# Abstract

Under this contract research was conducted to examine two aspects of boundary layer flows: (1) the influence of free-stream turbulence on zero pressure gradient, full-turbulent boundary layer flow; and topic (2) the combined effects of free-stream turbulence and favorable streamwise pressure gradients on transitional boundary layer flow. For topic (1) experimental convective heat transfer coefficients and boundary layer mean velocity and temperature profile.
An Experimental and Analytical Study of Boundary Layers in Highly Turbulent Freestreams

Final Technical Report

Contract No. F-9620-78-C-0064
Project-Task 2307/A4
61102 F

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FOREWORD

This report was prepared for the Air Force Office of Scientific Research, United States Air Force by the United Technologies Corporation Research Center, East Hartford, Connecticut, under Contract F49620-78-C-0064, Project Task No. 2397-AW-12102-F. The performance period covered by this report was from 1 June 1978 to 31 March 1981. The project monitors were Col. Robert C. Smith (Ret.), Dr. D. G. Samaras, and Dr. James D. Wilson.

The experimental portions of the investigation were conducted in the UTRC Boundary Layer Wind Tunnel. This facility was constructed during 1977 and underwent a series of flow quality evaluation tests during 1978. The UTRC Uniform Heat Flux Flat Wall Model was also constructed, instrumented, and tested during 1978. Finally, a computer controlled data acquisition system for the UTRC Boundary Layer Wind Tunnel was designed, constructed and made operational during 1978. The construction and evaluation testing of the Boundary Layer Wind Tunnel, Uniform Heat Flux Flat Wall Model, and Data Acquisition system were conducted under UTC Corporate sponsorship.

Contract funded efforts have been devoted to the measurement and analysis of the heat transfer distributions, boundary layer profile and turbulence data discussed in this report.
An Experimental and Analytical Study of Boundary Layers in Highly Turbulent Free-streams

STATEMENT OF WORK

The Contractor shall furnish scientific effort, together with all related services, facilities, supplies and materials, needed to conduct the following research:

a. For fully turbulent boundary layer flow, convective heat transfer coefficients, boundary layer mean velocity and temperature profiles, wall static pressure distributions, and free-stream turbulence intensity, spectral, and longitudinal integral scale distributions shall be measured using the Contractor's instrumented flat wall installed in the Contractor's Boundary Layer Wind Tunnel. These data shall be obtained with a free-stream turbulence intensity level below 1 percent for two constant free-stream velocities and for three free-stream turbulence levels greater than 1 percent for one constant free-stream velocity (a total of five flow conditions). From these data the integral properties (momentum, displacement, and enthalpy thickness) of the boundary layers will be calculated, and where applicable, the profile data will be reduced to the "universal" coordinates for turbulent boundary layers.

b. The measured heat transfer distributions and turbulent boundary layer profile data obtained under paragraph a above shall be compared to predictions of the UTRC Finite-Difference Boundary Layer deck. The free-stream turbulence energy entrainment calculation procedure currently incorporated in the UTRC deck will be evaluated using these comparisons.

c. For transitional boundary layer flow, convective heat transfer coefficients, boundary layer mean velocity and temperature profiles, wall static pressure distributions, and free-stream turbulence intensity, spectral, and longitudinal integral scale distributions shall be measured using the Contractor's instrumented flat wall installed in the Contractor's Boundary Layer Wind Tunnel. These data shall be obtained for two free-stream acceleration levels with two free-stream turbulence levels each for a total of four flow conditions. From these data, the integral properties (momentum, displacement, and enthalpy thickness) of the boundary layers will be calculated, and, where applicable, the profile data will be reduced to the "universal" coordinates for turbulent boundary layers.
d. The measured heat transfer distributions and transitional boundary layer profile data obtained under paragraph c above shall be compared to predictions of the UTRC Finite-Difference Boundary Layer deck. The method employed in the UTRC deck to compute transitional boundary layers flows will be evaluated using these comparisons.
INTRODUCTION

Improved techniques for calculating heat transfer coefficient distributions on gas turbine airfoils have been sought by engine manufacturers for the entire history of the industry. These heat transfer distributions must be known so that cooling schemes can be tailored to produce the required metal temperatures. Accurate heat transfer predictions are an essential feature of gas turbine design because of the need to maximize performance through minimal use of cooling air and the need to minimize development costs through provision of adequate airfoil cooling on the initial design.

