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**TURBINE AEROTHERMAL
RESEARCH**



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14. ABSTRACT This is a summary of the work performed under Job Order Number 2307S315. This was an in-house task funded under AFOSR ILIR grants 92PR07COR and 02PR02COR. This task and its predecessors have been in in continual operation since 1985 and have covered a broad range of topics relating to the aerodynamics and thermodynamics of the turbine module of gas turbine engines. The work initially focused on the effects of very high turbulence freestream flows on the development of the boundary layers of the turbine component, with particular attention to the effect on heat transfer. It has also pursued techniques for the control of airfoil boundary layers and cooling flows and the development of advanced techniques for the measurement and study of these flows.					
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TABLE OF CONTENTS

List of Figures	iv
Summary	1
Heat Transfer and Film Cooling Research.....	1
Turbulence Model Development	5
Aerodynamic Flow Control	6
Passive Boundary Layer Control.....	6
Active Boundary Layer Control: Vortex Generator Jets	7
Active Boundary Layer Control: Atmospheric Plasmas:.....	9
Global Hawk LPT application	10
Personnel Supported 1985-2005	12
Honors & Awards Received	12
Appendix A: List of Publications	13

LIST OF FIGURES

Figure 1: Infrared images from transient pulsed heat transfer test.

Figure 2: Pulsed cooling flow reduced data.

Figure 3: Computed flow over spherical dimples on the suction side of a low pressure turbine airfoil

Figure 4: Effect of Vortex Generator Jet blowing on low pressure turbine blade pressure loss.

Figure 5: Streamwise and wall normal boundary layer velocity profiles without and with plasma discharge forcing.

Figure 6: Global hawk Cascade Blades

Figure 7: Dimpled HPT vanes for Turbine Research Facility

Figure 8: Wake traverse of dimples on roughened vanes.

SUMMARY

The objectives of this task are to increase turbine engine performance and lifetime by improving reliability, reducing cooling flows, increasing turbine efficiencies, increasing thrust to weight ratio, and reducing turbine engine design cycle time.

To that end, the program seeks to:

- Establish fundamental understanding of heat transfer and cooling mechanisms in gas turbine engines; provide an understanding of the effects of unsteady and free stream turbulence on turbine blade heat transfer; improve the accuracy of heat transfer predictions and computations; and develop concepts and strategies for the control of turbulent heat transfer.
- Investigate turbine flow control for reduction of secondary flow losses; reduction of losses associated with low Reynolds number separated flows; control of flow areas, flow direction, and airfoil circulation. Investigate technologies for turbine flow control, including passive and active fluidic, mechanical, and electromagnetic actuation.
- Transition basic research results to the gas turbine industry and to IHPTET and VAATE Technology Demonstrations.

Heat Transfer and Film Cooling Research

The primary source of error in the prediction of heat transfer and film cooling effectiveness in the turbine engine hot section is the inability to accurately model the effect of the highly unsteady environment found inside the turbine engine. Unsteadiness affecting the turbine section ranges from large scale, high amplitude, coherent unsteadiness due to shocks and wakes from upstream components down to fine scale isotropic turbulence. Unsteadiness across this wide range of amplitudes, scales, and frequencies significantly affect the development of the boundary layers on the hot section components, often in very complex ways. Understanding these complex interactions, and validating computational models of them, requires carefully executed precision measurements of heat transfer and film cooling under well defined unsteady forcing.

Initial experiments under this program were performed using a wall jet facility (essentially a long, instrumented flat plate with a high speed rectangular jet blown along it) in order to produce

a boundary layer with very high levels of unsteadiness outside the boundary layer. Hot wire anemometers and pitot-static pressure instrumentation were used to quantify the boundary layer and external flow fluid mechanical properties. Fast response thermocouples were used to quantify the flow temperatures and measure the response of the wall temperature to rapid changes in the external temperature. The wall temperature response, combined with knowledge of the thermodynamic properties of both the boundary layer flow and the wall, were used to extract the heat transfer coefficient under various flow conditions at various points under the boundary layer. The major findings of these experiments were that the levels of turbulence that exist in high pressure turbines from wakes, upstream disturbances, film cooling, horseshoe vortices and secondary flows results in levels of 10-20%. The initial wall jet experiments showed augmentation of heat transfer by factors of 2 to 4. Previous experiments on the effects of turbulence on heat transfer showed only marginal effects for levels of 1-6% and this is because the near wall shear layer of a “fully turbulent” boundary layer already has a peak in turbulence of typically 8-10% so these free stream levels of 1-6% had little effect - but the wall jet, with increased levels of 10-20%, had significant increases in heat transfer. Correlations of the wall heat flux from high response series thermopiles with the free stream fluctuations showed correlations of 50 to 60 % indicating new physics for computations. The turbulent Prandtl Number now required significant modification and these measurements and calculations were also accomplished in this facility for these conditions. These initial experiments were initiated to explain engine measurements which showed increases of engine heat transfer by factors of three - 4 over that expected for a fully turbulent boundary layer as this was the highest value thought possible. Detailed results from these experiments are available in publications listed in appendix A.

