

Chapter 7

Conclusions and Recommendations

The objective of this research effort was to reduce the severity of the thermal environment for a high-pressure turbine vane through reduction of the turbine passage secondary flows. This was accomplished by modifying the vane/endwall junction to include a leading edge fillet. The approach was to employ a commercial optimization software package in conjunction with a computational fluid dynamics package in the optimized design of a fillet. Upon completion of the optimization, the resulting leading edge fillet was tested in a large-scale, low speed turbine vane cascade to experimentally verify the predicted thermal performance. A unique element of this facility is a combustor simulator located immediately upstream of the vane cascade, which emulates the flow in a typical aircraft engine combustor and generates more realistic inlet conditions to the turbine vane test section. The use of a combustor simulator distinguishes this investigation from most previous studies of turbine passage secondary flows and heat transfer, which have predominately assumed a two-dimensional turbulent boundary layer inlet condition. The results of this investigation underscore the importance of properly modeling the inlet conditions to the turbine vane.

7.1 Fillet Computational Optimization

Fillet optimization studies were conducted for several different inlet boundary conditions, combustor simulator/turbine interface configurations, and fillet geometric definitions. First, a preliminary fillet optimization study was conducted, for which the applied inlet conditions consisted of a turbulent boundary layer profile superimposed with a temperature profile representative of engine conditions. The fillet geometry for this preliminary effort was defined by four design variables, and a linear cross-sectional profile was specified. The results of this study clearly indicated a thermal benefit with the addition of a leading edge fillet. A general trend of increasing thermal performance with increasing fillet dimensions was predicted, showing the strongest correlation with H_{\max} . While a significant thermal benefit was predicted for the endwall, the maximum predicted benefit occurred on the vane itself between 10 and 20% span. Flow and thermal field results indicated that the optimized fillet creates a favorable redistribution of

the thermal field, thereby enhancing coolant effectiveness. In addition, formation of a leading edge horseshoe vortex was eliminated, while development of the passage vortex was also significantly affected.

Upon completion of the preliminary optimization effort, an optimization study using more realistic inlet conditions, as measured at the exit of the combustor simulator, was initiated. To properly model the interface between the combustor and vane cascade, a backward-facing slot was added to the computational model upstream of the vane leading edge. As a result of the geometric constraint imposed by the location of the slot relative to the vane leading edge, an elliptical fillet shape rather than linear was selected for optimization, while the four fillet design parameters remained the same. Design of Experiments was used for design space exploration. Similar to the preliminary optimization effort, the results of the DOE study indicated maximum thermal benefit for maximum fillet dimensions. The effect of varying the locations of maximum fillet height, H_{\max} , and extent, D_{\max} , was also explored. Additional thermal benefit was achieved by relocating H_{\max} and D_{\max} along the suction surface of the vane. The thermal benefit of off-stagnation fillet designs was discovered to correlate well with the amount of slot blockage, indicating that the acceleration of coolant exiting the slot is beneficial. A secondary benefit to this geometric modification was a reduction in total pressure loss through the passage. Despite the predicted thermal benefits, investigation of the secondary flow and thermal fields yielded unfavorable results in regard to the effectiveness of slot injected coolant. For both the baseline and optimized off-stagnation fillet, accumulation and lift-off of the slot injected coolant was predicted.

Based on the results of the elliptical fillet optimization, a study was conducted to compare the thermal performance of an elliptical fillet to that of a linear fillet, without a backward-facing slot. From comparison of the computational results, the linear fillet was found to outperform the elliptical fillet, though both designs exhibited a beneficial redistribution of the thermal field with improved coolant coverage of the endwall and vane surfaces. Coolant lift-off, which was predicted with slot injection, did not occur for this configuration. Based on the results of this comparison, the off-stagnation linear fillet was selected for experimental verification.

To evaluate the sensitivity of fillet thermal performance to inlet conditions, computations were performed with a more highly peaked inlet total pressure profile. The increased peak in total pressure in the near-wall region resulted in increased penetration of the secondary flow field to the vane midspan, as observed from the thermal field and midspan flow angle distributions. Transport of cooler fluid up the vane surface all the way to midspan was predicted for both the baseline and filleted cases. All flow surfaces indicated thermal improvement with the fillet, and the spanwise distribution of benefit was observed to be nearly uniform over a large portion of the vane span.

