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REVIEW AND ASSESSMENT OF THE HOST TURBINE HEAT TRANSFER PROGRAM

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ABSTRACT

The objectives of the HOST Turbine Heat Transfer subproject were to obtain a better understanding of the physics of the aerothermodynamic phenomena occurring in high-performance gas turbine engines and to assess and improve the analytical methods used to predict the fluid dynamics and heat transfer phenomena. At the time the HOST project was initiated, an across-the-board improvement in turbine design technology was needed. Therefore, a building-block approach was utilized, with research ranging from the study of fundamental phenomena and analytical modeling to experiments in simulated real-engine environments. Experimental research accounted for 75 percent of the project, and analytical efforts accounted for approximately 25 percent. Extensive experimental datasets were created depicting the three-dimensional flow field, high free-stream turbulence, boundary-layer transition, blade tip region heat transfer, film cooling effects in a simulated engine environment, rough-wall cooling enhancement in a rotating passage, and rotor-stator interaction effects. In addition, analytical modeling of these phenomena was initiated using boundary-layer assumptions as well as Navier-Stokes solutions.

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TURBINE HEAT TRANSFER PROGRAM

In the multidisciplinary HOST Project each participating discipline selected its own objective based on the greatest need in that particular area, rather than some common interdisciplinary goal. In Turbine Heat Transfer it was decided, based on evaluations of the type performed by Stepka (1980), that an across-the-board improvement in turbine heat transfer technology was needed. A ratcheting up of the overall technology, a moving from a correlation base to a more analytical base, was identified as the Turbine Heat Transfer Subproject goal. It was also identified that the existing data base was insufficient to support this movement and that increasing both the size and quality of the data base was essential. It was further recognized that HOST alone could not achieve this goal. It was hoped that HOST could be a sufficient catalyst and provide a sufficient forum to make this goal one that all of the partners - government, industry, and universities - would find obtainable and worth pursuing.

Objectives

- **OBTAIN A BETTER UNDERSTANDING OF THE PHYSICS OF THE AEROTHERMODYNAMIC PHENOMENA OCCURRING IN HIGH-PERFORMANCE TURBINES**
- **ASSESS AND IMPROVE THE ANALYTICAL METHODS USED TO PREDICT THE FLOW AND HEAT TRANSFER IN HIGH-PERFORMANCE TURBINES**

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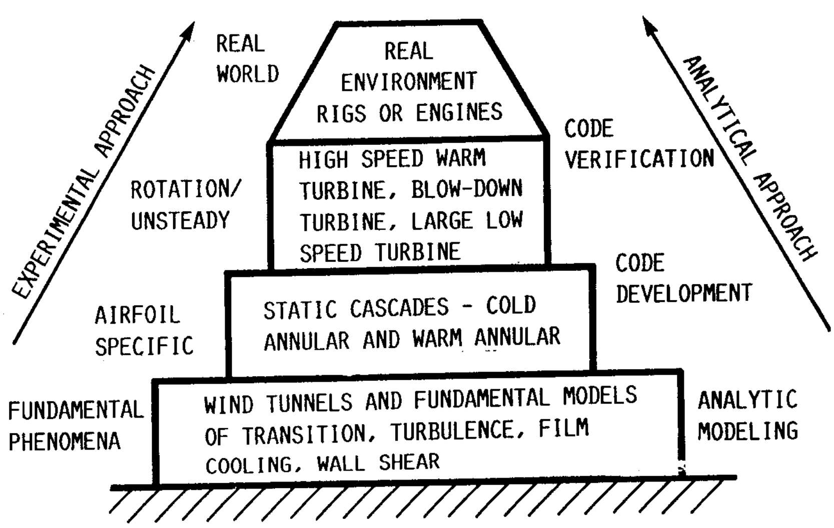
RESEARCH APPROACH

The research program of the Turbine Heat Transfer Subproject was based on the idea that an across-the-board improvement in turbine design was needed. It was also based on an overall philosophy at NASA Lewis Research Center of taking a building block approach to turbine heat transfer. The research for this program ranged from the study of fundamental phenomena and analytical modeling to experiments in real engine environments. Both experimental and analytical research were conducted.



