AFRL-SR-BL-TR-98

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0210

REPORT DOCUMENTATION PAGE

OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
Feb. 15, 1998

3. REPORT TYPE AND DATES COVERED
Final Report

4. TITLE AND SUBTITLE
Fluid Mechanics and Heat Transfer in the Transitional Boundary Layer

5. FUNDING NUMBERS
F49620-92-J-~~059~~ 0459

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Office of Scientific Research
Bolling AFB, DC 20331-6448

NA

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Program Monitors: Dr. James M. McMichael and Dr. Mark Glauser

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited

12b. DISTRIBUTION CODE

19980310 032

13. ABSTRACT (Maximum 200 words)

This EPOSR Fellowship program has supported students in conducting research for the parent programs (AFOSR Grant No: AFOSR-89-0324 and No. F49620-94-1-0126). In four years one doctoral and two master students completed their degrees with the support of this program. Their research areas are associated with experimental investigation of the flow and thermal structures in transitional boundary layers with both favorable and adverse pressure gradients and with/without leading edge roughness. The results have been submitted as three separate AFOSR technical reports. The primary conclusions from each part of the investigation are summarized in this report. The detailed information is referred to in corresponding technical reports and papers.

14. SUBJECT TERMS
Boundary Layer Transition, Roughness, Conditional Sampling

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

CLEMSON UNIVERSITY

FLUID MECHANICS AND HEAT TRANSFER IN THE TRANSITIONAL BOUNDARY LAYER

Final Report

By

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Department of Mechanical Engineering

Program Managers

Dr. James M. McMichael
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Prepared Under the Financial Support of the
Air Force Office of Scientific Research

Grant Numbers: F49620-92-J-0459

February 1998

FINAL REPORT

FLUID MECHANICS AND HEAT TRANSFER IN TRANSITIONAL BOUNDARY LAYERS

Grant No: F49620-92-J-0459 (EPSCoR Fellowship Program)

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Funding Period: (September 1, 1992 – December 31, 1997)

Parent Programs Supported:

1992-1994: F49620-92-J-0459
1994-1997: F49620-94-1-0126

ABSTRACT

This EPSCoR Fellowship program has supported two students each year in conducting research for two parent programs (AFOSR Grant No: AFOSR-89-0324 and No. F49620-94-1-0126). In four years one doctoral and two master students completed their degrees with the support of this program. Their research areas are associated with experimental investigation of the flow and thermal structures in transitional boundary layers with both favorable and adverse pressure gradients and with/without leading edge roughness. The results have been submitted as three separate AFOSR technical reports. The primary conclusions from each part of the investigation are summarized in this report. The detailed information is referred to in corresponding technical reports and papers.

OBJECTIVES

The main objective of this EPSCoR Fellowship program is to provide financial support to two graduate students each year to support research in parent programs related to boundary layer transition with application to gas turbines. The objective of the parent program is to systematically investigate the flow and thermal structures in transitional boundary layers under the influence of various parameters including favorable and adverse pressure gradients, free-stream turbulence intensities (between 3% to 7%), and surface roughness.

Number of Students Supported:

This program has supported six students. One graduated with a Ph.D. degree and two graduated with masters degrees as listed below:

F. Jeffery Keller (1992-1993) --- Ph.D. graduated in 1993
Scott Mislevy (1992-1994) --- MS graduated in 1994
Scott Farley (1994-1995) --- went to work in industry in 1995
Rangadhar Dash (1994-1996) --- did not complete the Ph.D. program
Mark Pinson (1994-1997) --- expected to graduate in 1998
Matthew Rice (1996-1997) --- expected to graduate in 1998

EXECUTIVE SUMMARY

Since this is a fellowship grant, the achievements of this program were summarized in terms of the individual student's accomplishments.