After the effects of high freestream unsteadiness were quantified in the wall jet facility, model film cooling holes were introduced to study the interaction of film cooling with the turbulently driven boundary layer. Of primary interest was the influence of the cooling film injection on the wall heat transfer in the vicinity of the holes and the effect of unsteadiness, both in the holes and outside the boundary layer on the film cooling effectiveness (essentially a measure of how well the cooling flow is working).

Extraction of both heat transfer and film cooling effectiveness required development of a three-temperature testing technique. By setting the freestream, cooling flow, and wall to one set of three initial temperatures, running the test, and then repeating the same with another set of three initial temperatures while holding all the fluidic conditions constant, it is possible to solve a pair of coupled non-linear equations for both the heat transfer coefficient and the film cooling effectiveness coefficient. The usefulness of these measurements was increased greatly by the introduction of first Thermochromic Liquid Crystals (a surface coating which changes color with temperature) and then accurate infrared temperature measurements which allowed simultaneous measurement of temperature over the entire surface, instead of just the few dozen points measurable with thermocouples. One of the major findings of these experiments was that it is not sufficient to simply increase film cooling effectiveness. Because of the complex coupling between film cooling and heat transfer, it is possible to increase film effectiveness, but at the same time increase heat transfer to such an extent that your overall heat transfer situation actually degrades. Detailed results from these experiments are available in publications listed in appendix A.

Later experiments sought to increase the realism of the flows studied. Large scale coherent unsteadiness was added to try to emulate the sorts of aerodynamic forcing the turbine components see due to upstream wakes. External pressure gradients were imposed in order to emulate the effects of pressure variations on the suction and pressure sides of turbine airfoils. A facility was designed and built to study the influence of the high curvature and saddle-type flow kinematics on and near the leading edge of turbine blades. Detailed results from these experiments are available in publications listed in appendix A.

Most recently, experiments have been conducted to try to demonstrate how unsteadiness might be used to improve the performance of the cooling system. By pulsing the film cooling flow it has been demonstrated that a significant reduction in film cooling mass flow (75%) at the same effectiveness is possible without a corresponding increase in heat transfer coefficient. Pulsed film cooling has been applied to both straight, cylindrical, holes and shaped holes.

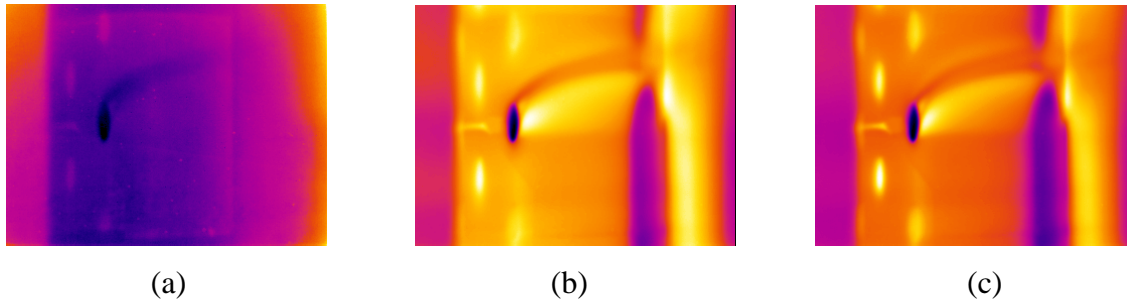


Figure 1: Infrared images from transient pulsed heat transfer test. (a): Start of test, $t = 0$; (b) $t = 25$ sec; (c) $t = 70$ sec.