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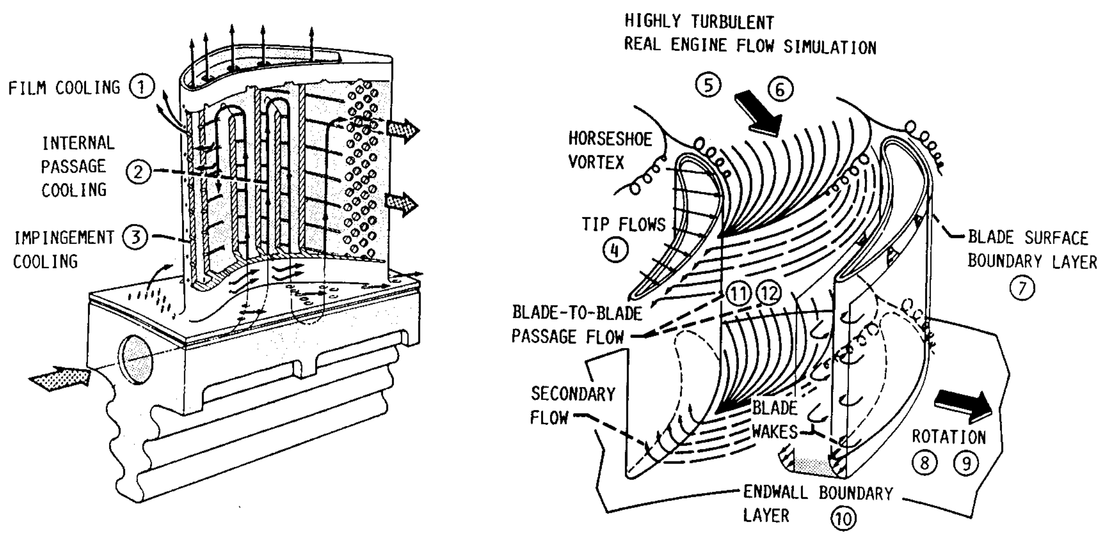
PHYSICAL PHENOMENA INVESTIGATED

The range of phenomena addressed in the Turbine Heat Transfer Subproject are identified by numbers and arrows on the following figure. One can see from this figure that the Turbine Heat Transfer Subproject covered most of the key heat transfer points on the turbine airfoil: film-cooled airfoils, passage curvature, endwall flows, transitioning blade boundary layers, tip regions, and free-stream turbulence on the external surfaces. The subproject included impingement and turbulated serpentine passages on the internal surfaces. In addition, the program broke some new ground. An experiment was conducted which obtained heat transfer data on the surfaces of the airfoils in a large, low-speed one and one-half stage rotating turbine. Another experiment acquired data on the internal turbulated serpentine passages subject to rotation at engine condition levels. Finally, vane heat transfer data were acquired in a real engine type environment behind an actual operating combustor.



