MULTIOBJECTIVE OPTIMIZATION OF A FILM JET PERFORMANCE FOR THE IMPINGEMENT CUM FILM COOLED GAS TURBINE NOZZLE GUIDE VANE

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ABSTRACT

The novel configuration such as impingement with film holes on the gas turbine nozzle guide vane causes the hot gas ingestion within in the film holes and hot spots on the vane surface. And hence the performance and longer operating time of a typically cooled vane is decreases. This recommends the coolant flow performance optimization for the combined impingement and film hole configuration of a vane surface. In the present paper the optimization is performed for the two different objectives of minimizing the coolant pressure drop across the each hole and maximizing the jet heat pick up. The second order response surface method is used to develop the mathematical form of two objective functions. The Pareto optimal solutions are obtained for all the rows of film holes with non-dominated sorting genetic algorithm (NSGA-II) using MATLAB2014a.The optimized results shows augmented overall film cooling effectiveness values compares to the baseline conditions. Moreover, these solutions are free from the hot gas ingestion and insignificant pressure drop within a film hole. This recommends the higher durability of a typically cooled NGV surface.

KEYWORDS: Combined Impingement and film cooling, Hot gas ingestion, Hot spot, RSM, Correlation factor, Multi-objective genetic algorithm, Pareto front.

1. Introduction:

Generally, a gas turbine engine works on the thermodynamic Brayton cycle, especially the net power developed at the engine shaft of the system and its thermal efficiency. The performance of a gas turbine engine is expressed by means of thermal efficiency. In order to increase the engine life span and its durability, gas turbine designers always aim at reducing both the thermal stresses and high metal surface temperature on the NGV. This necessitates the more advanced cooling technique such as combined impingement and film cooling to be used. The secondary air subjected as a coolant to the external film holes of the NGV is a critical issue because of increased thermal loads. Large amounts of secondary coolant flow supplied at the plenum leads to thermal stresses and overall gas turbine engine efficiency decreases. This in turn leads to a decrease in the vane life and its durability by decreasing the core mass flow. Therefore, the present multi-objective optimizations are performed to reduce the plenum flow rate and m the coolant jet exit temperature.

Probably, the first work reported by Brevet et al.[1] investigated the influence of the jet to plate spacing, jet Reynolds number and jet to jet spacing. The results shows that the reduction in pitch of the holes and increase of jet Reynolds number was enhances the heat transfer rates. Nowak and Wróblewski [2] were optimized the plenum cooling passages of a gas turbine blade subjected to the conjugate heat transfer. Lee et al.[3] reported on the multi-objective optimization for the film cooling effectiveness and aerodynamic loss of film cooled holes with the help of NSGA-II and SQP algorithm. The optimal design points enabled an improvement in the objective function values when compared to the conventional experimental designs. Girardeau et al [4] have been optimized for the conflicting objectives such as minimization of a global cost indicator and maximize global desirability of a nozzle guide vane design.Viana et al. [5] reported on the coolant flow optimization in the film holes without cause of hot gas ingestion. They claimed that the optimized results with significant improved temperature distribution while reducing the amount of used cooling flow. Kim et al. [6] determined an impinging jet design that achieves the lowest thermal stress in an impingement-cum-effusion cooling system.

The optimized results indicated that higher values of stresses were obtained near the film cooling holes at low average temperature. Ayoubi et al. [7] investigated an aerothermal performance optimization for the pressure side film holes of a gas turbine vane. The optimized results show that the blowing ratio was slightly higher than that of a thermal optimum. CFD results tend to over predict changes in cooling effectiveness and under predict changes in aerodynamic loss. The optimization was performed with GA with the help of RBNN for the shape optimization of a fan-shaped film cooling hole by Wang et al. [8]. The optimized double-jet film-cooling performance achieved was 19.01% higher in comparison to the baseline geometry. Most recently Kukutla and Prasad [9-10] investigated the computational analysis of a coolant flow performance for the leading edge film cooled holes of an NGV. The results show that non-uniform distribution of ejected jet flow rates under a given plenum supply flow rates. This nonlinear behavior recommended for the coolant flow performance optimization of all the film holes. The computational results have a good agreement with PIV results.

