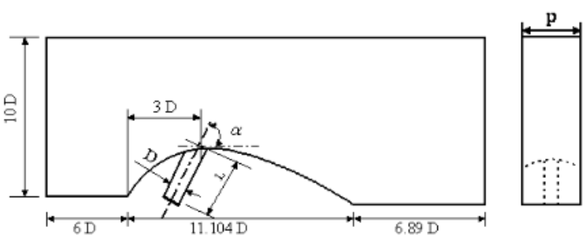

Figure: 2.5: Geometric Model of Turbine Blade

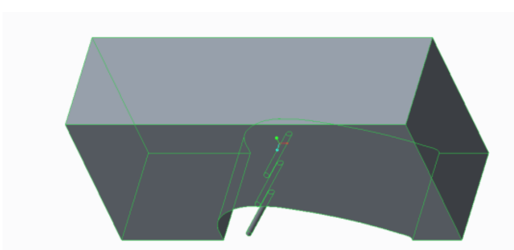

Figure: 2.6: CREO Model of Turbine Blade

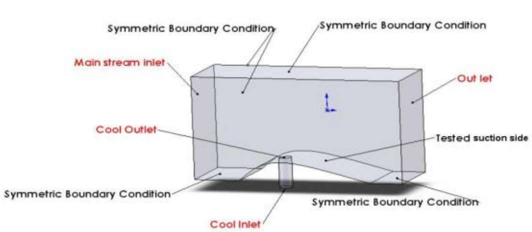

Figure: 2.7: Boundary Conditions

In the Present Simulation, the maximum and minimum ratios of velocity & density given in Sinha et al(1991) are taken and an analysis was performed and the results obtained were tabulated.

The Initial Boundary Conditions are tabulated below:

Condition : C1 [DR = 1.2, VR = 0.208]	
Temperature of Mainstream (T∞)	300 K
Temperature of Coolant/Jet (Tc)	250 K
Velocity of Mainstream (V∞)	20 m/s
Velocity of Coolant/Jet (Vc)	4.16 m/s
Condition : C2 [DR = 2, VR = 0.208]	
Temperature of Mainstream (T∞)	300 K
Temperature of Coolant/Jet (Tc)	150 K
Velocity of Mainstream (V∞)	20 m/s
Velocity of Coolant/Jet (Vc)	4.16 m/s
Condition : C3 [DR = 1.2, VR = 0.83]	
Temperature of Mainstream (T∞)	300 K
Temperature of Coolant/Jet (Tc)	250 K
Velocity of Mainstream (V∞)	20 m/s
Velocity of Coolant/Jet (Vc)	16.6 m/s
Condition : C4 [DR = 2, VR = 0.83]	
Temperature of Mainstream (T∞)	300 K
Temperature of Coolant/Jet (Tc)	150 K
Velocity of Mainstream (V∞)	20 m/s
Velocity of Coolant/Jet (Vc)	16.6 m/s
Other Parameters	
Turbulence – Mainstream	Low (1%)
Turbulence – Coolant Flow	Low (1%)
Pipe Wall	Free Slip Condition +Adiabatic
Test Plate	Free Slip Condition + Adiabatic
Wall	Symmetry Condition

Table-2.2: Initial boundary conditions

III. Results and Discussions

The surface temperature Contours obtained from CFX results are shown below:

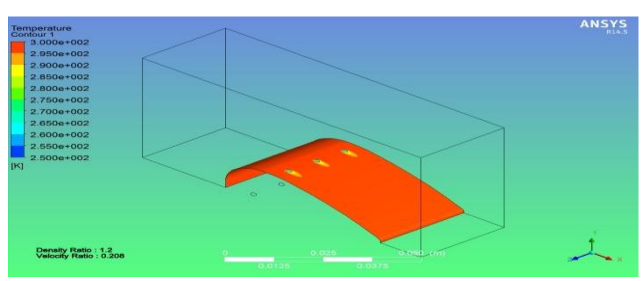

Figure-3.1 :Surface Temperatures for Condition "C1"