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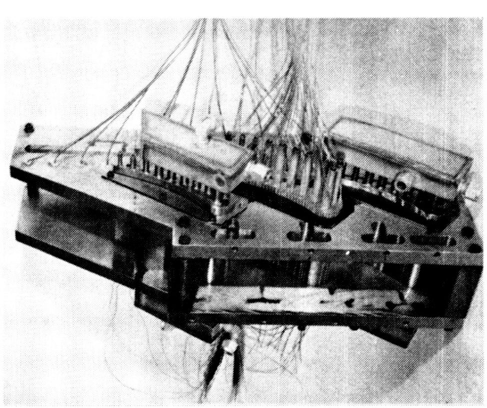
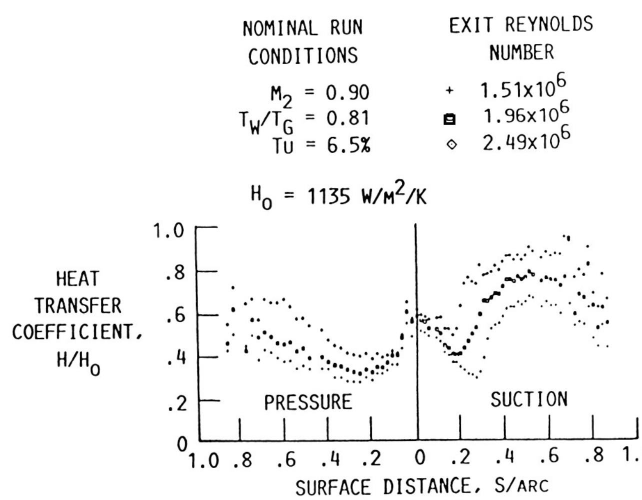
STATOR-AIRFOIL HEAT TRANSFER

One of the initial research efforts was the stator-airfoil heat transfer program performed at the Allison Gas Turbine Division (Nealy et al., 1983; Hylton et al., 1983; Hylton et al., 1988; Nealy et al., 1984; Turner et al., 1985; Yang et al., 1985). This research consisted of determining the effects of Reynolds number, turbulence level, Mach number, temperature ratio, acceleration, and boundary-layer transition on heat transfer coefficients for various airfoil geometries at simulated engine conditions. This research was conducted for non-film-cooled airfoils, showerhead film-cooled designs and showerhead "gill-region" film cooling concepts. Typical results of this research are shown in the following figure. A typical cascade configuration is shown in the photograph (fig. (a)). Two-dimensional midspan heat transfer coefficients and static pressure distributions were measured on the central airfoil of the three-vane cascade. Non-film-cooled data are shown in figure (b), where the boundary-layer transition is clearly identified as a function of Reynolds number on the suction surface. Figure (c) shows the effect on heat transfer in the downstream recovery region to the addition of showerhead film cooling. Data are presented as Stanton number reductions. A detrimental effect is noted in the boundary-layer transition region of the suction surface to the addition mass at the leading edge. Figure (d) shows a strong dependence on "gill-region" film cooling, which is consistent with experience. However, when combining showerhead with "gill-region" film cooling, more mass addition is not always better as indicated by the Stanton number reduction data on the pressure surface. This is a very extensive dataset which systematically shows the important effects of modern film cooling schemes on modern airfoils. It went beyond the traditional effectiveness correlations to provide actual heat transfer data. It should provide a valuable baseline for emerging analysis codes.

(A) THREE-VANE CASCADE



(B) NONFILM-COOLED AIRFOIL HEAT TRANSFER COEFFICIENTS



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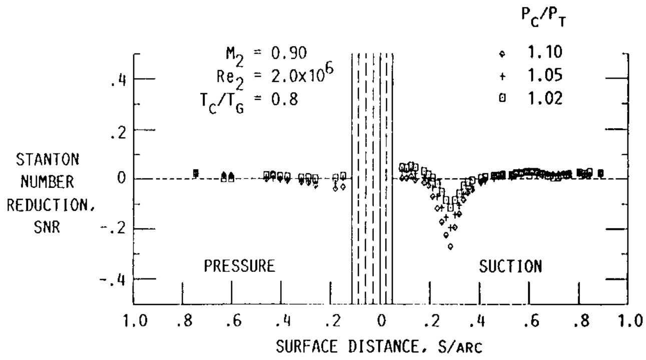
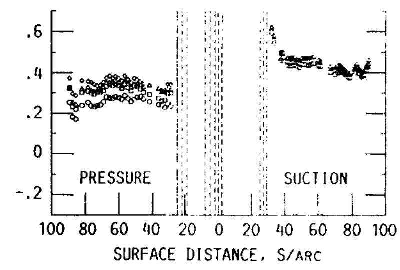
(C) INFLUENCE OF LEADING EDGE FILM-COOLING ON HEAT TRANSFER