A transient IR measurement was used to obtain the film effectiveness and heat transfer on a representative turbine leading edge with pulsed film cooling. The transient IR technique allows the measurement of both film effectiveness and heat transfer coefficient using wall temperatures from a single transient test run. Temperature data from two different times in the run, instead of two separate runs as is traditionally required for accurate transient thermochromic liquid crystal measurements, are used to solve the pair of coupled equations describing the evolution of the wall temperature. This same technique could also be used with thermochromic liquid crystals but because the temperature range of available liquid crystals is so limited, accurate measurements are not possible. The transient IR technique has been shown to be more accurate than transient LC in a direct comparison using matching flow conditions. This is due to the single run, the availability of the initial temperature distribution, and the wide temperature range over which accurate IR measurements can be made.

Figure 1 shows typical transient IR measurements of the surface temperature on the cylindrical leading edge of a turbine blade model with pulsed injection at 10 Hz. Measurements are shown for three times during a single test run. Figure 2 shows the resulting heat transfer coefficient and film cooling effectiveness distributions that are obtained from processing of the IR temperature measurements.

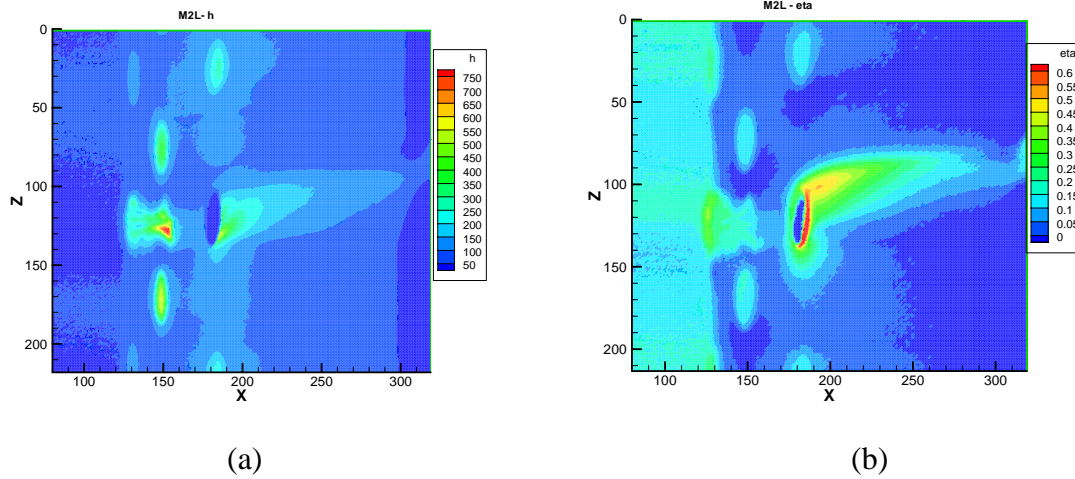


Figure 2: Pulsed cooling flow reduced data. (a).Heat transfer coefficient (h) distribution. (b) Cooling effectiveness (η) distribution.

Reduction of the duty cycle of the pulsing (ratio of the flow on time to the total cycle time), at a given pulse rate, reduces the mean coolant mass flow. Current measurements have shown that the duty cycle can be reduced to 25% (flow on only one quarter of the time) without losing cooling effectiveness. The ability to reduce film cooling flow directly translates into a proportional increase in turbine engine thrust. For more details see list of publications.

Turbulence Model Development:

The primary focus of this task was to obtain detailed experimental measurements of the aerothermodynamics of turbine related flows under highly unsteady conditions for use by researchers outside of the organization to develop models. There was some successful model development under this task however. Edward Michaels, while working on his Doctoral Dissertation, developed a very accurate two-scale turbulence model for the prediction of heat transfer and skin friction under high freestream turbulence conditions. He was able to predict these parameters to within 2%, an accuracy not provided by any other current models. Outside organizations have picked up this model and are working on extending and applying it.

Aerodynamic Flow Control

The aerodynamic loading and efficiency of the turbine components play a large role in the overall efficiency and power output of the the gas turbine engine. The low pressure turbine presents significant opportunities for improvements in this regard. A typical commercial aircraft turbine engine or ground power unit can have anywhere between five and twelve low pressure turbine stages. Low bypass engines used in high performance military engines will typically have two to four stages. Increasing blade loading allows for significant reduction in part count, and has the potential to allow the removal of whole stages of the low pressure turbine module, which translates into significant weight, performance, and cost savings.

