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CALCULATION OF GAS TURBINE BLADE TEMPERATURES USING AN ITERATIVE CONJUGATE HEAT TRANSFER APPROACH

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INTRODUCTION

One of the most important goals of the gas turbine industry is to produce a gas turbine with an increased thermal efficiency, higher power to weight ratios and reliability. The gas turbine industry is continuously putting an effort on increasing the turbine inlet temperatures to increase the turbine efficiency. But increasing inlet temperature has adverse effects on the life and reliability of the components of the gas turbine. Thus it is important to accurately predict the heat load applied to the components and their temperatures near the combustor for these high inlet temperatures.

Analytical Studies: Numerous studies have been done in the past on gas turbine heat transfer. The simultaneous calculation of conduction and convection is called conjugate heat transfer. Luikov [1974] presented a solution for laminar, incompressible flow over a flat plate. His results made a good agreement with the exact solution for local Brun number in the range $0 < Br_x < 1.5$. Researchers [1974-1999] presented solutions for flow over flat plate, vertical plate, cone, and wedge. They also showed the conjugate results fit analytical results and are better than the ones obtained using non-conjugate method. They achieved accuracies of 1-2% for Nusselt number for low thermal conductivity and 5% for high values of thermal conductivity.

Numerical and Experimental Studies: Rigby and Lepicovsky [2001] presented two simple cases to validate the conjugate heat transfer code for turbomachinery applications. Discrepancies in results of Nusselt number comparison was due to the assumption of one dimensional heat conduction. Bohn et al. [1997] presented a 3D simulation of the film cooled turbine blade and showed that for 3D simulation for exact determination of boundary conditions from the experiments is necessary. Their conjugate studies to a film cooled turbine blade predicted 8% of difference in temperatures for conjugate and decoupled conventional approach. York et al., [2003] presented a complete 3D conjugate heat transfer simulation on C3X turbine blade and compared the results with the data of Hylton et al., [1983]. They simulated the two cases for different Mach numbers and their results showed a very good agreement(within ~7-8%) with the experimental results.

The conjugate approach involves time consuming calculation as the number of grid points increase as both fluid and solid domain have to be taken in to consideration. An enormous care need to be taken while meshing the interface as the temperature gradient is high in this region and also time averaged turbulence quantities such as turbulent kinetic energy and its dissipation need to be resolved accurately. However conjugate approach makes it possible to specify more accurate boundary conditions. In certain situations the calculations of the gas side heat transfer coefficients are in error due to complex geometries such as film cooling and inability of turbulence models to predict the flow correctly especially in the near field of the film cooling holes. In fact even in simple geometries simulations can give 5-10% deviation from data for heat transfer coefficients. To get around this problem in calculating gas turbine blade temperatures some designers prefer to use their experimental data taken on gas side heat transfer coefficients and solve the heat transfer problem within the solid itself only. However, gas side boundary condition usually specified in terms of heat flux on surface or surface temperature. Although ‘h’ is known, calculation of heat flux requires an assumed surface temperature. This assumption requires iteration of temperatures of the surface until given heat flux, h and temperatures all fit together. In FLUENT code these iterations are carried out internally by supplying “h” and using a convective boundary condition. In this paper this new approach is introduced where only conduction in the blade material will be solved using experimental heat transfer coefficient “h” on the gas side as boundary condition.

OBJECTIVES

The objective of this manuscript is to present the results of iterative conjugate heat transfer(CHT) calculations of gas turbine blade temperatures obtained using FLUENT [2006] code. One of the goals is to discuss the similarities and differences between the results of iterative CHT, full CHT and non-CHT calculations as well as compare them with experimental data. One very important objective is to supply information to gas turbine industry and researchers about the new iterative technique for calculating blade temperatures.

ITERATIVE TECHNIQUE

Simulations of an incompressible, 2D, turbulent flow over Mark-II blade [Hylton, 1983] was carried out using FLUENT code. The simulation geometry and grid are prepared using the preprocessor GAMBIT [2007]. An unstructured grid is used for the overall domain(both for gas and solid) and boundary layer grid was used to resolve the near wall region(both for gas and solid).For turbine blade calculations 111815 grid points were used. Boundary conditions applied were given in the experimental study carried by Hylton et al., [1983]. The two-equation Realizable k-ε model was used in simulations since it was shown that the model gave better results for heat transfer coefficients and temperatures compared to Standard and RNG model for flat plate boundary layer baseline studies. The problem is solved by two approaches, one is constant wall temperature and the other is conjugate. In the iterative approach, only solid blade is simulated and the boundary condition for the blade surface is found using experimental data on “h”. Data for heat transfer coefficient for blade suction and pressure surface is plotted in MATLAB. A 10^{th} order polynomial is used to fit the data and an equation was obtained for the heat transfer coefficient as a function of distance along the blade surface. The boundary condition of heat flux obtained from assumed wall temperatures and heat transfer coefficient on the pressure and suction surfaces was supplied to FLUENT using the User Defined Functions (UDF) feature.

RESULTS AND DISCUSSION

Figure 1 shows the heat transfer coefficient normalized by h_{ref}(given on the figure) along the blade surface with both non-conjugate and full conjugate simulations. Non-conjugate calculations are carried out using a constant wall temperature. Overall conjugate results are 13% higher compared to the data. But near the leading edge error is about the 40% and that can be because of acceleration after stagnation point and FULENT code cannot predict the relaminarization at this point. Overall it can be seen that conjugate results agree with data much more than non-conjugate results. The non-conjugate simulation results are under predict the data in the range of 20% and for the downstream of suction edge deviations from data are around 25%. From the results it can be seen that the more realistic results are obtained by full conjugate analysis.

