STUDIES ON FREE STREAM TURBULENCE AS RELATED TO GAS TURBINE HEAT TRANSFER
A REVIEW OF AUTHORS' PAST WORK AND FUTURE IMPLICATIONS

Savas Yavuzkurt* and Ganesh R. Iyer**
*Department of Mechanical and Nuclear Engineering
The Pennsylvania State University, University Park, PA 16802 USA
**Caterpillar Inc.
100 N.E. Adams Street, Peoria, IL 61629

This paper presents a review of the past work done by the authors on free stream turbulence (FST) as applied to gas turbine heat transfer and discusses implications of the results for future studies. It is a comprehensive approach to the results of many individual studies in order to derive the general conclusions that could be inferred from all rather than discussing the results of each individual study. Three experimental and four modeling studies are reviewed.

The first study[1-3] was on prediction of heat transfer for film cooled gas turbine blades. An injection model was devised and used along with a 2-D low Reynolds number k-ε model of turbulence for the calculations. Reasonable predictions of heat transfer coefficients were obtained for turbulence intensity levels up to 7%. Predictions of heat transfer coefficients on blade surfaces required the free stream form of the k-ε model equations to be corrected for pressure gradient effects by adding a production term to the turbulent kinetic energy (TKE) equation. Turbulence intensities of 7% in the free stream are considered to be a moderate (less than 10%) level of FST. In fact, all experimental and modeling studies carried out indicate that below 10% turbulence intensity in the free stream, the effect of FST on surface heat transfer is rather small, whereas when turbulence intensity is higher than 10% (High FST) the effect on wall heat transfer rates is considerable.

Following this modeling study, a series of experimental studies were undertaken at The Center for Turbulence Research at Stanford University and Wright Labs at Wright Patterson Air Force Base by the first author[4-6]. The objective of these studies was to gain a fundamental understanding of mechanisms through which FST augments surface heat transfer. It was theorized that FST must stir the near wall layer of the turbulent boundary layer, thereby increasing heat transfer. It was hoped that this understanding would lead to improvement of the turbulence models used to predict heat transfer coefficients under high FST. Experiments were carried out in the boundary layer and in the free stream[4-5] downstream of a gas turbine combustor simulator which produce initial FST levels of 25.7% and large length scales (about 5-10 cm for a boundary layer 4-5 cm thick). Using two triple hot wire probes, all three components of mean velocity and 6 Reynolds stresses were obtained along with length scales of normal Reynolds stresses in vertical and transverse directions using space correlation and in the axial direction via auto correlations. Also from quadrant plots of axial and vertical components of turbulent fluctuating velocities, the number of ejection events near the wall were determined. This data and its analysis showed that the number of ejection events increased with increased FST turbulence intensity levels. Increased ejection events should lead to an increase in heat transfer. This result showed that one possible mechanism through which FST caused an increase in heat transfer is by increasing the number of ejection events. This result was later confirmed by a study carried out in a wall jet[6]. During this study instantaneous heat transfer rates at the wall were measured by a hot film probe positioned flush with the surface at several axial locations in the wall jet flow. It was seen that an increase in the turbulence intensity lead to an increase in the high peaks observed in the instantaneous wall heat transfer. From the results of studies[4-5] a dimensionless free stream turbulence number was obtained using length and velocity scale data. This quantity did not contain any viscosity and correlated well with Stanton number data. This result also lead to the conclusion that in a high FST (> 10%) boundary layer, heat transfer is mainly determined by the FST and not by the production of turbulence near the wall due to mean shear. As a result of these studies it was theorized that the only way FST can affect the processes near the wall is through diffusion of this high FST through the boundary layer towards the wall. This diffusion is mainly caused by normal Reynolds stress components and particularly the normal Reynolds stress in the direction perpendicular (vertical) to the wall. This idea was later used in the improvement of k-ε models of turbulence for the prediction of heat transfer and skin friction under high FST.

