

Final Technical Report

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**ADVANCED TURBINE COOLING, HEAT TRANSFER,
AND AERODYNAMIC STUDIES**

Part 1: Effect of Rotation on Enhanced Cooling Passage Heat Transfer
Part II: Effect of TBC Spallation on Surface Heat Transfer
Part III: Effect of Surface Roughness, and Trailing Edge
Ejection on Turbine Efficiency under Unsteady Flow Conditions

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EXECUTIVE SUMMARY

Part I

This study investigated the effect of rotation on cooling passage heat transfer from a two-pass square channel model. In the current designs, heat transfer from the trailing wall (pressure side) is enhanced and heat transfer from the leading wall (suction side) is reduced for radially outward flow. However, the reverse is true for radially inward flow. Unlike the existing designs, the cooling channels are reoriented in such a way that allows the radial outward flow channels on the pressure side and the radial inward flow channels on the suction side of the blade. Results show that this new cooling channel orientation can enhance the cooling effect on both the training and leading walls (pressure and suction side) (see attachment #1). To further maximize the cooling effect, three heat transfer enhancement designs have been applied to the above-mentioned now coolant channel arrangement. The first design uses V-shaped staggered rib turbulators, the second design employs impingement cooling, and the third design incorporates the use of angled rig turbulators and impingement cooling. All three designs have been tested and compared under several combinations of Reynolds numbers, rotation numbers and wall heating conditions (buoyancy effect). Results show that the heat transfer enhancement with the V-shaped staggered ribs is higher than the angled ribs under the same rotating condition (see attachment #1). Results also show that rotation reduces the jet impingement heat transfer enhancement on both the smooth and angled ribbed walls (see this report). This study also investigated detailed heat transfer distributions on non-rotating two-pass channels with rib turbulators and bleed holes for coolant extraction using a transient liquid crystal image method. Results show that the overall heat transfer coefficients inside a non-rotating two-pass channel are not reduced by the presence of film holes for external cooling (see attachments #2 and #2). Turbine designers can use these results to improve current rotor blade cooling passages or to provide options for new rotor blade cooling designs.

Part II

Thermal barrier coatings (TBC) protect the metal surfaces in advanced gas turbine engine components from high temperature gases. Spallation of the TBC (coating loss) may occur locally due to thermal stress, erosion, and/or corrosion. This study investigated the effect of TBC spallation on surface heat transfer from turbine components. Loss of TBC (spallation) not only exposes metal surfaces to hot gases, but also increases local and downstream heat transfer coefficients. The effect of simulated spallation's size, depth, shape, and location on local and downstream heat transfer coefficients has been investigated using a transient liquid crystal image method. This investigation has been carried out for flow over a flat plate model and for flow across a cylindrical leading edge model under various combinations of Reynolds numbers and free stream turbulence levels. Results show that local heat transfer coefficients inside the spallation cavity for flow over a flat plate with 10% free stream turbulence level can be increased up to 30%. However the rate of increment is reduced in the downstream region (see this report and attachment #4). Results also show that heat transfer enhancement depends on the

spallation location for flow across a cylinder with a 7% free stream turbulence level. Heat transfer enhancement inside the spallation cavity is highest, up to 20%, for a spallation at 20° - 40° from the leading edge, while the enhancement in the downstream region can be up to 40% of the smooth surface values (see attachment #5). This information can be used by turbine designers to predict local hot spots, adjust coolant flows, and prevent airfoil failure as a result of TBC spallation.

Part III

Comprehensive unsteady turbine cascade aerodynamic studies at the Turbomachinery Performance Laboratory focused on (1) the boundary layer transition under unsteady flow condition and (2) the optimization of trailing edge ejection and mixing losses. The objectives of the unsteady boundary layer investigations were to: (1) establish an unsteady boundary layer transition correlation, and (2) develop a theoretical framework for predicting the characteristics of turbomachinery turbulent wake flow. A large-scale high subsonic research facility to simulate the periodic unsteady flow was developed to experimentally investigate the unsteady boundary layer transition and development on a turbine cascade. Four different unsteady inlet conditions with the corresponding passing frequencies, wake structures, and free-stream turbulence intensities were investigated. Detailed unsteady boundary layer velocity, turbulence intensity, and pressure measurements were performed along the turbine blade surfaces (see this report). To develop a comprehensive unsteady transition model, complementary unsteady boundary layer experiments were carried out on a curved plate and new correlations for unsteady intermittency distributions were found. The correlations were implemented into a boundary layer and heat transfer calculation code. This results show that the new unsteady intermittency correlations are capable of accurately predicting the effect of unsteady inlet flow conditions on the boundary layer and heat transfer on a curved plate (see attachment #6). Efforts are underway to transfer the results to gas turbine blades. To find the optimum criteria for the turbine blade trailing edge ejection mixing losses, a special blade with an internal cavity and external ejection slots was integrated into the turbine cascade facility. Total pressure flow angles, turbulent intensity, turbulent normal, and shear stresses were measured using pneumatic and x-wire measurement techniques. A theoretical framework that allows the prediction of trailing edge mixing losses was developed. To examine the predictive capability of the theory, a comprehensive experimental investigation was conducted and the results were compared with the theory. The results will allow the turbine aerodynamicist to minimize the mixing losses and to increase the efficiency of cooled gas turbine blades (see attachment #7).