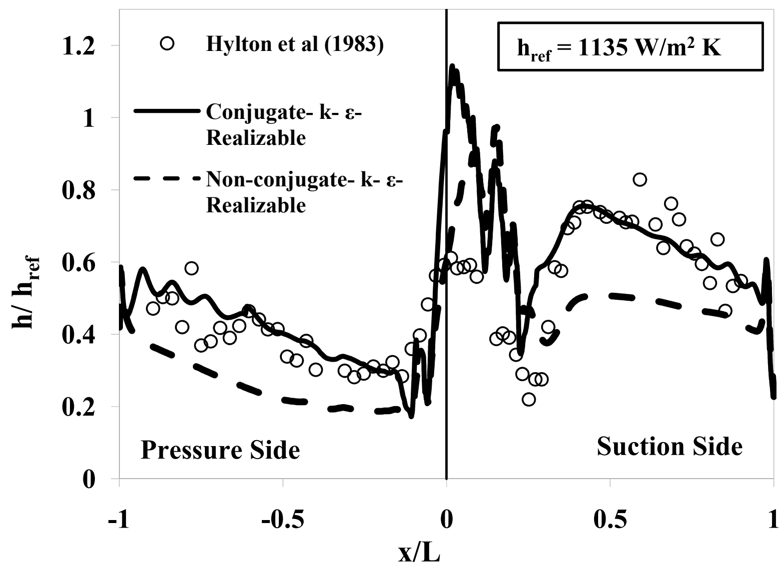

Fig 1.Heat transfer coefficient along the blade surface

Figures 2 and 3 show the dimensionless temperature distribution along pressure and suction surfaces of the blade respectively obtained using full conjugate and iterative conjugate simulation. Results were compared with the experimental data. In the full conjugate simulation, average error on the pressure side is much less than the error on the suction surface which is around 14%. Discrepancies up to 10% are generally accepted when simulations are done using k-ε turbulence model. The deviations from data near the leading edge are large as 20%.

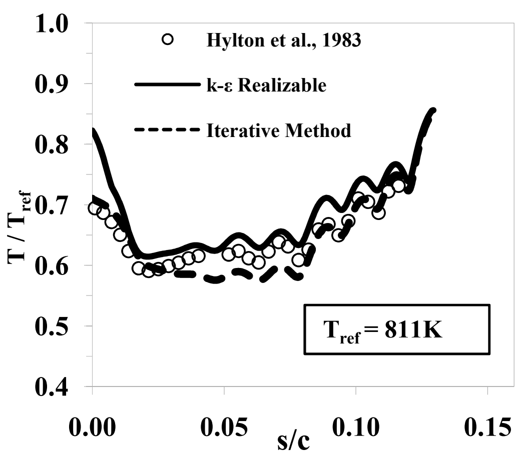

Fig 2. Temperature along the pressure surface

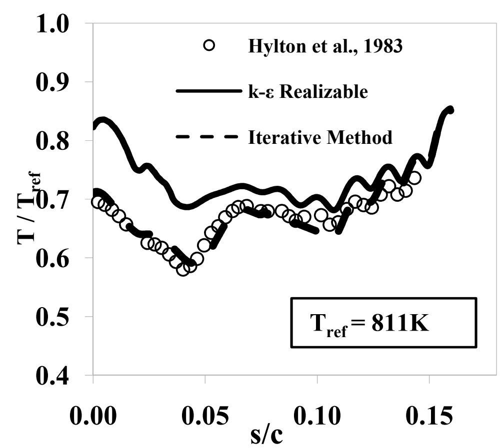

Fig 3. Temperature along the suction surface

In iterative conjugate analysis the experimental heat transfer coefficient obtained from Hylton [1983] is used as a boundary condition and hence the results were much more accurate than the conjugate results. The surface temperatures were over predicted near the leading edge by about 7% and under predicted over the surface by 4%. Near the trailing edge again the results were over predicted by 5%. The average deviation from data with the iterative method is around 5%. The research on prediction of heat transfer characteristics of film-cooled blades using this technique is continuing.

CONCLUSION

Data from Mark II blade was used to study the conjugate heat transfer for a gas turbine blade using FLUENT code. Realizable k-ε model with enhanced wall treatment was used in simulations. Requirement of care in setting up exact boundary conditions from experimental data are the basis of using conjugate simulations. The results from conjugate approach were compared with conventional non-conjugate approach. It was seen that the conjugate calculations resulted much better predictions of heat transfer coefficients when compared to experimental data. Near the leading edge both approaches deviated about 30% of the data. The relaminarization at the leading edge due to high flow acceleration is thought to be the cause of this which cannot be simulated in FLUENT code at this point. In the new iterative conjugate approach only conduction heat transfer within the blade material is calculated using experimental heat transfer coefficient as a boundary condition which cuts down the computational time in a great extent. The local heat transfer coefficient was supplied to FLUENT code through UDF. The change in local surface temperature before every iteration was observed and iterative technique was validated. It can be seen that the iterative technique gives much better blade temperatures than the full conjugate analysis since the calculation of flow field in full conjugate has error whereas experimental "h" is much more reliable.

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