The primary obstacle to increasing loading is maintaining efficiency. For the low pressure turbine a major cause of loss of efficiency is flow separation on the rear of the turbine airfoil, where there is a strong adverse pressure gradient.. Controlling this separation requires reenergizing the boundary layer flow in order to make it more separation resistant. There are many techniques for accomplishing this, but they can be separated into two broad categories: active techniques, which rely an the application of external energy; and passive techniques, which rely on making fixed surface or profile modifications to the airfoil in order to influence the boundary layer. Both passive and active separation control techniques were studied under this work unit, in cooperation with work performed under work units 2302NP01 and 2307NP01.

Passive Boundary Layer Contol

Passive separation control techniques studied include suction side v-grooves, slots, trips, turbulators, and spherical and asymmetric dimples. Of the passive techniques studied, the dimples proved to be the most effective at flow separation while cause a minimum of adverse affects on the airfoil loss characteristics. Figures 3a and 3b show a computation of the flow over a single row and a double row of spherical dimples respectively. The effect of the dimples is to generate a streamwise vortex pair in the boundary layer near the wall. This vortex pair serves to pump high energy fluid from outside the boundary layer down into the boundary layer near the wall, energizing the boundary layer. It also serves to trip a laminary boundary layer, speeding transition to turbulence, which again increases the boundary layer's resistance to separation.

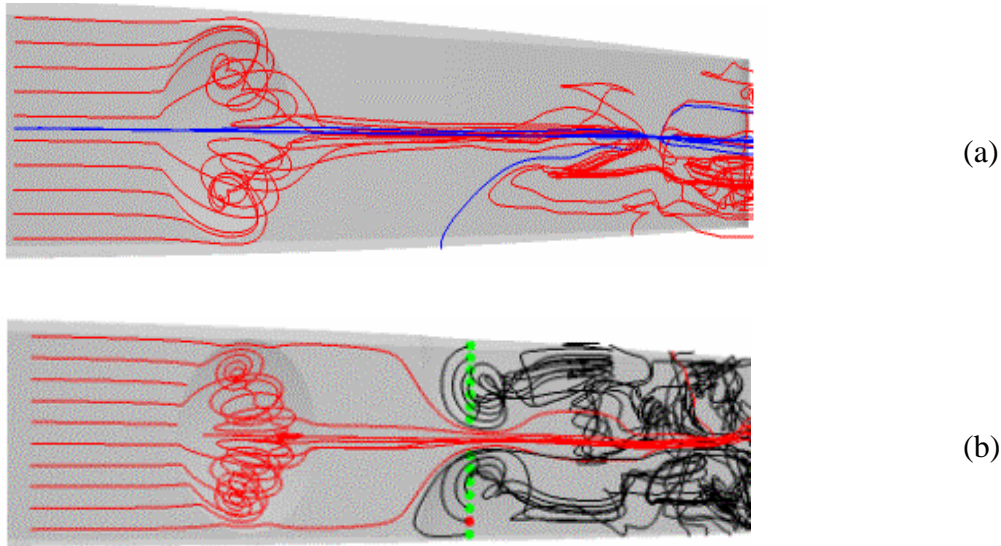


Figure 3: Computed flow over spherical dimples on the suction side of a low pressure turbine airfoil. Spanwise periodic boundary conditions. (a) Single row of dimples. (b) Double row of dimples.

Active Boundary Layer Control: Vortex Generator Jets

A number of active boundary layer control actuators were considered for study, including Helmholtz resonators, micro-electro-mechanical devices (MEMS), thermal actuators, plasma actuators, and Vortex Generator Jets (VGJs). The last, VGJs, were chosen to be the focus of study because of their proven effectiveness in external flows, and because of their physical similarity to the film cooling technologies already found in gas turbine engines. More recent work has examined the use of plasmas for forcing. That work will be discussed in the next section.

Vortex Generator Jets are small jets that are injected through the airfoil surface into the boundary layer. VGJs are typically configured with a low pitch angle (30-45 degrees) and aggressive skew angle (45-90 degrees) to the local freestream flow direction. Here pitch angle is defined as the angle the jet makes with the local surface and skew angle is defined as the angle of the projection of the jet onto the surface relative to the local freestream direction. In this skew configuration,

the VGJ creates a horseshoe vortex pair with one very strong leg accompanied by a weak leg of opposite sign. The result is a single, dominant, slowly-decaying streamwise vortex downstream rather than the two weaker counter-rotating horseshoe vortices generated by a jet with 0 degrees skew or a symmetric passive boundary-layer obstruction. It has been shown that this single-sign vortex energizes the separating boundary-layer by effectively bringing high momentum freestream fluid down to the wall.