F. Jeffery Keller

The last year of Jeffery Keller's four-year doctoral research was supported by this fellowship. He graduated in 1993, but he continued to collaborate with the PI to publish his research results until 1998. He started the program with a detailed heat transfer and fluid mechanics study of the **baseline case,** which is a case in which the boundary layer underwent transition from laminar to turbulent flow on a flat, smooth surface with zero pressure gradient. Then various strength of favorable streamwise pressure gradients were imposed on the test surface by varying the outer wall of the test section. To separate the intermittent flow in the transitional flow into the turbulent and non-turbulent part respectively, a conditional sampling technique was developed with a comparison of pros and cons of seven different criterion functions. Eventually, conditionally sampled flow in accelerating conditions was analyzed.

Jeffery Keller has co-authored with the PI five conference papers, five journal papers, and one AFOSR technical report. His achievements are summarized below.

Summary of the Baseline Case

The baseline case with low FSTI and zero pressure gradient on a smooth surface was conducted. The transition onset for the baseline case occurred at $Re_X = 5.5 \times 10^5$ ($Re_\theta = 492$) which is earlier than the transition onset for a free-stream turbulence intensity (FSTI) value of 0.5% predicted from correlations. Apparently, factors other than FSTI influence transition onset. Onset of transition was taken at the point of minimum skin friction (and/or Stanton number). Measurements of the Reynolds normal stress indicated that the flow in the transition region is much less isotropic than the flow in a fully turbulent boundary layer. The Reynolds shear stress was shown to be generated within the boundary layer ($Y^+ = 70 \sim 100$) and imposed on the wall shear. Mean temperature profiles lagged in development compared to the mean velocity profiles and the values of the Reynolds analogy factor, $2St/C_f$, in the late-transition early-turbulent region were lower than the 1.2 value known to apply to the high-Reynolds-number turbulent flow. These results indicate a slower response of heat transport in this region compared to that of momentum transport.

The streamwise gradients of the streamwise Reynolds normal stress, $\partial u'^2/\partial x$, and the streamwise Reynolds heat flux, $\partial \overline{ut}/\partial x$, were shown to be of significant magnitude in the transition region and should not be ignored in transitional flow models when computational methods are used. The profiles of Reynolds cross-stream heat flux showed negative values in the near wall region. The region of negative $\overline{vt}$ narrowed as the flow proceeded downstream. These negative values of $\overline{vt}$ in a flow with a negative mean temperature gradient result in negative eddy thermal diffusivity and negative Pr_t, which are not physically appropriate. It is speculated that the negative values might be caused by the size of the sensor and the three-dimensional behavior of transition. The difference between eddy viscosity and eddy thermal diffusivity distributions reflected the apparent disparity between turbulent momentum and thermal transport mechanisms in the transitional boundary layer.

Summary of the Streamwise Accelerating Cases

Streamwise acceleration was shown to delay the point of transition onset both in terms of physical distance, x, and Reynolds number based on x. The transition onset momentum Reynolds number, $Re_{\theta s}$, was relatively insensitive to acceleration. In general, the physical length of transition increased with increasing K ($\equiv \frac{\nu}{U^2}\frac{dU}{dx}$). This was supported by the boundary layer thickness and integral parameters which indicated that an increasing favorable pressure gradient suppresses boundary layer growth and development through the transition region. The Reynolds normal stresses were suppressed in the near-wall region ($Y^+ < 50$) relative to the baseline case as K increased. This was believed to be caused by a thickening of the viscous sublayer relative to the boundary layer thickness. The lag that was observed between the mean temperature profiles and the mean velocity profiles for the baseline case became more pronounced with increasing K. Comparison of the evolution of RMS temperature fluctuations to the evolution of Reynolds normal stresses indicated a lag in the RMS temperature fluctuations. This supported the observation from the mean temperature and velocity profiles that the thermal transport lags behind the momentum transport in the transition region, and that the effect is more pronounced as K increases.