The aforementioned literature reveals that, hitherto there was no coolant flow performance optimization for the combined Impingement and film cooled rows of a high pressure NGV. However, a less number of investigations were reported on the optimization of a film cooling effectiveness and aerodynamic losses of a film holes. But, these optimization studies were limited to the flat plate with suction and pressure side of the nozzle guide vane without use of the multiple jet impingement action.
Therefore, the multi-objective optimization was performed for the aerothermal analysis of coolant flow for the fully covered film holes on the vane surface subjected to the multiple impingement action.

2. Physical Model

The coupled impingement–film cooled first stage NGV was used for the current investigation. The geometry comprised two cooling passages, namely Leading Edge (LE) and Trailing Edge (TE) cooling passages. The external surface of the NGV was divided into three sections: (i) pressure surface (PS), (ii) LE and (iii) suction surface (SS) regions. The entire surface of the NGV was provided with thirteen film cooled rows. The LE circuit consisted of five showerhead rows at the LE region, whereas the pressure and suction surfaces had two film cooled rows on each surface, covering a total number of 101 film holes. On the other hand, TE circuit consisted of two film cooled rows on both the surfaces of the NGV, which covers a total of 55 film holes provided on the either side of surfaces as shown in Figure 1. And thus the entire vane surface consisted of 156 film cooled holes. The secondary air entered at the LE and TE circuits, and finally the impinging action took place on the inner surface of the NGV. This necessitated that the film cooled jet must be ejected at the mainstream interaction surface. The LE circuit was made up of five showerhead rows (SH1 to SH5). There were two film cooled rows on the suction surface (SS1 and SS2) and the pressure surface (PS3 and PS4) of a NGV span-wise direction.. The secondary air supplied to the TE circuit, after impinging action, came out from the two suction surface rows (SS3 and SS4) and two pressure surface film cooled rows (PS1 and PS2).

. 3. Computational Methodology

The computational analysis was carried out on two fluid zone regions and one solid zone region. The mainstream flow and the secondary air flow from the plenum to the ejected film cooled jet at the interaction surface were considered as fluid zones 1 and 2 respectively. The computational mesh was created by GAMBIT 2.3.16 as depicted in Figure 2. The span-wise averaged effectiveness at various stream-wise locations of the vane was calculated as plotted in Figure 3. When the mesh was improved from coarse to medium, a maximum difference in a span-wise film cooling effectiveness value of about 3% was noticed. However, further refinement with fine mesh showed a maximum difference of film cooling effectiveness values of less than 1% in comparison to the medium mesh values which indicates that on additional usage of 2.4 million cells, the difference in film cooling effectiveness was insignificant. This justifies adopting medium mesh for the present computational model. In this mesh, a y+ value of less than 0.8 was ensured throughout the vane surface as shown in Table 1.

3.1 Numerical solution

The computations were performed considering velocity boundary condition at the inlet to the linear cascade. The mainstream turbulence intensity of 1% was chosen at the film cooled jet exit condition. The film cooled jet, after hitting the NGV surface, exited into the atmosphere in the transverse direction all around the vane surface, where uniform atmospheric pressure was maintained at the outlet condition The end walls of the domain were subjected to periodic boundary condition for the linear cascade model analysis.
The three-dimensional flow numerical analysis was investigated under conjugate heat transfer condition with the following assumptions: (i) steady flow, (ii) constant thermo fluid properties (iii) incompressible fluid, (iv) viscous dissipation, natural convection and radiation effects are ignored. The 3D CFD simulations were carried by the Ansys Fluent17.2. The pressure velocity coupling was done by a SIMPLE algorithm. Residual convergence was selected as 10-4 for the continuity equation, and 10^{-6} for both the momentum

and turbulence equations. The κ-ω SST model was used for the turbulence modeling. The simulations were continued on the entire solid surface till the NGV reached a steady state condition.