Figure 4 shows the effect of VGJ blowing on the pressure loss through low pressure turbine cascade at low Reynolds number. The blowing ratio is the ratio of the momentum flux per unit area exiting the VGJ to the momentum flux per unit area of mid-channel flow outside the hole. At a blowing ratio of 0 (no flow through the VGJs) the flow over the LPT is separated and the loss coefficient (a normalized measure of the energy lost going through the cascade) is large. Once the blowing ratio is increased above a certain critical value, here approximately $B=1.0$ for steady blowing, the flow separation is greatly reduced and the loss is cut by approximately 60%.

Also shown on figure 4 are the results for pulsed VGJs. Here the jet flow is turned on periodically for only a fraction of the total cycle time. The effect is to greatly reduce the required mass flow from the VGJs. As can be seen in figure 4, a pulsed VGJ with an effective average blowing ratio of $B=0.02$ still effectively suppresses the separation and drives the losses down by 60%. Detailed results from these experiments are available in publications listed in appendix A.

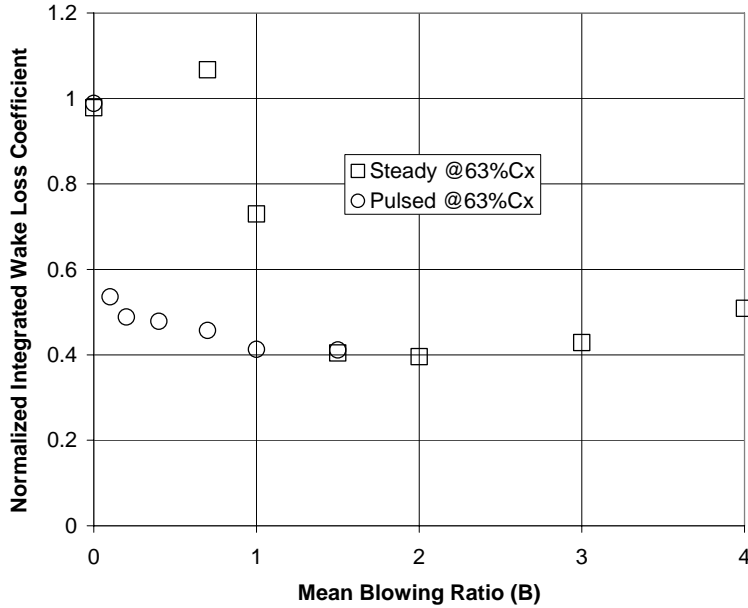


Figure 4. Effect of Vortex Generator Jet (VGJ) blowing on low pressure turbine blade pressure loss coefficient. Steady and unsteady VGJ flow.

Active Boundary Layer Control: Atmospheric Plasmas:

Work on flow control using plasma discharges has recently begun and has demonstrated a significant ability to modify the velocity profiles near the wall. Multi-kilohertz double pulsed lasers and cameras have been acquired and used to obtain velocity measurements that resolve the non steady flows occurring in the high frequency pulsed plasma applications.

The control of the voltage current characteristics for atmospheric glow discharges for control of subsonic flows has been investigated for high frequency AC and pulsed DC sources of excitation. Uniform atmospheric AC glow discharges were obtained from 1 kHz to 10 kHz for various electrode lengths of ~26 cm, 56 cm and 78 cm. Uniform Pulsed DC glow discharges were obtained with pulse widths from 22 nanoseconds to 2 micro seconds at a pulse rate of 100 pulses/second, for electrode lengths of ~ 26 cm, 56 cm and 78 cm. Calculated pulsed discharge peak power levels exceed 20-50KW. The discharge impedance was inductively and frequency matched for high frequency AC excitation and resistively matched for the pulsed DC case. The glow discharge with various electrode configurations has been installed in the 2D boundary layer tunnel and boundary layer and PIV measurements initiated. Figure 5 shows PIV boundary layer

profiles with and without plasma at low freestream velocities with an augmentation of the wall velocity to ~ 3.3 m/s. Boundary layer traverses with freestream velocities of 2.5, 4, 5.8, 18.5 m/s, indicate a decreasing % augmentation of the wall $\delta P/P$. The PIV laser and camera were upgraded to provide kHz double pulse capability for resolution of the plasma discharges and the pulsed vortex generator jets. Shown below are the u and v velocity profiles averaged correlations from hundreds of PIV individual images with plasma on (dashed) plasma off (solid). The v component shows a very large component just down stream of the electrodes. The capability to extend these averages to several thousand frames and perform phase locked PIV with discharge voltages / currents can now be accomplished.