In the design of an airfoil cooling scheme the lack of any required heat transfer distribution information may be compensated for by simply overcooling the component. This overcooling may easily exist since gas turbine thermal design systems are typically not based on fundamental fluid mechanics and heat transfer data and analysis alone but rather are calibrated, or adjusted, to provide agreement with engine experience. Among the more obvious benefits that result from elimination of overcooling are reduced aerodynamic cooling penalties, increased burner and turbine mainstream mass flow rates (i.e., increased power) and potentially reduced cost for the fabrication of the airfoil cooling scheme. Furthermore, without a more complete first-principles understanding there is the likelihood that a designer will unknowingly go beyond the range of validity of the design system calibration. There is, then, a clear requirement for the development of airfoil heat transfer distribution prediction procedures which are based on fundamental fluid mechanics and heat transfer data. The great emphasis placed on the development of accurate boundary layer calculation techniques over the past few years reflects the recognition of this need.

One particularly important topic in the general context of turbine airfoil convective heat transfer is the influence of the freestream turbulence on both transitional and fully turbulent boundary layer profile development. It has, of course, long been recognized that increasing the freestream turbulence level can cause a forward shift of the laminar to turbulent transition region. This particular phenomenon, the reduction of the boundary layer transition Reynolds number with increased freestream turbulence level, is well documented in the open literature for zero pressure gradient flows and can be accurately predicted with at least one currently available boundary layer prediction scheme. The influence of the freestream turbulence on fully turbulent boundary layers, however, is less certain. A number of investigators have studied the effects of freestream turbulence level on flat wall turbulent boundary layer heat transfer rates and have reported conflicting results. One group of experiments has shown significant effects of the freestream turbulence on heat transfer while a second group has indicated negligible or very small influence. Other experiments with a limited the effects of freestream turbulence on boundary layer growth, profile structure, and skin friction...
distribution consistently reported very large and important influences. The current contract was conducted in order to clarify these contradictions. Both wall heat transfer and detailed boundary layer profile data were obtained for fully turbulent boundary layers for a range of freestream turbulence levels to provide data which will definitively indicate the influence that freestream turbulence level has on fully turbulent boundary layer heat transfer. In addition, these experimental data were employed to evaluate the turbulence entrainment models currently incorporated in an existing boundary layer calculation technique.

As previously discussed, the effects of freestream turbulence on the zero pressure gradient boundary layer transition Reynolds number are well understood. The influence of the freestream turbulence on the transition process becomes considerably less well defined, however, for cases in which the boundary layer is also exposed to a pressure gradient. The net result of the combined influence of turbulence and pressure gradient is dependent upon the sign of the pressure gradient and the relative strength of the two effects. For adverse pressure gradients both the turbulence and the deceleration promote the transition process and in this case the net result is simply to hasten transition. For favorable pressure gradients, however, the flow acceleration acts to stabilize the boundary layer and tends to counteract the effect of the freestream turbulence. This interplay of pressure gradient and turbulence results in at least two effects on the transition process: (1) the location of the onset of transition is influenced and (2) the length and character of the transitional boundary layer flow region may be altered significantly. At the present time, only very limited experimental data documenting these effects are available. To further complicate the matter, much of the currently available data are contradictory making it impossible to assess the relative quality of boundary layer calculation techniques for these flows. For these reasons, as part of the present contract both wall heat transfer and detailed velocity and temperature profile data were obtained for accelerating transitional boundary layer flows exposed to high freestream turbulence levels. These data were utilized to evaluate the current capability of an existing boundary layer calculation procedure to predict boundary layer development with combined favorable pressure gradient and freestream turbulence levels.