Summary of the Conditional Sampling Technique

Nine different criterion functions were investigated for conditional sampling technique. Criterion functions based on correlations schemes consistently resulted in intermittency values

0.14 to 0.38 lower in the outer boundary layer region ($y/\delta^* > 4.0$) than the values found from single signal schemes. No differences were found using the temperature based criterion function to support the use of a separate thermal intermittency factor in accelerating flows. Inherent differences were shown to exist between each criterion function's turbulence recognition capabilities. Each criterion function weights different areas within a turbulent spot. As a result, different criterion functions may result in the same overall intermittency factor, but analysis of the turbulent and non-turbulent portions would not always yield the same result.

A criterion function based on Reynolds stress, $(\partial \overline{uv} / \partial \tau)^2$, resulted in the sharpest demarcation between turbulent and non-turbulent portions of the flow. This criterion function also had a negligible variation of threshold value throughout the transition region with the lowest sensitivity of the resultant intermittency to the variation of the threshold. These results indicate that using the Reynolds shear stress for turbulent/non-turbulent discrimination in a heated transitional boundary layer is superior to a single velocity or temperature scheme. The intermittency across the boundary layer for the baseline and each accelerating case were obtained. Peak values in intermittency for the early to mid-transitional regions were found to occur away from the wall at approximately $y/\delta = 0.3$ for the baseline case and three accelerating cases. To match the universal intermittency distribution of Dhawan and Narasimha (1958), the values of intermittency at the near-wall minimum $y/\delta = 0.1$ should be used as the representative "near-wall" values.

Summary of the Conditional Sampling Results of Accelerating Flow Cases

The conditionally sampled distribution of the skin friction coefficients revealed that values for C_f in the non-turbulent and turbulent portions significantly deviated from the respective laminar and turbulent correlations. Reconstructing the local overall C_f value using the laminar and turbulent correlations consistently overestimates the experimentally determined unconditioned C_f values. The results indicate that a single representative near-wall intermittency value may not be the characteristic property for the transition region and that the intermittency variation across the boundary layer may play a more important role than previously thought. Evaluation of the conditionally sampled momentum thickness confirmed that the higher loss of momentum in the transition region is a direct result of the turbulent portion of the boundary layer. The mean velocity profiles from the turbulent portions had the appearance of a low-Reynolds-number turbulent boundary layer with a large wake region. In the late transition region, as K increased, the wake region in the turbulent portion was suppressed relative to the unconditioned result.

The increased magnitude of the streamwise Reynolds normal stress was discovered to be a direct result of the fluctuations in the turbulent portions and not a result of the "mean-step" contribution. The "mean-step" change indicated the step change between the turbulent and non-turbulent mean values. The peak intensity of the streamwise Reynolds normal stress in the non-turbulent portion was suppressed at an earlier stage as K increased. The Reynolds shear stress was normalized by the individual C_f values obtained for each portion. The peak magnitudes of Reynolds shear still exceeded the wall shear but not by the magnitudes previously seen. The results indicated that the turbulent shear was generated in the boundary layer at $Y^+ \approx 100$ and imposed on the wall shear and that the "mean-step" contribution was negligible. As K increased, $\overline{uv}$ in the turbulent portion was more uniformly distributed through the inner boundary layer than the unconditioned results. The peak intensity in the RMS temperature fluctuations in the non-turbulent portions increased in magnitude relative to the unconditioned data and the values in the turbulent portion at Y $\approx$100. These values eventually became greater than the turbulent and unconditioned values in the late transition region. The streamwise Reynolds heat flux in the turbulent portion increased in magnitude as K increased.

Scott Mislevy

Scott Mislevy graduated from the masters program at Clemson University in 1995. His research focused on the effect of adverse pressure gradient on the flow and thermal characteristics in the transitional boundary layer. He has co-authored two conference papers, two journal papers, and one AFOSR technical report.