Table 1. Details of cells used for meshing

	No. of cells (Millions)	Value of y+
Fine	15.1	0.5
Medium	12.7	0.8
Coarse	9.8	1.5

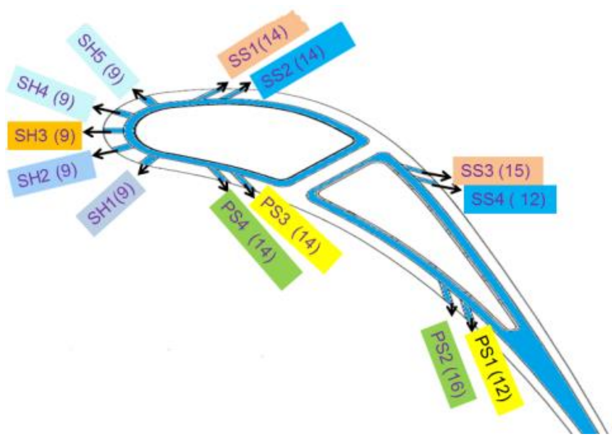


Figure 1. Thirteen rows of film holes on the vane surface

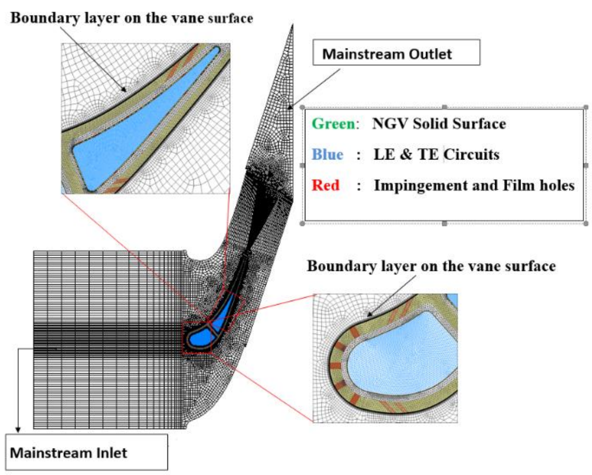


Fig. 2 Mesh used for computation

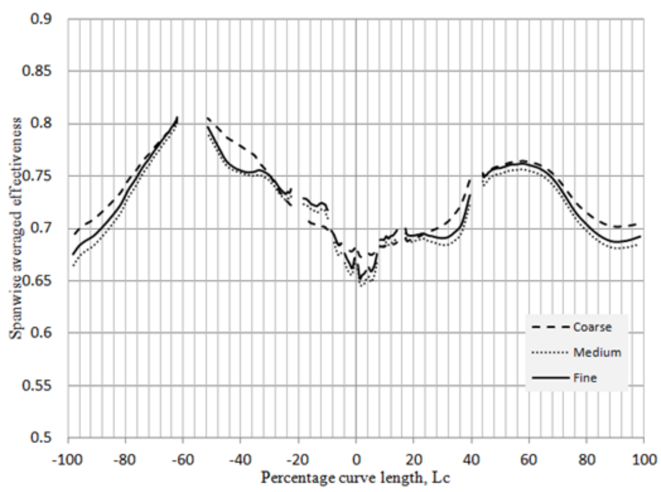


Fig. 3 Grid independency study

4. Optimization Methodology

4.1. Regression Analysis

The main aim of the polynomial regression model is to establish an approximate function between the input design variables and the output responses through a special series of statistical analysis.

$$F(x) = \beta_0 + \sum_{j=1}^{N} \beta_j x_j + \sum_{j=1}^{N} \beta_{jj} x_j^{2} + \sum_{i=1}^{N} \beta_{jj} x_j^{3}$$

Where F(x), x and N are the objective function, design variable and the number of design variables respectively. The surrogate model is constructed for the numerical obtained results jet by means of statistical software XLSTAT 16.5.

