Numerical Optimization of Trench Film Cooling Parameters using Response Surface Approach

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Abstract. Film cooling is a widely used cooling method to safeguard the surface of gas turbine components from adverse impact of hot mainstream gases. The trench film cooling is a type of film cooling were the film cooling holes are placed within the cut slots designed on the film cooling surface. Numerical optimization is performed on trench film parameters using response surface based approach. The trench parameters used in this study are trench length, trench depth, trench film hole compound angle, blowing ratio and area averaged film effectiveness is used as the response factor. Response surface contours were generated and analysis of variance was performed. The results of the study show that the trench parameters viz., trench depth, blowing ratio have higher significance on response factor. The optimized trench parameters were trench length 2D , trench height 0.83D, trench film hole compound angle 83.12° and blowing ratio of 1.96.
Keywords: trench parameters, film cooling, response surface approach

1 Introduction

Gas turbines are widely used in electric power generation; aircraft propulsion units, marine propulsion systems. Most of the components of gas turbine may require extensive cooling, in order to safeguard itself from hot combustion gases. The gas turbine operates above a temperature range of 1500°C and most of the materials used on turbine components may melt at these higher temperature environments. In order to safeguard the gas turbine components and for its continuous operation the cooling modes are applied on both internal and external surfaces of turbine components. The internal cooling is applied through impingement jets and film cooling is used for external surface cooling. The low temperature air required for film cooling is obtained from compressor stages and this air is directed through ducts and are finally ejected through film cooling holes available on the cooling surface. In traditional film cooling the film cooling holes are directly placed on the surface that require protection from hot stream gases, however this method can lead to decreased effects on film cooling with increase in coolant ejection rates. In trench film cooling, the film cooling holes are embedding within cut slots and cooling air is ejected from film holes are passed through the trenched slots. Lu et al. [1] performed experimental studies to understand the effects of trench geometry on film cooling performance. The results of their study showed that the height of the trench have a significant influence on trench cooling performance and a trench length of 2 times the film hole diameter delivered higher cooling effectiveness. Lee and Kim [2] performed numerical studies with the goal to identify the effective trench dimensions. In comparison with other trench geometry a trench length of 2 times the film hole diameter and trench depth of 1 times the film hole diameter delivered higher cooling performance. Lakzian [3] carried out numerical studies to determine the optimum parameters on film cooling. The optimized film parameters determined from the study are blowing, density ratio, and turbulence intensity. Alshehaby et al. [4] performed numerical studies to optimize the shaped film holes parameters. The results of their study determined the optimized size of slot film hole. Elsayed et al. [5] used CFD and simplex method to optimize the film cooling parameters that can deliver maximum film cooling effectiveness. The results of the study show that decrease in stream angle of film hole lead to higher film effectiveness at higher blowing rates. Lee et al. [6] used advanced algorithm with surrogate method to optimize the parameters of laid shaped film holes with the aim to obtain higher FCE and lower aerodynamic losses. Savastano et al. [7] performed numerical studies and optimized the parameters of effusion plates. Wang et al. [8] used NN-GA method and optimized important parameters of fan film holes that can deliver enhanced film cooling effectiveness. Oguntade et al. [9] performed numerical investigations and showed that modifications on trench outlets delivered improved film effectiveness on cooling surface. It is observed from the literatures that very few or no studies have been carried out on the optimization of trench film cooling parameters. The aim of the present study is to perform numerical optimization of trench film cooling parameters with the goal to maximize the trench film effectiveness using response surface approach. The trench FC parameters used for this study are trench length (w), trench height (d), trench hole compound angle (β) and Blowing rate (M).

2 Response Surface Approaches

The response surface approach is a statistical method to develop approximate quadratic model based on input parameters and response factor. The range of trench parameters used in this study are trench length (2D – 3D), trench height (0.5D – 0.9D), trench hole compound angle (45^0 - 135^0), blowing ratio (0.4 - 2.0) and D is the diameter of the film hole (4mm). The AA film effectiveness is chosen as a response factor. The BBD is used and the chosen range of trench parameters and arranged in to an experimental matrix system (EMS). The modeled EMS consists of 29 cases of different combination s of trench paramters. Computational investigations were carried out to determine the response factor for each case of EMS.

