Under this contract research was conducted to examine two aspects of boundary layer flow: (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. 2317.A-41102.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 temperature. 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 these needs.

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 flow 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 turbulent 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 NBS 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 Code. A technical report (Ref. 1) "UTRC R80-91-386-12, 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 R80-91-386-13 "Final Data Report- Vol. 1 - Velocity and Temperature Profile Data for Zero Pressure Gradient, Fully Turbulent Boundary Layers") contains the raw, 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 15 above the low free-stream turbulence skin friction coefficient for the same Re. were measured for a turbulence intensity of 0.1. See Fig. 11 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 is defined as the ratio of turbulence production to free-stream kinetic energy—and presented in Figs. 16–19 as a function of turbulence intensity and length scale of turbulence. For these data are given in Figs. 16 and 17 of Ref. 1, respectively. In addition, Stanton number is given as function of turbulence intensity in Figs. 17 and 18 of Ref. 1. Examination of Figs. 16 and 17 show that for the low free-stream turbulence test case, the 0.8 turbulence case the present data agrees very well with the predicted heat transfer distribution of Haddad and Jones. In addition it can be seen that the local Stanton number increased progressively with increasing turbulence intensity. As an example, for turbulence intensity the measured heat transfer coefficients were approximately 15% greater than the low free-stream turbulence values (see Figs. 16 and 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 growth factors (e.g., C1/CF) are presented as a function of free-stream turbulence intensity in Figs. 16–20. It can be seen that at low turbulence levels the present data tested very well with the results of Refs. 16, 17, and 18. A progressive increase of boundary growth factor with increased turbulence is evident.

4. Although the above effects are primarily a function of the local free-stream turbulence intensity, it has been shown that the turbulence length scale over Figs. 16–20 of Ref. 1 are the momentum thickness with the ram jet in Fig. 22 also shows 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. 26 and 28.

5. The wind tunnel data with three velocity and temperature profiles were observed to be significantly affected with increasing free-stream turbulence. Changes in the skin friction and Stanton numbers have been reported for a range of turbulence intensities, with both wall and freestream turbulence intensity, by B. Brown and R. A. Trimble (Ref. 10). The data Interfered channels were shown to be consistent with the "wall interfered" channel increased in turbulence (1) and (2).

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

\[
\frac{C_f}{C_{f_{0}}} = \text{Const} + 92 \left( \frac{Re_p}{C_{10}} \right)^{0.4} T
\]
Influence of turbulence on heat transfer

\[ \frac{S}{S_{ref}} = 0.98 + 2.5 C \left( \frac{Re_d}{1000} \right) \ \text{T} \]

Influence of turbulence on the Reynolds Analogy Factor

\[ \frac{S}{S_{ref}} = 1 + 0.7 \]

5. The turbulence model of Mcdonald and Kremkovsky 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. 25. The predictions are seen to underestimate the effect of the turbulence for all Re ranges studied.

For topic 12: 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 "d" of the Statement of Work. In addition, in fulfillment of task "e" of the Statement of Work, comparisons were made between the data of task "d" and predictions of the "The Finite-Difference Boundary Layer Code. A technical report (Ref. 11 - "THC Final Report," "Combined Influence of Free-Stream Turbulence and Favorable Pressure Gradient on Transient Boundary Layer Transition and Heat Transfer") was prepared describing the data..." data conducted for topic 12. Reference 11 contains the following data: multi-component free-stream turbulence intensity distributions for all five test cases, freestream number density boundary layer profile and integral property data, momentum and displacement thickness data for all four test cases.

Analysis of the results for topic 12 indicate that the data were accurate and consistent, and that the effects of boundary layer were highly two-dimensional. The free-stream turbulence distribution generated for these tests was shown to be important since it was near the critical turbulence intensity. It is anticipated that these results will provide a second set of fundamental, well documented experimental test cases to which analytically similar boundary layer predictions can be compared. The following results are compiled from the tests conducted for topic 12:...
1. Heat transfer distribution measurements were obtained for five freestream turbulence intensity level 1 test of the present study at acceleration in total of ten flow conditions. These data, measured in the turbulence level with a fixed streamwise acceleration $A = 0.95 \times 10^{-5}$ are presented in Fig. 3.