fPD, LEC = -2106.90*x(1)+14.53*x(2)-3.54*x(3)+1735702.03*x(1)^2-2.50E-02*x(2)^2+1.14*x(3)^2-7.27E-02*x(3)^3

fJHP,LEC=-295442.13-2190855.39*x(1)+1064.94*x(2)-853.65*x(3)+131025660.20*x(1)^2-0.34*x(2)^2+143.176137985413*x(3)^2-7.18*x(3)^3

fPD,TEC=3065.69+3003.42*x(1)-20.72*x(2)-4.64*x(3)+3011846.71*x(1)^2+3.51E-02*x(2)^2+2.14*x(3)^2-3.19486166072703E-03*x(3)^3

fJHP,TEC= -100208.23-918651.85*x(1)-199.43*x(2)-1054.61*x(3)+26363427.80*x(1)^2+1.71*x(2)^2+171.50*x(3)^2-7.19*x(3)^3

4.2. Objective Function and Design Variables

The global optimization was conducted on all the 156 film holes of the NGV. The optimization was performed for two different objective functions. Firstly, minimization of the film cooled jet static pressure drop was performed.

$$\mathbf{f_1} = \mathbf{Min}(|\Delta\mathbf{P}|)$$

The second objective function was minimization of the coolant jet heat pick-up with convective heat transfer from the mainstream cross flow and conduction heat transfer from the vane surface. The coolant comes out of the plenum, impinges on the back side of the vane and travels to the film hole. The coolant picks-up heat during this process, thereby increasing the temperature at the inlet of the film hole ($T_{c,i}$) more than that in plenum. This pick-up of heat is defined by a quantity called jet heat pick-up (JHP):

$$\mathrm{JHP} = \frac{T_{c,i} - T_p}{T_m - T_p}$$

Where $T_{c,i}$ is the coolant jet temperature at the film hole inlet and T_p is the coolant temperature in the plenum (FIT or AIT) and T_m is the mainstream inlet.

The following are subjected constrains for the multiobjective optimization.

1. (a) $0.0037 \leq X_1 \leq 0.0075$ at FIT plenum
   (b) $0.0073 \leq X_1 \leq 0.0148$ at AIT plenum
2. $288 \leq X_2 \leq 296$ both the Plenums
3. $3 \leq X_3 \leq 10$

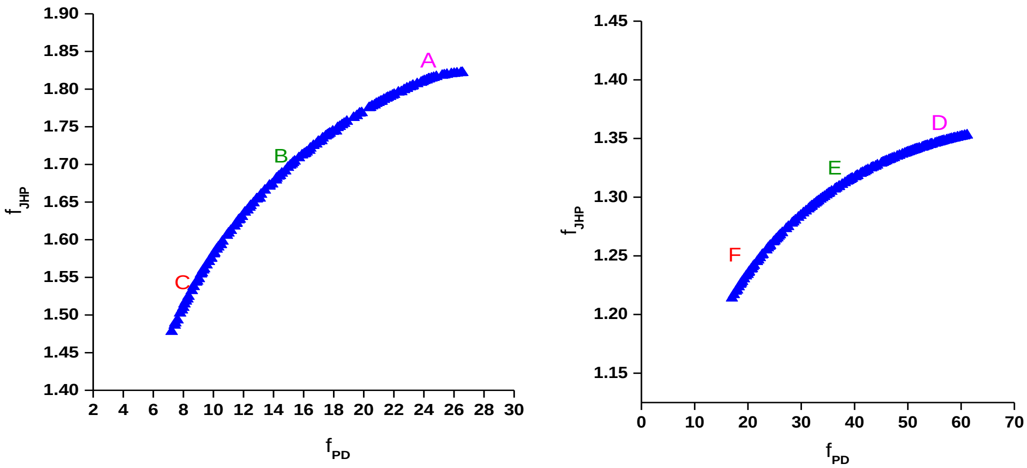
Where
X_1: plenum coolant mass flow rates
X_2: Plenum coolant temperature (K)
X_3: Mainstream Velocity (m/s)