The present contract program provides wall heat transfer and detailed mean boundary layer profile development data required to determine the influence of freestream turbulence level on both fully turbulent and accelerating transitional boundary layers. These data are fundamental in nature and can be employed by both """" and other workers in the field of boundary layer transition for evaluation of analytical models. In addition, the contract experiments provide a valuable body of detailed heat transfer and boundary layer profile data directly relevant to the problem predicting heat transfer distributions on gas turbine airfoils. Finally, as mentioned above, the information could result in more accurate blade heat transfer distribution prediction techniques and thereby the more efficient use of blade cooling air.
The contract effort consisted of the documentation and analysis of experimental flat wall boundary layer profile and heat transfer data to determine the influence of freestream turbulence on transitional and fully turbulent boundary layer flows. For fully turbulent, zero pressure gradient boundary layer flows the following data were obtained for a range of freestream turbulence intensities: convective heat transfer coefficients; boundary layer mean velocity and temperature profiles; test wall static pressure distributions and freestream turbulence intensity, spectral and longitudinal integral scale distributions. These same measurements were obtained for various combinations of favorable pressure gradients and freestream turbulence levels for transitional boundary layer flows. From these data the integral properties of the test boundary layers were calculated and, where applicable, the profile data were reduced to the "universal" coordinates for turbulent boundary layers $U^+$, $Y^+$ and $T^+$. Finally, the measured heat transfer distributions and boundary layer profile development were compared to predictions of the UTRC Finite-Difference Boundary Layer Deck. These comparisons were employed to evaluate the computation methods currently incorporated in the UTRC deck.
STATUS OF THE RESEARCH EFFORT

Under this contract, research was conducted to examine two aspects of boundary layer flow: topic (1) the influence of free-stream turbulence on zero pressure gradient, fully turbulent boundary layer flow; and topic (2) the combined effects of free-stream turbulence and favorable streamwise pressure gradient on transitional boundary layer flow.

For topic (1) experimental convective heat transfer coefficients, boundary layer mean velocity and temperature profile data and wall static pressure distribution data were obtained for five flow conditions of constant free-stream velocity and free-stream turbulence intensities ranging from approximately 1/4% to 7%. Free-stream multi-component turbulence intensity, longitudinal integral scale, and spectral distributions were obtained for the various turbulence levels. These data fulfill task "a" of the Statement of Work. In addition, in fulfillment of task "b" of the Statement of Work, comparisons were made between the data of task "a" and prediction of the UTRC Finite-Difference Boundary Layer Deck. A technical report (Ref. 1) "UTRC R80-914388-12, The Influence of Free-Stream Turbulence on the Zero Pressure Gradient Fully Turbulent Boundary Layer" was prepared describing the details of the work conducted for topic (1). Reference 1 contains the following: (1) a complete description of the newly constructed wind tunnel in which these experiments were conducted as well as details of a series of flow quality evaluation tests of the facility, (2) details of the boundary layer and turbulence data acquisition and analysis techniques employed, (3) multi-component free-stream turbulence intensity distributions and longitudinal integral scale and spectral distributions for all flow conditions, (4) Stanton numbers, skin friction coefficients, boundary layer profile and integral property data (momentum, displacement and enthalpy thicknesses) for all flow conditions, (5) an analysis of the experimental results and (6) comparisons of the present experimental results with predictions of the UTRC Finite-Difference Boundary Layer Code. In addition, a data report (Ref. 1 - UTRC R80-914388-15 "Final Data Report-Vol. 1 - Velocity and Temperature Profile Data for Zero Pressure Gradient, Fully Turbulent Boundary Layers") containing the raw data and plotted profile data for topic (1) was assembled. Numerous data quality checks and measurements to insure data consistency were obtained during the course of this experiment. In addition, for applicable cases, comparisons were made between data obtained in the present program and the results of other workers. This in-depth examination of the present data indicated that they were of extremely high quality and free of anomalies.

Analysis of the data indicates that the heat transfer, skin friction, velocity and temperature mean profile, and free-stream turbulence data form a self-consistent set of information. The following conclusions were reached from the work conducted for topic (1). These conclusions indicate that for gas turbine applications, where free-stream turbulence levels can be extremely high, the influence of the turbulence on the aircraft heat transfer could be significant.

1. For zero pressure gradient, turbulent boundary layer flow, the skin friction coefficient increases with increasing free-stream turbulence level. As an example,
increases of approximately 1.5 to 2.0 above the low free-stream turbulence skin friction coefficient for the same Re were measured for a turbulence intensity of 1%. (See Fig. 21 of Ref. 2).

3. Heat transfer rates also increased with increasing turbulence level. Stanton numbers measured for a wide range of free-stream turbulence intensities-turbulence intensity were presented in Fig. 14 as a function of turbulence intensity and length scale of turbulence. For these data are given in Figs. 3, 4, and 5 of Ref. 1 respectively. In addition, stanton number is given as function of turbulence intensity in Fig. 11 of Ref. 1. An examination of Fig. 11 reveals that for the low free-stream turbulence test cases, i.e., 1, 2, 3, 4, and 5, no turbulence until the present data agreed very well with the predicted heat transfer distribution of efficiency (Ref. 3). In addition, it can be seen that the local Stanton number increased progressively with increasing turbulence intensity. As an example, for 1 turbulence intensity the measured heat transfer coefficients were approximately 15% greater than the low free-stream turbulence values (see Fig. 17 of Ref. 1).