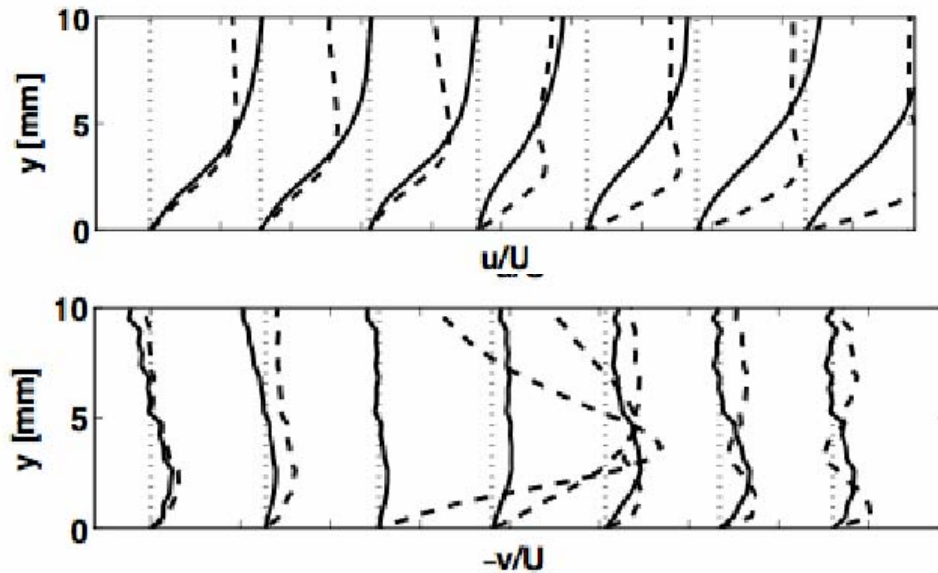


Figure 5. u (streamwise) and v (wall normal) boundary layer velocity profiles without (solid) and with (dashed) plasma discharge forcing, $U_\infty = 1.0$ m/s

Global Hawk LPT application:

The Low Reynolds number low pressure Turbine work is progressing to investigation of application of Dimples to the Global Hawk's AE3007H low pressure turbine, to correct for losses incurred at altitude. Three sets of scaled up cascade blades have been fabricated, first vane, first rotor, and third rotor, figure 6. These will be run in back to back tests without and with dimples in the linear cascade to determine the relative importance of individual stage losses. These blades were installed in the low speed Cascade in 2005.



Figure 6. Global hawk Cascade Blades

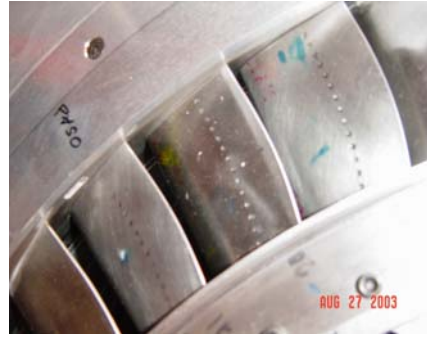


Figure 7. Dimpled HPT vanes for TRF

Dimples have been machined on two high pressure first vanes, figure 5. Pressure transducers for the Turbine Research Facility's (TRF) rakes have been upgraded for the Reynolds number range of interest for the AE3000H. Initial tests TRF tests were run in 2004 at nine Reynolds numbers with a rainbow array of HPT vanes. The array included 3 dimpled vanes, two rough vanes, and six clean vanes. A high Reynolds number TRF wake traverse of the rainbow array is illustrated in figure 6. A new set of four low Re TRF runs was carried out in 2005. Analysis of these runs is continuing.