Collectively, the computational optimization studies indicate that significant reductions in adiabatic wall temperature can be achieved through application of a leading edge fillet. Several different methods of analysis were developed to quantify fillet thermal performance, all of which suggest a benefit with the addition of a fillet. In all optimization studies, a general trend of increasing thermal performance with increasing fillet dimensions was predicted, indicating that a large fillet will yield maximum benefit. While the initial fillet design intent was to provide an improved thermal environment for the vane passage endwall, computational results also predict significant benefit to the vane surfaces. Flow and thermal field results show that a fillet can produce a favorable redistribution of the thermal field, can prevent formation of the leading edge horseshoe vortex, and can preclude full development of a passage vortex.

7.2 Fillet Thermal Testing

Upon completion of the optimization studies, a linear off-stagnation fillet was selected for experimental verification in the wind tunnel vane cascade. Four different cascade inlet conditions were investigated to evaluate the effectiveness and robustness of the fillet in reducing endwall adiabatic temperature levels relative to a baseline unfilleted vane. Two of the tested inlet conditions were for a flush combustor/cascade interface without slot coolant injection, while the remaining two were for two different slot blowing ratios. For the flush interface, the thermal performance of the fillet was evaluated for two different inlet total pressure profiles. Both profiles feature a near-wall peak in total pressure, which is characteristic of typical combustor exit conditions. To determine fillet robustness and performance sensitivity to the inlet conditions, the

nominal peak of the design profile was roughly doubled to achieve the off-design inlet condition. With the addition of a backward-facing slot, the inlet total pressure profile was fixed at the design condition while the flow rate of coolant exiting the slot was varied. For each inlet condition considered, baseline tests were conducted without the fillet to provide a basis of comparison for the results with the fillet. The primary measurements used to evaluate fillet performance were endwall temperature measurements and thermal field measurements.

For the design inlet condition without slot coolant injection, the fillet was found to have a positive impact on the endwall temperature distribution as well as on the passage thermal field. Improved coolant coverage through the vane passage and a reduction in size of the region of lowest effectiveness were observed. Despite the height of the fillet in the spanwise direction, improved thermal protection was shown about the vane leading edge. Lateral-averaged adiabatic effectiveness values indicated consistent thermal performance improvement at all axial locations with the fillet. Area-weighted average improvement in effectiveness was calculated to be 9.5%, compared to a predicted improvement of 1.5%. Thermal benefit to the vane suction surface was observed from the thermal field results in the passage.

For the off-design inlet condition, the leading edge fillet was observed to have a slightly negative impact on the endwall adiabatic temperature distribution; however, passage thermal field results indicate a thermal improvement for the vane suction surface. Lateral-averaged adiabatic effectiveness values showed mixed fillet performance throughout the vane passage. In the upstream leading edge region, the fillet was found to have a negative impact on lateral-averaged effectiveness with reductions between 2 to 4%, while slight thermal improvement was observed over a small axial range midway through the vane passage. Area-weighted average improvement in effectiveness was calculated to be -1.7%, compared to a predicted improvement of 0.8%. Despite this slight thermal detriment on the endwall, thermal field results in the passage show that the fillet has a positive effect on the vane suction surface, with the transport of cooler fluid up the vane surface.

To evaluate fillet performance with slot coolant injection, the interface between the combustor simulator and vane cascade was modified to reintroduce the backward-

facing slot. For the design slot flow rate, the fillet clearly presented a thermal improvement. Though the measured endwall adiabatic effectiveness levels with the leading edge fillet indicated a narrowing of the region of peak effectiveness, improved thermal protection was observed adjacent to the vane suction side shoulder. A slight improvement was observed in the pressure side endwall corner as well. Comparison of lateral-averaged effectiveness distributions between the baseline and fillet results indicated thermal improvement through the majority of the vane passage. A slight thermal detriment was observed in the leading edge region due to the channeling effect of the fillet on the coolant. Area-weighted average percentage improvement in effectiveness was calculated to be 2.0%. In comparison, the predicted improvement in effectiveness on the endwall and fillet surfaces for an elliptical fillet with slot coolant injection was 3.4%. Thermal field results in the passage showed a dramatic improvement with the addition of the fillet. Without the fillet, coolant lift-off was observed, leaving only a small amount of coolant on the endwall for thermal protection. With the fillet, coolant lift-off was prevented and higher values of nondimensional temperature were measured, indicative of reduced coolant mix-out.