2.1 Numerical and Experimental details

The computational domain is scaled down based on experimental test section geometry. The domain consists of mainstream section, trench section and film cooling hole. The critical regions of computational domain with higher thermal and pressure gradients are regions close to the wall surface, trench region and film hole system. A higher dense mesh system is used to cover the critical regions of the computational domain. The details of computational model used in the study are shown in figure 1. The x-axis and z-axis represent the longitudinal and lateral extent of the computational domain and y-axis represent the vertical extent of the domain.

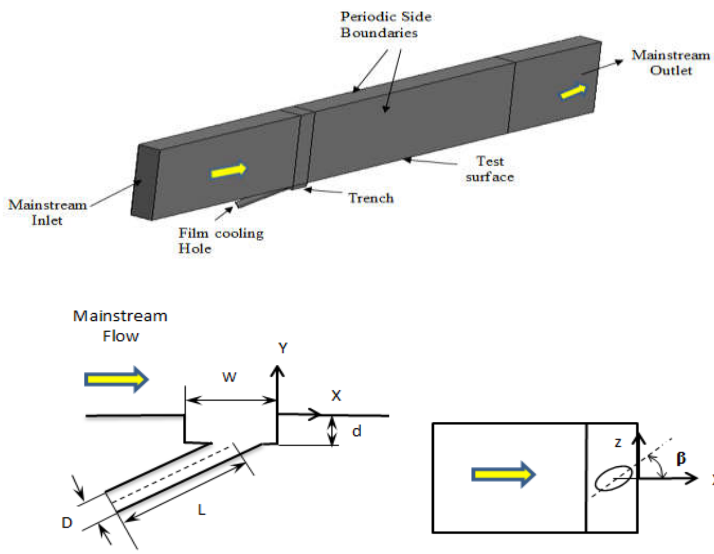

Figure 1. Computational details and trench film paramters

Structured cluster mesh system is used for mainstream with trench region and unstructured mesh model is used for film hole. Grid independence test is carried out with three different meshes viz., 0.85, 2.1, and 3.8 million cells and with span averaged FCE used as assessment parameter for grid independence tests. The R-k-ε model with EWT is used for turbulence modeling. The vertical sides of the computational domain are specified with periodic BC's. The mainstream flow is maintained at a velocity of 13 m/s. The velocity of the coolant stream is varied as per the requirement of blowing ratio.

The experiments were carried out on facility developed at the laboratory were the free stream flow is heated with a matrix of heater assemblies. The test section is a square duct made of Plexiglass sheet assembled at the center of the test facility. The unit other than test section is fabricated out of MS sheet of thickness 3.5mm. The film cooling air is supplied at room temperature from storage tanks. The test section is fabricated from low thermal conductivity material to make it to satisfy the adiabatic wall boundary condition. K type thermocouples were used for the measurements of temperatures along the test plates.

3 Results and Discussions

The computational results need to be validated and this is carried out with a single case identified from EMS of response surface methodology. The figure 2 shows the plot for the comparison of numerical results with the experimental data for an M of 1.2. The computational results are mostly lower than experimental results all along the test surface.

