FINAL REPORT

Vortex-Generator Induced Enhanced Heat Transfer in Gas Turbine Blade Coolant Channels With Rotation

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Executive Summary

The research described in this report deals with the internal cooling of gas turbine blades under both stationary and rotating conditions, and examines the potential of using vortex generators to enhance heat transfer from the coolant passages. This work is based on the premise that the separated flow behind the ribs could be manipulated by introducing longitudinal and/or spanwise vorticity into the flow using vortex generators, and that by "tuning" the vorticity introduced, the mixing and heat transfer across the separated shear layer could be considerably increased. As part of the DOE-ATS program, spanwise-cylindrical vortex generators were primarily studied. In addition, explorations have been preformed with vertical cylinders, and delta tabs.

The studies were primarily conducted in a rotating facility that permitted measurements of the surface mass transfer rates from a two-pass (radially-outward and radially inward) rotating channel. Measurements were made for a maximum Reynolds number of 40,000 and a maximum Rotation number of 0.4. The non-dimensional mass transfer rates (Sherwood number) were then converted to non-dimensional heat transfer rates (Nusselt number) using the heat-mass transfer analogy.

Preliminary smooth walled experiments have been performed in order to validate the experimental techniques used through comparison with published correlations and results. Agreement with published heat and mass transfer results over a range of Reynolds and rotation numbers effectively supports the use of mass transfer (naphthalene sublimation technique) as an alternative to heat transfer measurements. In addition to allowing for a simpler test section design, particularly for rotating experiments, the naphthalene sublimation technique allows for the acquisition of local results in much greater detail than is practicably possible in heat transfer experiments. This advantage was shown in the presentation of detailed mass transfer distributions in selected developing and fully developed regions of the channel.

Detailed mass transfer profiles presented support theoretical and computation predictions through the use of the mass and momentum transfer analogy: regions of increased mass transfer occur in regions of increased wall shear stress. Since these detailed distributions were measured along all walls of the channel, some insight into the near wall velocity profiles has been gained. For example, regions of mass transfer reduction in the rotating channel spatially correlate with regions in which fluid is expected to be transported away from the wall. Although these detailed profiles cannot be compared to published results, they do at least qualitatively agree with theoretical predictions and should serve to validate future computational predictions.

Mass transfer distributions for the ribbed-wall channel have been presented for the non-rotating baseline case as well as for a range of rotation numbers. Centerline averaged results have shown a trend of increasing mass transfer with increasing rotation. Local centerline profiles have shown that this trend is due to the fact the increases in destabilized regions are greater than the corresponding decreases in stabilized regions. In fact, decreases in mass transfer are not significantly affected by increasing rotation and remain nearly constant for all rotation numbers. Mass transfer increases along destabilized walls are greater for high rotation numbers. Additionally, side wall profiles have shown a general increase in mass transfer with increasing rotation. Experimental limitations are believed to result in the observed decrease in both local and average mass transfer at higher Reynolds numbers for Ro=0.3.

Detailed results for the non-rotating case have shown local features of inter-rib mass transfer behavior that are not typically reported in the literature. These results have shown local regions of reduced mass transfer that correspond to regions of flow separation down stream of the ribs. These regions are followed by a peak mass transfer rate that occurs near the point of flow separation. Increasing mass transfer down stream of this reattachment point indicates the redevelopment of the shear layer which is followed by a small region of separation immediately upstream of the following rib. This second region of flow separation has been shown to increase local mass transfer, unlike the behavior exhibited in the first region of separation.

Cross stream mass transfer profiles in the fully developed region of the channel have shown reasonably uniform mass transfer along the leading and trailing walls. Side wall mass transfer, however, shows increased mass transfer near the corner regions that are affected by the presence of the ribs and decreasing mass transfer near the centerline. Symmetry between opposing side walls and with respect to the centerline improves with increasing Reynolds number.

Similar results presented for the rotating channel have shown that rotation does not significantly influence the structure of separated shear flow. Mass transfer profiles in regions of separation and reattachment have not shown and change in reattachment of development length. Centerline profiles over the entire length of the walls have shown that centripetal force has a strong influence on inlet duct mass transfer. This influence is seen through the increasing mass transfer farther from the entrance. The side wall mass transfer distributions, on the other hand, are markedly different from those of the non-rotating case. Rotation-induced secondary flow is clearly visible in the sloping cross stream profiles of the side walls. This behavior is expected as the side walls show transition from leading wall to trailing wall behavior. Increased mass transfer near the corner regions of the side walls does not show any significant change in behavior besides the relative increase or decrease that is expected.

Experiments performed with the cylindrical spanwise-horizontal vortex generators indicate that for the higher pitch case (P/e=21), significant enhancement due to the vortex generators is obtained along the ribbed walls in the developing region of the inflow passage. In the periodically developed region, the profile is more uniform, with degradation in the initial separated region and enhancement in the later regions of the inter rib module. The enhancement levels and coverage substantially exceed the corresponding degradation quantities. Along the smooth walls, the horseshoe vortices in the wake of the vortex generator are associated with high levels of mass transfer enhancement. The wakes from each vortex generator are deflected away from the rib, and appear to merge downstream. The wake effect is seen to decrease somewhat with Reynolds number. Spanwise average profiles in the developed regions indicate an average 50% increase in the mass transfer from the side walls due to the vortex-generators. Along the ribbed walls the average enhancement levels are lower. Local enhancement levels can be substantially higher-reaching values in the vicinity of 300% along the side walls.

For the lower pitch (P/e=10.5), the general behavior is the same as that for P/e=21. Enhancement levels are somewhat lower and the wake interference and merging effects along the side walls are weaker. For the lower Reynolds number of 5,000, the highest mass transfer enhancement is obtained at s/e=0.55, with 30 to 40 percent augmentation of side walls. For the two higher Reynolds numbers of 10,000 and 30,000, the highest mass transfer enhancement is achieved at s/e=1.5.

In the rotating cases, the Coriolis effect is dominant. The presence of vortex generators tends to reduce the asymmetry caused by rotation between stabilized and destabilized walls. Vortex generators appear to be particularly effective in enhancing mass/heat transfer rates at high Reynolds and Rotation numbers. However, the vortex generators cause mass transfer degradation at low Reynolds and Rotation numbers. The vortex generators appear to be more effective in enhancing mass transfer on the side walls of the ducts. In examining the enhancement levels on the ribbed surfaces, it is also noted that the vortex generators are more effective on the stabilized walls of the rotating ducts.