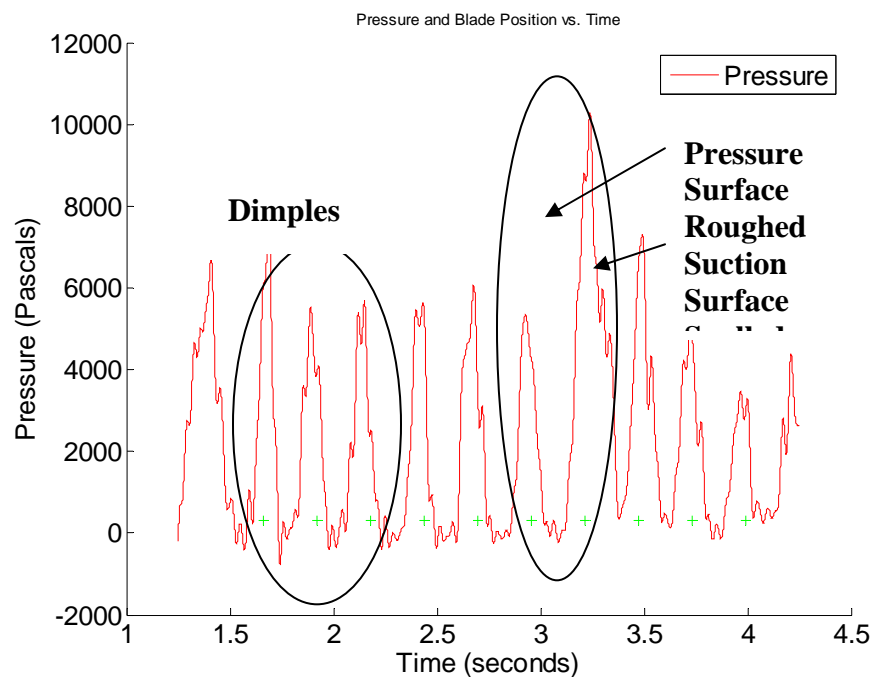


Figure 8. TRF wake traverse of dimples on roughened vanes, $Re = 272,457$

The TRF will be used to evaluate full scale AE3007H engine hardware. A 3 stage LPT for the AE3000H engine has been obtained and has been inspected and refurbished for a back to back test with out and with Dimples. Funding for modification of TRF and the required instrumentation has been obtained and construction is continuing.

PERSONNEL SUPPORTED 1985-2005:

Drs. R. B. Rivir, R. Sondergaard, S. Ou, G. Cala, J. Bons, C. Murawski,, and R. Anthony AFRL/PRTT.

Dr. Isaac Boxx , NRC Fellow

Lts B. Balcer, J. Newcamp, AFIT.

K. Moore, N. Woods Wright State University,

B. Eckerly, OSU

HONORS & AWARDS RECEIVED

ASME Fellow and AFRL Fellow 1998, 1993

AIAA Associate Fellow 1993

Three Propulsion Directorate S. D. Heron Awards 1988, 1995, 2001

APS Gallery of Fluid Motion 1995

E. C. Simpson Award, Propulsion Directorate 1998

AIAA Joint Propulsion Award 2002

AIAA Joint Propulsion, Dramatic Benefit of Flow Control Poster Award, First 2002

ST 2002

ASME Aircraft Engine Committee Best paper GT2004-54328

APPENDIX A: List of Publications

“Turbine Blade Surface Deterioration by Erosion,” Hamed, Tabakoff, Arora, & Rivir, *ASME Journal of Turbomachinery*, Vol. 127 No 3, July 2005, pp 445-452.

“Control of Laminar and Turbulent Shear Flows Using Plasma Actuators,” Jacob, Ramakumar, Anthony, and Rivir, Fourth International Symposium on Turbulence and Shear Flow Phenomena, Williamsburg, Virginia, June 27, 2005.

“Innovative Technique to Obtain Heat Transfer Coefficient and Film Effectiveness,” Ou, Rivir, and Brown, *Air Force Research Laboratory Technology Horizons*, Vol. 8, No. 2, April 2005.

“Boundary Layer Control Using Plasma Induced Velocity,” 2nd Lt Brian E. Balcer, AFIT Thesis, AFIT/GAE/ENY/05-M03, March 2005.

“Effects of Strong Irregular Roughness on the Turbulent Boundary Layer to Flow,” Subramanian, King, Reeder, Ou and Rivir, *Flow, Turbulence and Combustion Journal*, Vol. 72: 2004, pp 349-368.

“The Effect of Jet Pulsation and Duty Cycle on Film Cooling from a Single Jet on a Leading Edge Model,” Ekkad, Ou and Rivir, IMECE2004 -60466, International Mechanical Engineering Congress & Exposition 2004, Anaheim CA, Nov 2004, also recommended for Journal.

“Time Resolved PIV Measurements of a Plasma Actuator Discharge in Boundary Layer Flow Control,” Jacob and Rivir, 57th Annual Fluid Dynamics Meeting of the American Physical Society, Seattle, Washington, November 2004.