4.3. Multi-Objective Optimization

Multi-objective genetic algorithm was performed for all the film cooled holes for the two objective functions of pressure drop within the film hole and film cooled jet heat pick-up. This was carried out using “gamultiobj” option, which was available in the optimization toolbox, a MATLAB R2014a. The fitness functions for the two objective functions were supplied in the vector form. The population type was considered of the double vector type. The scaling function was obtained based on the rank and tournament category rather than parent scores. A tournament selection operator with a tournament size of two was used to select the new individuals for the next generation. Crossover combines two individuals or parents to generate a new individual for the next generation, which mimics mating in biological populations. The crossover function was set to intermediate, which creates new individual (children) by a randomly weighted average of the parents. In this non-dominated sorting genetic algorithm approach, both the crossover fraction and the Pareto-front population fraction were maintained as 0.8. Meanwhile, the population size, number of generations and function tolerance were chosen as 150, 500 and 10–6.

5. Results and Discussion

Figure.4. provides the insightful information about Pareto front for the LEC and TEC film cooled rows subjected to constant mainstream temperature of 320K. These Pareto fronts are obtained based on the non-dominated sorting criteria. All these Pareto optimal solutions are independent of the effect of hot gas ingestion and hot spots on the NGV. These Pareto-optimal solutions represents the set of representative optimum solutions for the conflicting objectives of minimizing the film hole pressure drop and maximizing the effused jet heat pick up. Since, the obtained Pareto-optimal solutions resemble a concave front. It is noticed that the small change in the pressure drop leads to a detrimental change in the jet heat pick up and vice-versa. The designers are free to choose any optimum design points according to their requirement from the overall best Pareto optimal solutions. This is due to the coherence nature of the two objective functions. The three set of representative Pareto-optimal solutions (POS) namely A, B and C are chosen from the upper, middle and lower bounds of the overall best LEC Pareto front as shown in the Figure.4 (a). On the other hand, the three representative Pareto-optimal solutions (POS) namely D, E and F are selected from the highest, middle and lowest bounds of the TEC Pareto front as shown in the Figure.4 (b).



(a) (b)

Fig.4.Pareto optimal solutions (a) LEC film holes (b) TEC film holes

Figure.5. shows the Spanwise variation of averaged overall effectiveness for the fully covered nozzle guide vane surface. The comparisons are made between the baseline and optimized conditions for the mainstream temperature of 320K. The baseline condition is considered as follows: FIT mass flow rate is 0.0037kg/s. AIT mass flow rate is 0.0073 kg/s, Coolant temperature is 288K, mainstream velocity is 3m/s, mainstream temperature is 320K and Turbulent intensity of 1% respectively. The spanwise averaged overall effectiveness values are augmented for the design points A1, B1, C1, D1, E1 and F1 rather than its baseline condition. The overall effectiveness values are gradually decreases from the selected Pareto optimal design point A to C. The same trend is continued for the representative Pareto optimal design points D to F. Therefore, the highest effectiveness values are noticed at the representative Pareto optimal design points A and D. Meanwhile, the lowest performance of effectiveness are noticed for the representative Pareto optimal design points C and F respectively.

For the baseline condition, the peak value of effectiveness is 0.55 is observed for the PS1 and PS2 rows. While, the SS3 and SS4 rows with the 49.5% in the performance of effectiveness. These values for the showerhead rows are varies from 43% to 44%. The lowest film cooling performance 38% is observed for the TEC rows (PS3, PS4, SS1 and SS2). The three optimum deign points shows the improved overall effectiveness performance for the thirteen film cooled rows of a nozzle guide vane. The performance of film cooling effectiveness are enhanced from 21% to 31% at the POS: A for the LEC rows. Subsequently, the effectiveness performance is enhanced from 18% to 20% at the POS: D for the TEC rows. The overall effectiveness is gradually decreases from the upper bound (POS: A& D) to lower bound (C &F) of the Pareto optimal solutions. The similar trend is noticed from the optimal design point D to F. These augmentation is obtained with respect to the baseline condition. The TEC rows such as PS1, PS2, SS3 and SS4 are decreases from 3% to 6% for the representative Pareto optimal design points B and E respectively. These performances are further reduced from 10% to 11% for the representative Pareto optimal design points C and F respectively. It is evident that total rows of film cooling effectiveness values are higher than the baseline condition