Summary of the Adverse Pressure Gradient (Decelerating) Cases at Low FSTI

The effects of adverse pressure gradients on the thermal and momentum characteristics of a heated transitional boundary layer were investigated with free-stream turbulence ranging from 0.3 to 0.6 percent. The acceleration parameter K ($\equiv \frac{\nu}{U_\infty^{\,2}}\frac{dU_\infty}{dx}$) was kept constant along the test section. Both surface heat transfer and boundary layer measurements were conducted. The boundary layer measurements were conducted with a three-wire probe (two velocity wires and one temperature wire) for two representative cases, K1 = -0.51 x 10^{-6} and K2 = -1.05 x 10^{-6}. The surface heat transfer measurements were conducted for K values ranging from –045 x 10^{-6} to –1.44 x 10^{-6} over five divergent wall angles. The Stanton numbers of the decelerating cases were greater than that of the zero-pressure-gradient turbulent correlation in the low-Reynolds-number turbulent flow, and the difference increased as the adverse pressure gradient was increased. The adverse pressure gradient caused earlier transition onset and shorter transition length based on Re_x, Re_δ*, and Re_θ in comparison to zero-pressure-gradient conditions. As expected, there was a reduction in skin friction as the adverse pressure gradient increased. In the U^+-Y^+ coordinates, the adverse pressure gradients had a significant effect on the mean velocity profiles in the near-wall region for the late-laminar and early transition stations. The mean temperature profile was observed to precede the velocity profile in starting and ending the transition process, opposite from what occurred in favorable pressure gradient cases in previous studies. A curve fit of the turbulent temperature profile in the long-linear region for the K2 case gave a conduction layer thickness of Y^+ = 9.8 and an average Pr_t = 0.71. In addition, the wake region of the turbulent mean temperature profile was significantly suppressed.

The fluctuation quantities, u', v', and t', the Reynolds shear stress ($\overline{uv}$), and the Reynolds heat fluxes ($\overline{ut}, \overline{vt}$) were measured. In general, u'/U_∞, v'/U_∞ and $\overline{vt}$ have higher values across the boundary layer for the adverse pressure gradient cases than they do for the baseline case (K = 0). The development of v' for the decelerating cases was more actively involved than that of the baseline case. In the early transition region, the Reynolds shear stress distribution for the K2 case showed a near-wall region of high turbulent shear generated at $Y^+ = 7$. At stations farther downstream, this near-wall shear reduced in magnitude, while a second region of high turbulent shear developed at $Y^+ = 70$. For the baseline case, however, the maximum turbulent shear in the transition region was generated at $Y^+ = 70$, and no near-wall high shear region was seen. Stronger adverse pressure gradients appear to produce more uniform and higher t' in the near-wall region ($Y^+ < 20$) in both transitional and turbulent boundary layers. The instantaneous velocity signals did not show any clear turbulent/non-turbulent demarcations in the transition region. Increasingly stronger adverse pressure gradients seemed to produce large non-turbulent unsteadiness (or instability waves) at a similar magnitude as the turbulent fluctuations such that the production of turbulent spots was obscured. The turbulent spots could not be identified visually or through conventional conditional sampling schemes. In addition, the streamwise evolution of eddy viscosity, turbulent thermal diffusivity, and Pr_t were also measured.

Mark W. Pinson

Mark Pinson is a doctoral student. He has been supported for three years by this fellowship program. After its expiration, he will be supported by the Mechanical Engineering Department of Clemson University as a laboratory instructor. He is expected to graduate in August 1998.

Mark Pinson's research topic is related to the effect of surface roughness on flow and thermal structure in transitional and turbulent boundary layer flows. He is currently working on an appropriate way to describe the roughness characteristics appearing in aeroengines. He is also investigating the reasons why we ever want to characterize the roughness on the airfoils in the aeroengines, because several previous studies have shown that the characteristics of roughness in aeroengines significantly varies at various locations in the airfoils. They also vary from engine to engine under similar operating conditions. The roughness characteristics can be entirely different for engines operated over the ocean than those operated near deserts. Therefore, Mark is investigating whether large roughness structures may be the only things we should pay attention to instead of trying to characterize overall surface roughness. This is based on speculation that large roughness structures may dominate the flow structures downstream, irrespective of the roughness of small scales.