3. The Stanton number increased at a somewhat higher rate with increasing free-stream turbulence than all the skin friction. Calculated boundary layer factors (Ref. 1) are presented as a function of free-stream turbulence intensity in Fig. 11. It can be seen that at low turbulence levels the present data agreed very well with the results of Refs. 4, 5, and 6. A progressive increase of boundary layer factor with increased turbulence is evident.

4. Although these effects are primarily a function of the local free-stream turbulence intensity it has been shown that the turbulence length scale over Fig. 11 of Ref. 1 and the momentum thickness have no effect (Ref. 4) and also exert some influence. As examples of these correlations skin friction and heat transfer data from the present study and a number of other investigations are presented as functions of both turbulence and Re in Figs. 20 and 21.

5. The skin friction at both the mean velocity and temperature profiles were found to be significantly increased with increasing free-stream turbulence. Changes in the skin friction and Stanton numbers have been inferred from these data in previous papers in Refs. 1, 6, 7, and 8. However, the trends were shown to be consistent with the "wall inferred" changes discussed in references (1, and 2).

6. The following correlation represented the data obtained in the present program with reasonable accuracy:

\[ \frac{C_f}{C_{f,0}} = C_0 + C_1 \sinh \left( \frac{Re_p}{C_{00}} \right) \]

The turbulence model of McDonald and Kreskovsky provided a reasonably accurate prediction of free-stream turbulence effects on flat plate skin friction. Predictions of the effects of turbulence on heat transfer are presented in Fig. 21. The predictions are seen to underpredict the effect of the turbulence for all Reynolds studies.

For topic 1, experimental convective heat transfer coefficients, boundary layer mean velocity and temperature profile data, and wall static pressure distribution data were obtained for four combinations of streamwise acceleration and free-stream turbulence intensity. Free-stream multi-component turbulence intensity, longitudinal integral length scale, and spectral distribution data were obtained for the four test cases. These data fulfill the requirements of task "c" of the Statement of Work. In addition, in fulfillment of task "d" of the Statement of Work, comparisons were made between the data of task "c" and predictions of the "The Finite-Difference Boundary Layer Code." A technical report (Ref. 11 = "The University of Illinois - "Combined Influence of Free-Stream Turbulence and Favorable Pressure Gradients on Flat Plate Transition and Heat Transfer") was prepared describing the data and the errors.  The work conducted for topic 12, "Reference 11 contains the following: 1) finite difference free-stream turbulence intensity distributions for all the test cases at Mach number, free-stream boundary layer profile and integral properties, and momentum and displacement thicknesses for all the test cases; 2) experimental errors with predictions of the "The Finite-Difference Boundary Layer Code" in section 1, data report 11 = "The University of Illinois Final Data Report - Ref. 11 = "The University of Illinois Final Data Report - Mach Number, Pressure and Temperature, Heat Flux, and Transition, Boundary Layer, and Turbulence Measurements" indicating the accuracy and limitations of the data for topic 12.

Analysis of the results for topic 12 indicated that the data were accurate and that the recovered boundary layer was very two-dimensional. The free-stream turbulence distribution generated for these tests was shown to be in some sense of nearly one-dimensional. It is anticipated that these results will provide a second set of fundamental, well documented experimental test cases to which analytical and numerical predictions can be compared. The following results and conclusions are obtained for the work conducted for topic 12:
Heat transfer coefficient measurements were obtained for five freestream turbulence intensity levels at the bluff body surface in ten flow conditions. The results show that for the test section with a fixed streamline acceleration \( a = 0 \), the turbulent boundary layer apparently remained laminar for the entire length of the test section. With increasing turbulence, the transition process moved progressively upstream until, for grid 5, transition began about 3 inches from the plate leading edge. The data of \( a = 0 \) also indicate that, as usual, a transition from the laminar to turbulent regime was reached for the case of high turbulence level increases the heat transfer.

Heat transfer distribution measurements were also obtained at five levels of freestream turbulence and a constant streamline acceleration \( a = 0 \) and \( a = 5 \). For this streamwise acceleration level transition was retarded for the entire test flow length for both the no grid and grid 1 test cases. In addition, for grid 2 installed the length of the transition region was much greater for the case with the highly accelerated flow.