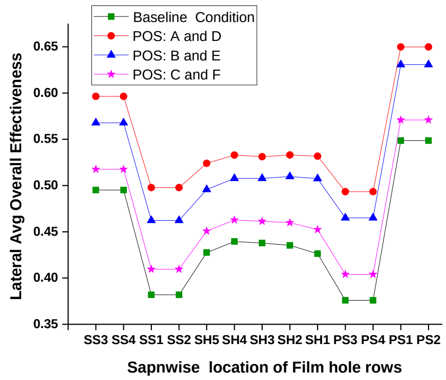


Fig.6. Comparison of overall effectiveness variation between the optimized and baseline condition.

Conclusions

Aerothermal coolant flow performance was optimized for the fully covered film holes of a typically cooled high pressure nozzle guide vane. The optimal plenum coolant mass flow rate and mainstream velocity are affected by the higher mainstream temperature of 320K, while maintaining the remaining parameters are constant. The following conclusions can be made from the present study as follows: The validated CFD results shows that, both the pressure drop and jet heat pick up values are under predicted and over predicted within 5% for the LEC and TEC plenums. The optimal coolant mass flow rate is augmented by 7.27% at the LEC plenum. Subsequently, this value is reduced by 6.55% at the TEC plenum. Whereas, the optimal mainstream velocity is higher by 27% both at the LEC and TEC plenums. However, there is no significant change for the optimal coolant temperature values.The multi-objective optimization of a coolant flow performance for the combined impingement and film cooled gas turbine NGV may be referred as paving the way for the film cooled jet studies with film cooled geometry changes, and simultaneously followed by conjugate conditions.

References

1. Brevet P, Dejeu C, Dorignac E, Jolly M, Vullierme JJ. Heat transfer to a row of impinging jets in consideration of optimization, International Journal of Heat and Mass Transfer, 45 (20), 4191–4200 (2002).
2. Nowak G, Wróblewski W. Optimization of Blade Cooling System with use of Conjugate Heat Transfer Approach, International Journal of Thermal Sciences, 50(9):1770-1781 (2011).
3. Lee KD, Kim SM, Kim KY. Multi-Objective Optimization of a Row of Film Cooling Holes Using an Evolutionary Algorithm and Surrogate Modeling, Numerical Heat Transfer, Part A: Applications. 63: 623–641 (2013).
4. Girardeau J, Pardo F, Sebastian P, Pailhès J, Nadeau JP. Turbine Blade Cooling System Optimization, ASME Journal of Turbomachinery.135 (6): 061020 (2013).
5. Viana FAC, Madelone J, Pai N, Khan G, Baik S. Temperature-Based Optimization of Film Cooling in Gas Turbine Hot Gas Path Components, ASME Paper No. GT2013-94293 (2013).
6. Kim KM, Moon H, Park JS, Cho HH.Optimal design of impinging jets in an impingement/effusion cooling system, Energy. 66:839-848 (2014).
7. Ayoubi CEL, Ghaly WS, Hassan IG. Aerothermal optimization and experimental verification for discrete turbine airfoil film cooling, AIAA Journal of Propulsion and Power. 31:543-558 (2015).
8. Wang C, Zhang J, Zhou J. Optimization of a fan-shaped hole to improve film cooling performance by RBF neural network and genetic algorithm, Aerospace Science and Technology. 58:18-25 (2016).
9. Kukutla PR, Prasad BVSSS. Secondary flow visualization on stagnation row of a combined impingement and film cooled high-pressure gas turbine nozzle guide vane using PIV technique, Journal of Visualization. 20:817-832 (2017).
10. Kukutla PR, Prasad BVSSS.Numerical Study on the Secondary Air Performance of the Film Holes for the Combined Impingement and Film Cooled First Stage of High-Pressure Gas Turbine Nozzle Guide Vane, International Journal of Turbo and Jet Engines. Published Online:2017-07-26, DOI: https://doi.org/10.1515/tjj-2017-0022 (2017).