Mark Pinson has so far co-authored one conference paper, one journal paper, and one AFOSR technical report. His research results on the effect of leading edge roughness on laminar-turbulent transitional flow and heat transfer is summarized below.

Summary of the Effect of Leading Edge Roughness

An experimental study was undertaken to gain insight into the physical mechanisms that affect the laminar-turbulent transition process downstream of the leading-edge roughness condition. In order to simulate the randomly distributed roughness located near the leading edge of the turbine blade, 1200, 180, and 40 GRIT sandpaper strips were adhered to the leading edge of the test surface. Similarly, 0.762, 1.59, and 2.31 mm diameter cylinders were chosen to simulate the relatively isolated peak nature of the roughness structure. A total of eight different leading-edge conditions and 56 test cases were examined. The roughness Reynolds number ranged from 2 to 2840. Tests were also conducted by using a smooth strip of tape at the leading edge to determine the relative effects of the sandpaper backing and the actual roughness of the sandpaper. All of these leading-edge conditions were compared to the undisturbed leading edge.

Overall, greater maximum roughness height was observed to induce greater enhancement of the surface heat transfer than the undisturbed case. Depending on the free-stream velocity and the distance from the leading edge disturbance, the enhancement ranged from negligible to 200%. At low free-stream velocities (U_∞ = 5 m/s), the maximum roughness height was the primary contributor to deviations observed from the undisturbed case, irrespective of the roughness geometry. At higher free-stream velocities, 5-7 m/s, the Stanton number versus Re_x correlation exhibited dual slope region between the typical laminar and turbulent correlations, also irrespective of the roughness geometry. Although the first slope was significantly different from the laminar correlation (as much as 88% higher), inspection of the mean velocity profiles, RMS fluctuations, Reynolds shear stress, and instantaneous velocity signals indicated that the boundary layer was pre-transitional in this region. The second segment of the dual-slope Stanton number distribution was steeper than the first and the junction between these two segments was determined to be the approximated onset of boundary layer transition.

Matthew C. Rice

Matthew Rice is a masters student. He started his master's program in January 1997. He has been supported by this fellowship for one year. After the expiration of this fellowship, he is supported by the Department of Mechanical Engineering of Clemson University as a Teaching assistant.. His research focuses on investigating the effect of high free-stream turbulence on flow and heat transfer over roughened surfaces. Matthew is expected to graduate in December 1998.

Overall, the students supported by this fellowship completed three technical reports, presented 8 papers at conferences, and published 8 journal papers.

Technical Reports:

Keller, F.J. and Wang, T., "Flow and Thermal Structures in Heated Transitional Boundary Layers with and without Streamwise Acceleration," AFOSR Final Technical Report, 1993.

Mislevy, S. and Wang, T., "The Effects of Adverse Pressure Gradients on the Momentum and Thermal Structures in Transitional Boundary Layers," Research Report, Air Force Office of Scientific Research, 1995.

Pinson, M. and Wang, T., "The effects of Leading Edge Roughness on Flow and Heat Transfer in Transitional Boundary Layers," Research Report, Air Force Office of Scientific Research, 1998 ---- submitted with this final report.

Journal Publications

1. Wang, T., J. F. Keller, and Zhou, D. D., "Flow and Thermal Structures in a Transitional Boundary Layer," J. of Experimental Fluid and Thermal Science, Vol. 12, pp.352-363, 1996.

2. Keller, F. J. and Wang, T., "Flow and Heat Transfer Behavior in Transitional Boundary Layers with Streamwise Acceleration," ASME Journal of Turbomachinery, Vol. 118, pp. 314-326, 1996.