“Simultaneous Determination of Local Heat Transfer Coefficients and Film Cooling Effectiveness Using Transient Infrared Thermography,” Ekkad, Rivir, and Ou, *Journal of Turbomachinery*, Vol. 126, No 4, October 2004, pp 597-603.

“A Large Scale Investigation of Pulsed Vortex Generator Jets using PIV”, K. Moore, J. M. Wolfe, M. Polanka, and R. Sondergaard, *11th International Symposium on Flow Visualization*, University of Notre Dame, Notre Dame, IN, USA, August 9-12, 2004.

“Boundary Layer Flow Control Using AC Discharge Plasma Actuators,” Jacob, Rivir, Carter, and Estevaeordal, AIAA 2004-2128, AIAA 2nd Flow Control Meeting, Portland, OR, July 2004.

“Parameterization of Boundary Layer Control Dimples on a Low Pressure Turbine Blade”, J. P. Casey, P. I. King, and R. Sondergaard, *40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, AIAA-2004-3570, Ft. Lauderdale, FL, USA, July 11-14, 2004.

“A PIV Study of Pulsed Vortex Generator Jets”, K. Moore, J. M. Wolfe, and R. Sondergaard, *40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, AIAA-2004-3927, Ft. Lauderdale, FL, USA, July 11-14, 2004.

“Analytical Investigation of Rotating Disks with and without Incorporating Rotating Heat Pipes,” Ling, Cao, Rivir, and MacArthur, *Journal of Engineering for Gas Turbines and Power*, July 2004 , pp 680.

“Turbine Blade Surface Deterioration by Erosion,” Hamed, Tabakoff, Arora, & Rivir, ASME IGTI-2004-54328, IGTI Vienna, Austria, June 2004,

“Simultaneous Determination of Local Heat Transfer Coefficients and Film Cooling Effectiveness Using Transient Infrared Thermography,” Ekkad. Rivir, and Ou, ASME IGTI-2004-54236, June, 2004.

“Thermal-Control Experiments on Airfoils,” Yurchenko and Rivir, IV International Workshop Models and Methods of Aerodynamics, Evpatoriya, Ukraine, June, 2004.

“Control of Separation in Turbine Boundary Layers,” Rivir, Sondergaard, Bons, and Yurchenko, AIAA2004-2201, 2nd AIAA Flow Control Conference, Portland, OR, June 2004.

“Boundary Layer Flow Control Using AC Discharge Plasma Actuators,” Jacob, Rivir, Carter, and Estevaeordal, AIAA 2004-2128, AIAA 2nd Flow Control Conference, Portland, OR, June 2004.

“AC and Pulsed Plasma Flow Control,” Rivir, Jacob, White, Carter, Ganguly, Forelines, & Crafton, AIAA 2004 -0847, Aerospace Sciences, Reno, Jan 2004.

“Effect of Dimples on Boundary Layer Separation on a Low Pressure Turbine Blade”, K. P. Rouser, P. I. King, and R. Sondergaard, 16th *International Symposium on Air Breathing Engines, ISABE-2003-1097*, Cleveland, OH, USA, September 2003.

“Control of Low-Pressure Turbine Separation Using Vortex Generator Jets”. R. Sondergaard, J. P. Bons, and R. B. Rivir, *AIAA J. Propulsion and Power*, Vol. 18, No. 4, pp. 889-895. Jul/Aug 2002.

“Reducing Low-Pressure Turbine Stage Blade Count Using Vortex Generator Jet Separation Control”, R. Sondergaard, J. P. Bons, M. Sucher, and R. B. Rivir, *Proceedings of ASME Turbo Expo 2002: International Gas Turbine Conference*, GT-2002-30602, Amsterdam, The Netherlands, June 2002.

“The Fluid Dynamics of LPT Blade Separation Control Using Pulsed Jets”. J. P. Bons, R. Sondergaard, and R. B. Rivir, *ASME J. Turbomachinery*, vol. 124, pp 77-83. January 2002.

“Three Component Velocity Field Measurements in the Stagnation Region of a Film Cooled Turbine Vane,” M. Polanka, J. Cutbirth,, and D.Bogard, *International Gas Turbine Conference*, New Orleans, Louisiana, June 2001.

•

“Inlet Flow Effects on Turbine Tip and Endwall Heat Transfer and Loading”, M.D. Polanka, D.A. Hoying, M. Meininger, C.D. MacArthur, and J.P. Clark,” *International Gas Turbine Conference*, New Orleans, Louisiana, June 2001.

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