The heat transfer distribution, presented in Fig. 3 demonstrate the progressive streamwise movement of the transition process with increasing freestream turbulence. At a turbulence level of $A = 0.95 \times 10^{-5}$ the test section was apparently remained turbulent for the entire length of the test section. With increasing turbulence the transition process moved progressively upstream until, for grid $A$, transition began about 3 inches from the plate leading edge. The data of Fig. 3 also indicate that, as would be expected from the results of Table 1, for the fully turbulent region of the various flows the freestream turbulence level increases the heat transfer.

Heat transfer distribution measurements were also obtained at five levels of freestream turbulence and a streamwise acceleration $A = 0.95 \times 10^{-5}$ and $A = 0.95 \times 10^{-5}$ as shown in Fig. 4. For this streamwise acceleration level transition was achieved for the entire test flow length for both the model and model 1 test cases. In addition to grid 2 installed the length of the transition region was much shorter for the more highly accelerated case.

2. Sample velocity profile data obtained for one of the test flow cases $(A = 0.95 \times 10^{-5}$ and $A = 0.95 \times 10^{-5}$ are presented in Fig. 5. These profile data, presented in the universal form in Fig. 6 demonstrate the progressive change from fully turbulent to three-layer boundary layer flow along the test wall. In Fig. 7 the streamwise distribution of the internal boundary layer thicknesses, $\theta'$ and $\theta''$, are presented for all test flow conditions.

The detailed study of the transitional velocity profile data indicates that fully turbulent mean velocity profiles are maintained up to the test length and heat transfer rate. The data indicate that the internal layer profile is established in a shorter length than is necessary for the development of the equilibrium turbulence condition.

Transition rates, based on obtained in the present program, agree very well with results of other that will be used for both zero pressure gradient and accelerating flow. These test results are given for predicting the wall transition position with the common means of freestream turbulence and streamwise acceleration.

The agreement of the 1D Boundary Layer Code indicates that the transitional flow model of Martin and Freilich provides accurate prediction of transitional boundary layer shape factor for cases with a small pressure gradient and freestream turbulent effects. Heat transfer predictions were found to be in excellent agreement.
Figure 1. Influence of Mixing and Free-Stream Turbulence on Heat Transfer and the Reynolds Analogy Factor.
Figure 7: Influence of Free-Stream Turbulence Intensity and $\text{Re}_0$ on Skin Friction and Heat Transfer

\[
T = \sqrt{\frac{1}{3} (u'^2 + v'^2 + w'^2) / U_e \times 100}
\]

\[
\frac{C_l}{C_{l,0}} - 0.98 = \frac{1}{(\text{Re}_0/1000)^{0.4}} \text{Re}_g = \text{CONST}
\]

\[
T = \sqrt{\frac{1}{3} (u'^2 + v'^2 + w'^2) / U_e \times 100}
\]

\[
\text{MEER} \& \text{KREPLIN}
\]

\[
C_l/C_{l,0} = 0.98 + 0.02 \text{Re}_g/1000
\]

\[
\text{SMOOGCH} \& \text{BRAHAM}
\]

\[
\text{SMOOGCH} \& \text{BRAHAM}
\]

\[
\text{SMOOGCH} \& \text{BRAHAM}
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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
Dring, Robert P. - Supervisor, Gas Turbine Technology Group, Gas Dynamics Section

Werle, Michael, J. - Section Chief, Gas Dynamics Section

INTERACTIONS

a. Spoken Papers

1. 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. Consultive 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. He will serve as data evaluator of the Group II-3 Flow Cases - "Effect of Free-Stream Turbulence on Boundary Layers" for the 1980-81 AFOSR-HTM-Stanford Conference on Complex Turbulent Flows: Comparison of Computation and Experiment.

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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