Sample velocity profile data obtained for one of the test flow cases \( a = 5 \) are presented in Fig. 5. These profile data, presented in the universal form, demonstrate the progressive change from fully developed to laminar boundary layer flow along the test wall. In Fig. 5, the streamline distribution of the laminar boundary layer thickness \( \delta' \) and thickness \( \delta' \) are presented for all test flow conditions.

The measured transitional velocity profile data indicate that fully turbulent heat transfer coefficients are significantly higher than laminar heat transfer rates. The data also indicate that the transition point is established in a shorter length than is required for the development of the equilibrium turbulence structure.

Transition results obtained in the present program are very well with correlation factors that will enable for both zero pressure gradient and accelerating flows, the transition curves are given for predictions of the transition point with the empirical analysis of free-stream turbulence and streamwise acceleration.

The agreement of the turbulent boundary layer code indicated that the transitional heat transfer model of M. L. H. Plesset provides accurate predictions of transitional boundary layer growth factor for cases with a moand pressure gradient and free-stream turbulence effects. Heat transfer predictions were found to be in close agreement.
Figure 1. Influence of increasing Free-Stream Turbulence on Heat Transfer and the Reynolds Analogy Factor

\[ T = \sqrt{\frac{1}{3} \left( \frac{u'^2}{U_e^2} + \frac{v'^2}{U_e^2} + \frac{w'^2}{U_e^2} \right)} \]
Figure 2. Influence of Free-Stream Turbulence Intensity and $Re_{\theta}$ on Skin Friction and Heat Transfer
Figure 3: Acceleration and Heat Transfer Distributions for Wedge 1 With 1 Free-Stream Turbulence Levels
Figure 4: Acceleration and Heat Transfer Distributions For Wedge 2 and 3 Free-Stream Turbulence Levels
Figure 1: Development of the Mean Velocity Profiles Along the Test Wall
For $K = 0.20 \times 10^{-6}$ And Grid 2 - Universal Turbulent Coordinates
References


LIST OF WRITTEN PUBLICATIONS

The following papers are currently being prepared for submission to conferences and journals. Copies of these papers will be sent to AFOSR simultaneously with their submission for publication. Likely titles, authors and journals are as follows:

1. Title - Development of a Large-Scale Wind Tunnel for the Simulation of Turbomachinery Airfoil Boundary Layers.

   Authors - Blair, M. F., Bailey, D. A. and Schlinker, R. H.


   Note - Most of the work reported in this paper was funded by United Technologies Corporation. Some data from task "a" of the Statement of Work of the present contract were used to demonstrate the tunnel performance.

2. Title - The Influence of Free-Stream Turbulence on Skin Friction and Heat Transfer for a Turbulent Boundary Layer

   Author - Blair, M. F.

   Journal - ASME Journal of Heat Transfer

3. Title - Combined Influence of Free-Stream Turbulence and Favorable Streamwise Pressure Gradients on Boundary Layer Transition

   Author - Blair, M. F.

   Journal - ASME Journal of Heat Transfer

LIST OF PROFESSIONAL PERSONNEL ASSOCIATED WITH THE RESEARCH EFFORT

Blair, Michael F. - Senior Research Engineer, Gas Turbine Technology Group, Gas Dynamics Section - Principal Investigator and Project Manager
INTERACTIONS

a. Spoken Papers

   Title - Influence of Free-Stream Turbulence on Turbulent Boundary Layer Heat Transfer

   Speaker - Blair, M. F.

   Forum - Lehigh University - Mechanical Engineering and Mechanics Seminar

   Date - March 27, 1981

b. Consultative and Advisory functions - Discussions have been held with Professor David Walker of Lehigh University concerning the use of a turbulent boundary layer/pressure gradient data analysis developed by him. Professor Walker's data analysis system was developed under AFOSR funding.

c. Communications with Professor Peter Bradshaw of Imperial College, London, England regarding the subject material of this contract have proved to be extremely useful. Professor Bradshaw has requested that he be kept informed of the progress of our investigation and has provided a number of helpful suggestions concerning the interpretation of our data. A number of papers by himself and theses by his graduate students have proved particularly useful. Professor Bradshaw's expertise in this area is widely recognized.


LIST OF NEW DISCOVERIES OR PATENTS

No specific new discoveries or patents have resulted from any work conducted under this contract.
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