Trial No	Design Matrix				Centreline Effectiveness	
	X0	X1	X2	X12	Y1	Y2
1	1	-1	-1	1	0.08	0.07
2	1	1	-1	-1	0.06	0.05
3	1	-1	1	-1	0.16	0.15
4	1	1	1	1	0.26	0.25

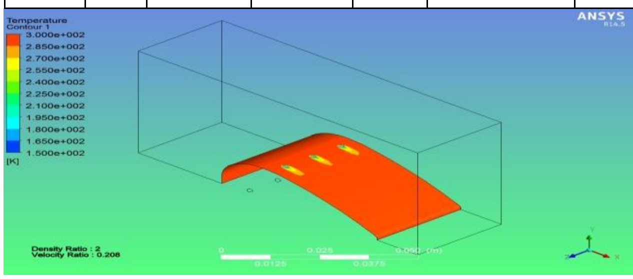

Figure-3.2 :Surface Temperatures for Condition "C2"

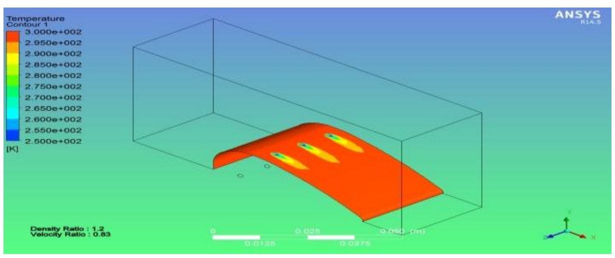

Figure-3.3 :Surface Temperatures for Condition "C3"

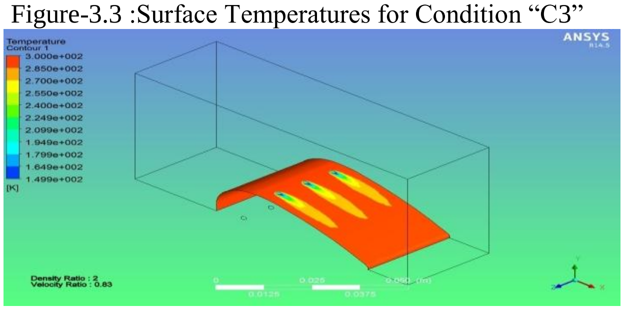

Figure-3.4 :Surface Temperatures for Condition "C4"

Centreline refers to a virtual line drawn on the centre of the blade on X-Z plane and the temperatures were recorded along this line. It can be observed from figures 3.1 – 3.4, the effectiveness of the plate has increased when the velocity ratio was increased.

Design of Experiments: The design of experiments is the procedure of selecting the number of trails and conditions for running them, essential and sufficient for solving the problem that has been set with the required precision. In design of experiments, numbers of trails to be conducted are determined by factorial method and design matrix is constructed. After getting design matrix, regression coefficients are calculated.

The mathematical model is developed by using factorial design of experiments to predict the Maximum Centreline Effectiveness .The Two factors namely, the Density Ratio and Velocity Ratio are analyzed at X/D=5. The developed model is tested for its adequacy and significance of each coefficient is checked by student's t-test at 5% significance level.

The Experiment (CFD Simulation) was conducted on a Gas Turbine Blade using Air as a Medium. Two Parameters were considered important for this study and were taken – Density Ratio & Velocity Ratio. The resultant centreline effectiveness was measured at X/D = 5. The design matrix was prepared and the trials were conducted according to the design matrix.

Table: 3.1: Experimentation Values of Centreline Effectiveness.