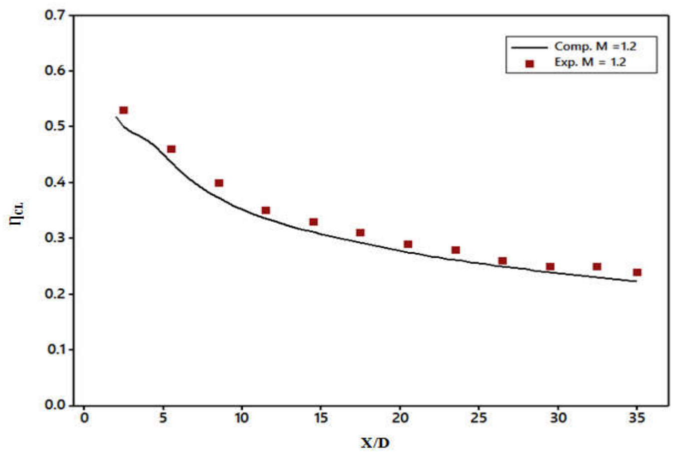

Figure 2. Comparison of computational and experimental results of at M of 1.2

The response surface plots generated were used to study the pattern of variation of trench parameters viz., trench length, trench height, film hole compound angle, and blowing rate against the area averaged film cooling effectiveness of test surface. The Analysis of variance was performed to identify the influential parameters that can affect the film cooling effectiveness on test surface. The parameter with the P value < 0.05 is considered to be significant for film effectiveness. Here the terms trench height and blowing ratio are more influential parameter followed by film hole compound angle. The figure 3 shows the variation of increase of trench height with blowing ratio against the response parameter. The higher trenches in the range of 2.8 - 3.6 mm have areas of higher film effectiveness. The variation of trench height and compound angle of film hole against the area averaged film effectiveness is shown in figure 4. The trench height above 0.7D and film compound angle around 90^0 have regions of higher film effectiveness and the numerical optimization is performed on trench parameters by setting it to be in the range of selected trench paramters and with a goal to maximize the response factor. The optimization is performed based on desirability function of response surface approach. The optimization is performed on trench parameters to satisfy a desirability value of 1. The optimized trench parameters are trench length 2D, trench height (or) depth 0.83D, trench film hole compound angle 83.12° and blowing ratio of 1.96.

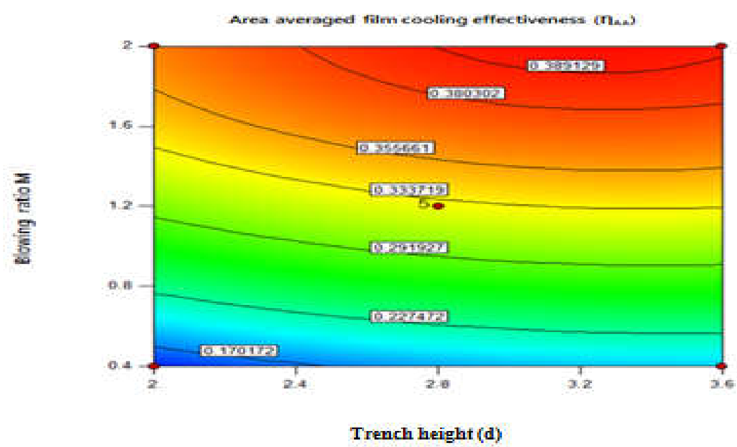

Figure 3. Variation of trench height and blowing ratio with AA film effectiveness

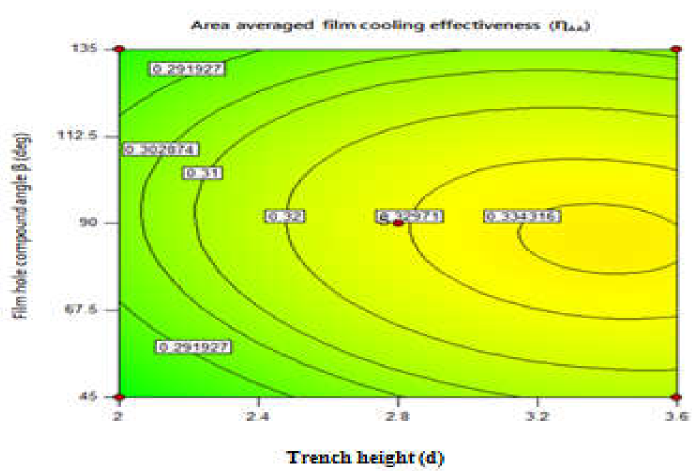

Figure 4. Variation of trench height and FHCA with AA film effectiveness

5 Conclusion

The numerical optimization of trench film cooling parameters viz.., trench length, trench depth, film hole compound angle and blowing ratio were performed based response surface approach. The AA film effectiveness were used a response parameter. Experimental matrix system based on BBD was generated based on the selected range of trench parameters. Computational study was used to determine the response factor of EMS. Experimental results performed for validation shows close agreement with numerical data. The optimized trench parameters were trench length 2D , trench height 0.83D, trench film hole compound angle 83.12° and blowing ratio of 1.96.

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