Thermal tests were also conducted at nominally twice the design slot flow rate to quantify the benefit of additional coolant mass flow exiting the slot. These tests also served to evaluate the sensitivity of fillet performance to changes in slot flow. By doubling the slot flow rate, area-weighted average effectiveness over the endwall and fillet surfaces increased approximately 7.5%, with slightly more improvement observed without the fillet than with the fillet. While increasing the flow rate of coolant exiting the slot enhanced endwall effectiveness levels, fillet thermal performance was found to be similar for the off-design slot flow rate as for the design slot flow rate. As for the design slot flow, narrowing of the region of peak effectiveness and improved thermal protection adjacent to the vane suction side shoulder were observed with the addition of the fillet. The calculated axial distribution of percentage improvement in effectiveness was also shown to be remarkably similar to that for the design slot flow rate; however, area-weighted average improvement in effectiveness was calculated to be less at 0.3%. Thermal field results in the passage also showed a significant improvement with the fillet. Coolant lift-off was prevented, providing better thermal protection to the fillet and

endwall, and higher values of nondimensional temperature were measured, indicating reduced coolant mix-out.

7.3 Potential Engine Benefits

The potential benefits of fillet application include a decrease in the necessary amount of turbine cooling flow, an increase in turbine life, an increase in the maximum allowable turbine inlet temperature, or a combination thereof. To relate the results of this investigation to an engine environment, an imaginary engine with a maximum combustor exit temperature of 1700°C, a coolant temperature of 600°C, and a metal temperature of 1050°C was assumed. For the design inlet conditions considered in this study, experimental results indicated a 9.5% improvement in area-weighted adiabatic effectiveness from approximately 0.45 without the fillet to 0.49 with the fillet. Extending this result to the engine, a 44°C (79°F) decrease in adiabatic wall temperature is calculated. The values of adiabatic wall temperature without and with the fillet are 1205°C and 1161°C, respectively. Assuming no detrimental effect of fillet application on the distribution of heat transfer coefficient, a reduction in adiabatic wall temperature offers either a reduction in cooling air requirements or a reduction in metal temperature and extended turbine component life. As small as a 30°C (54°F) reduction in metal temperature can result in nearly 2X part life. The final option for exploiting the thermal benefit offered by the fillet is to increase the maximum allowable combustor exit temperature. By maintaining the adiabatic wall temperature at 1205°C with the fillet, the improvement in adiabatic effectiveness permits a 90°C (162°F) increase in inlet temperature. The choice of fillet benefit option would depend on engine application and the requirements of the customer.

7.4 Recommendations for Future Investigations

Together, the computational and experimental results presented herein indicate that significant reductions in vane passage adiabatic wall temperatures can be realized through application of a leading edge fillet. Though the primary focus of the experimental phase of this investigation was to evaluate fillet thermal benefit to the endwall and fillet surfaces, thermal field measurements and computational results both

show promise of significant benefit to the vane surface as well. In continued studies of the leading edge fillet concept, the benefit to the vane surface should be evaluated experimentally.

Though the results of this investigation are promising, they are not sufficient to conclude that the fillet provides a net reduction in vane heat load. To make this claim, the impact of the fillet on the Stanton number distribution through the vane passage needs to be evaluated. In the steady-state facility used in this investigation, this could be accomplished through application of a constant heat flux boundary condition to the endwall, fillet, and vane surfaces. Operating the combustor simulator under isothermal flow conditions, the distribution of heater surface temperature could be recorded with an infrared camera from which the distribution of heat transfer coefficient can be determined. Along with heat transfer testing, flow field measurements in the vane passage should be performed to quantify the influence of the fillet on secondary flow development.

In addition to fillet thermal testing at low speed conditions, the fillet should undergo testing at high speed conditions. In particular, the impact of the fillet on vane aerodynamics should be addressed through detailed wake surveys in a steady-state transonic cascade. Ideally, heat transfer tests should also be conducted at high speed, engine representative conditions.

Continued efforts should be made to improve the prediction capability of fillet heat transfer performance. For the optimization approach of this investigation, several modeling simplifications were assumed that could have a pronounced influence on predictions. Computations should be performed with more accurate geometric modeling to determine the impact of these assumptions on fillet thermal performance predictions. Additionally, accurate predictions of Stanton number distribution should be pursued through improvements in near-wall modeling.

Finally, the results of this research effort underscore the importance of properly modeling the flow entering the first vane. Given the influence of inlet conditions on vane heat transfer, continued investigation of combustor/turbine interactions is essential. Such studies could aid in the development of a combined combustor/vane design methodology that minimizes cooling air requirements and enables higher turbine inlet temperatures.