In the above table,-1 , +1 corresponding to low and high level.the values of regression coefficients are given below:

b0	0.135
b1	0.02
b2	0.07
b12	0.03

Table-3.2: Regression Coefficients

The Final Form of the Equation would be in the form:

$Y = b_0X_0 + b_1X_1 + b_2X_2 + b_{12}X_1X_2$

i.e. $Y = 0.0135 + 0.02X_1 + 0.07X_2 + 0.03X_1X_2$

Analysis of Variance(ANOVA): The percentage contribution for each of the factors, namely the Density and Velocity Ratios are determined to know which of the factors has a considerable effect on the Centreline Effectiveness of Film Cooling at X/D = 5.

Factor	% Contribution
X1 (Density Ratio)	6.42
X2 (Velocity Ratio)	78.7
X3	14.45

Table-3.3: ANOVA

Optimization of Blowing Ratio : The Blowing Ratio or Mass Flux is the product of Density and Velocity Ratio (M = D.R * V.R). In this section, the results of optimisation are presented.To calculate the optimum value such that the Centreline Effectiveness at X/D = 5 , a program is written in Mat lab using Genetic Algorithm.

MATLAB CODE :

```
_ _ _ _ _ _
function  yp = centreline_effect(x)
yp = 0.135 + (0.02*x(1)) + (0.07*x(2)) + (0.03*x(1)*x(2));
_ _ _ _ _
```

```
function  negyp = centreline_effectmax(x)
negyp = -0.135 - (0.02*x(1)) - (0.07*x(2)) - (0.03*x(1)*x(2));
_ _ _ _ _ _
clc
clear
format short
numberOfVariables = 2;
LB = [1.2 0.208];
UB = [2 0.83];

FitnessFunction = @centreline_effect;
[x,fval] =
ga(FitnessFunction,numberOfVariables,[],[],[],[],LB,UB);
d = x(1)
v = x(2)

yp = fval

FitnessFunction = @centreline_effectmax;
[xmax,fa] =
ga(FitnessFunction,numberOfVariables,[],[],[],[],LB,UB);
d= xmax(1)
v = xmax(2)
yp = fa
```

III. Result

Optimization terminated: average change in the fitness value less than options.

d =1.9996
v =0.8300
yp =0.2829.
Note :
d= Density Ratio
v= Velocity Ratio
yp= Maximum Centreline Effectiveness at X/D = 5

IV. Conclusions

A parametric study is performed on blade film cooling to determine the optimum parameters .the effect of film cooling parameters such as density ratio, velocity ratio and blowing ratio on the cooling effectiveness are studied and optimum cooling parameters are selected. The numerical simulation of the coolant flow through hole system is carried out using the CFD package Ansys CFX coupled with the optimisation technique to maximise the film cooling effectiveness. In addition, the results indicate that the overall film cooling effectiveness is enhanced by velocity ratio from ANOVA.The current study indicate that the hole should be designed such that the coolant flow is in the direction of stream wise angle for high blowing ratio.It can be concluded from the present study that Velocity Ratio (i.e Velocity of Coolant to Velocity of Jet Stream) has a greater impact than the other density Ratio. This may be due to the reason that lower the velocity of the coolant. This can be partially accounted to Inertia & turbulence effects.Also, decrease in density ratio and increase in momentum flux ratio were found to reduce the spreading of the film cooling jet significantly and thereby reduce the effectiveness of film cooling.Also, from the optimization it can be concluded that the blowing ratio should be greater than unity (>1.5) for effective film cooling for an arrow of 30^0 jets on a blade profile. The present analysis and optimization gave an optimal blowing Ratio of 1.65. The maximum center line effectiveness was found to be 0.28.

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VI.Nomenclature

D	Hole diameter(m)
L	Hole Length(m)
M	Blowing ratio= $\rho_c V_c / \rho_h V_h$
ρ_c	density of coolant,kg/m^3
ρ_h	Density of hot gases,kg/m^3
V_c	Velocity of coolant,m/s
V_h	Velocity of hot gases,m/s
T_{aw}	Average wall temperature(adiabatic),(K)
T_∞	Temperature of Mainstream,(K)
T_c	Temperature of Coolant/Jet,(K)
η	film cooling effectiveness