In a number of modeling studies[7-9] several well known k-ε models were compared for their predictive capability of heat transfer and skin friction coefficients under moderate and high FST. Two data sets, one with moderate levels of FST and one with high levels of FST were used for this purpose. Although the models did fine in their predictions of cases with no FST (baseline cases), they failed one-by-one as FST levels were increased. Under high FST (25.7% initial intensity) predictions of Stanton number were between 35-100% in error compared to the measured values. Later a new additional production term indicating the interaction between the TKE and mean velocity gradients was introduced into the TKE equation. The predicted results of skin friction coefficient and Stanton number were excellent both in moderate and high FST cases. In fact these models also gave good predictions of TKE profiles whereas earlier unmodified models did not predict the correct TKE profiles even under moderate turbulence intensities. Although this new production term seems to achieve the purpose, it is the authors' belief that it is the diffusion term of the TKE equation which needs to be modified in order to fit the physical events in high FST boundary layer flows. Diffusion modeling is usually not very rigorous in many modeling applications since under low or no FST, diffusion terms are not that important compared to production and dissipation terms. However, in high FST flows it is believed that the diffusion term is a more important term in the TKE equation. In fact this is the mechanism which causes high FST to affect the events near the wall. The results of these studies are currently being used to develop a new diffusion model for the TKE equation. It is hoped that some of the results of this study will be available by the time the paper is submitted during the symposium.

The paper will contain many figures supporting the observations and statements made in the previous paragraphs as well as some new figures showing the results of the attempts made to model the diffusion term of the TKE equation.

REFERENCES

1. Tafti, D. K. and Yavuzkurt, S., Prediction of Heat Transfer Characteristics of Discrete Hole Film Cooling One-Row of Injection into a Turbulent Boundary Layer, paper presented at the 1988 ASME WAM, *ASME publication Heat Transfer in Gas Turbine Engines and Three Dimensional Flows*, Chicago, Illinois, pp. 45-52, Nov. 27-Dec. 2, 1988.

2. Tafti, D. K. and Yavuzkurt, S., Prediction of Heat Transfer Characteristics for Discrete Hole Film Cooling for Turbine Blade Application, paper presented at the ASME Intl. Gas Turbine and Aerospace Congress and Exposition, Toronto, Canada, June 4-8, 1989, *ASME paper No. 89-GT-139.*
3. Tafti, D. K., Prediction of Heat Transfer Characteristics for Discrete Hole Film Cooling on Flat Plate and Turbine Blades. *Ph.D. thesis*, Dept. of Mech. Engr., Penn State Univ., Aug. 1989
4. Yavuzkurt, S., Batchelder, S. K., A Correlation for Heat Transfer Under High Free Stream Turbulence Conditions, *Proceedings of 9th Symp. on Turbulent Shear Flows*, Kyoto, Japan, Aug. 15-20, 1993.
5. Yavuzkurt, S., Seo S., Effect of High Free Stream Turbulence on Ejection Events in a Boundary Layer, *Proc. of 10th Symp. on Turbulent Shear Flows*, University Park, PA, Aug. 14-16, 1995, pp. P2-31, P2-30.
6. Yavuzkurt, S., Effects of Free Stream Turbulence on the Instantaneous Heat Transfer in a Wall Jet Flow, *ASME Paper No. 95-GT-43*, presented at the ASME Intl. Gas Turbine and Aerospace Congress and Exposition, Houston, TX, June 5-8, 1995.
7. Iyer, G. R., Yavuzkurt, S., Comparison of k-ε Models in Predicting Heat Transfer and Skin Friction Under High Free Stream Turbulence, *ASME Paper No. 96-GT-537*, presented at the ASME Intl. Gas Turbine and Aerospace Congress and Exposition, Birmingham, UK, June 10-13, 1996.
8. Iyer, G. R., Yavuzkurt, S., A New Low-Reynolds Number k-ε model for Simulation of High FST Flows, ASME paper published in the proceedings of Fluids Engineering Division Summer Meeting in Washington, DC. (*ASME Paper No. FEDSM98-4851*), June 1998.
9. Iyer, G. R., Yavuzkurt, S., Comparison of Low-Reynolds Number k-ε models in Simulation of Momentum and Heat Transport Under High Free Stream Turbulence, *International Journal of Heat and Mass Transfer*, Vol. 42, No. 4, pp. 723-737, 1998.