3. Keller, F. J. and Wang, T., "Effects of Criterion Functions on Intermittency in Heated Transitional Boundary Layers with and without Streamwise Acceleration," ASME Journal of Turbomachinery, Vol. 117, No. 1, pp. 154-165, 1995.

4. Wang, T. and Keller, F.J., "Intermittent Flow and Thermal Structures of Accelerated Transitional Boundary Layers, Part 1:Mean Quantities" ASME paper GT-97-402, accepted for publication in the ASME Journal of Turbomachinery, 1997.

5. Wang, T. and Keller, F.J., "Intermittent Flow and Thermal Structures of Accelerated Transitional Boundary Layers, Part 2: Fluctuation Quantities" ASME paper GT-97-403, accepted for publication in the ASME Journal of Turbomachinery, 1997

6. Mislevy, S. P. and Wang, T., "The Effects of Adverse Pressure Gradients on Momentum and Thermal Structures in Transitional Boundary Layers. Part 1: Mean Quantities," ASME Journal of Turbomachinery, Vol. 118, pp. 717-727, 1996.

7. Mislevy, S. P. and Wang, T., "The Effects of Adverse Pressure Gradients on Momentum and Thermal Structures in Transitional Boundary Layers. Part 2: Fluctuation Quantities," ASME Journal of Turbomachinery, Vol. 118, 728-736, 1996.

8. Pinson, M. and Wang, T., "Effects of Leading Edge Roughness on Flow and Heat Transfer in Transitional Boundary Layers," International J. of Heat and Mass Transfer, Vol.40, No.12, pp 2813-2823, 1997.

Referred Conference Proceedings

9. Wang, T., J.F. Keller, and Zhou, D.D. "Experimental Investigation of Reynolds Shear Stresses and Heat Fluxes in a Transitional Boundary Layer," ASME paper HTD-Vol.226, pp.61-70, presented at the 1992 ASME Winter Annual Meeting.

10. Keller, F. Jeffrey, and Wang, T., "Effects of Criterion Functions on Intermittency in Heated Transitional Boundary Layers with and without Streamwise Acceleration," ASME paper 93-GT-67, presented at the 1993 International Gas Turbine and Aeroengine Congress, May 1993, Cincinnati, OH.

11. Pinson, M. and Wang, T., "Effects of Leading Edge Roughness on Flow and Heat Transfer in

Transitional Boundary Layers," ASME Paper 94-GT-326, Presented at the 1994 International Gas Turbine Congress, Netherlands, June 1994.

12. Keller, F. J. and Wang, T., "Flow and Heat Transfer Behavior in Transitional Boundary Layers with Streamwise Acceleration," ASME Paper 94-GT-24, Presented at the 1994 International Gas Turbine Congress, Netherlands, June 1994.

13. Mislevy, S. P. and Wang, T., "The Effects of Adverse Pressure Gradients on Momentum and Thermal Structures in Transitional Boundary Layers. Part 1: Mean Quantities," ASME paper 95-GT-4, presented the 1995 ASME International Gas Turbine Congress, Houston, June, 1995.

14. Mislevy, S. P. and Wang, T., "The Effects of Adverse Pressure Gradients on Momentum and Thermal Structures in Transitional Boundary Layers. Part 2: Fluctuation Quantities," ASME paper 95-GT-5, presented at the 1995 ASME International Gas Turbine Congress, Houston, June, 1995.

15. Wang, T. and Keller, F.J., "Intermittent Flow and Thermal Structures of Accelerated Transitional Boundary Layers, Part 1:Mean Quantities" ASME paper GT-97-402, presented at the ASME Turbo Expo'97, Orlando, Fl, 1997

16. Wang, T. and Keller, F.J., "Intermittent Flow and Thermal Structures of Accelerated Transitional Boundary Layers, Part 2: Fluctuation Quantities" ASME paper GT-97-403, presented at the ASME Turbo Expo'97, Orlando, Fl, 1997