(D) COMBINED LEADING EDGE AND DOWN-STREAM FILM-COOLING

DATA	M_2	Re_2	$P_{C,DS}/P_T$	$P_{C,LE}/P_T$	T_W/T_G
BASE	0.75	2.00E6			
○	.75	2.05E6	1.10	1.10	0.67
△	.74	2.00E6	1.10	1.05	.65
◇	.75	2.01E6	1.10	1.02	.65
□	.75	2.00E6	1.10	1.00	.66



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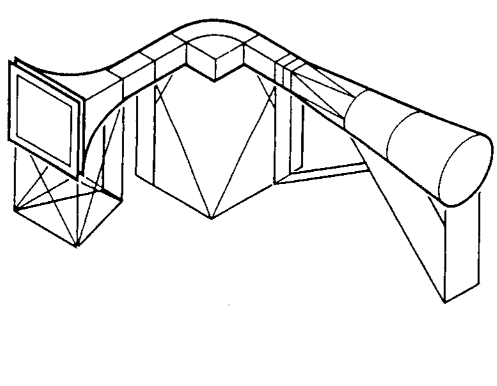
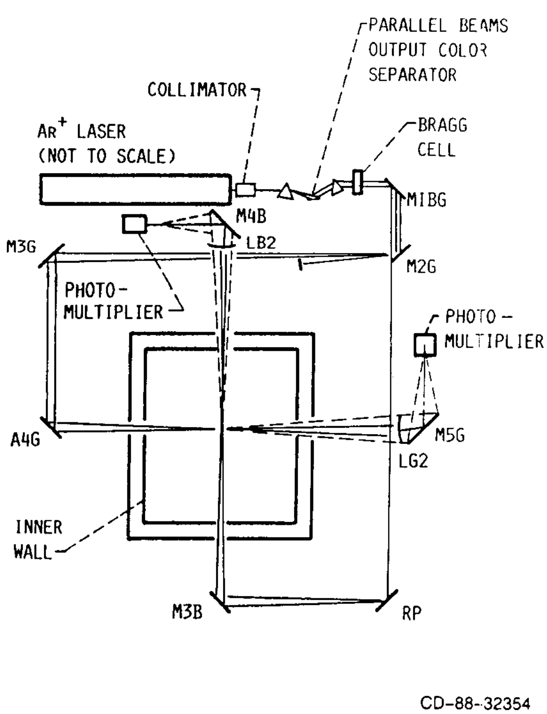
THREE-DIMENSIONAL FLOW FIELD IN CURVED PASSAGES

An investigation of secondary flow phenomena in a 90° curved duct was conducted at the University of Tennessee Space Institute (Crawford et al., 1985). The curved duct was used to represent airfoil passage curvature without the complexity of the horseshoe vortex. These data consist of simultaneous three-dimensional mean value and fluctuating components of velocity through the duct, and they compliment similar data in the literature. A schematic of the test facility and the three-dimensional laser velocimeter are shown in the following figure. The first phase of the research examined flows with a relatively thin inlet boundary layer and low free-stream turbulence. The second phase studied a thicker inlet boundary layer and higher free-stream turbulence. Typical experimental results of this research are also shown in this figure. The vector plot of cross-flow velocities clearly shows the development of a vortex in the duct corner near the low pressure surface. The University of Tennessee Space Institute also developed a three-dimensional viscous flow analysis capability for the curved duct experiment utilizing the P.D. Thomas code (Thomas, 1979) as a base. Some analytical results from this code are shown where a vector plot of the cross-flow velocities is compared with the experiment. In addition, a stream sheet is shown as it propagates through the duct and is twisted and stretched. Additional comparisons of analysis and experiment show that the thin turbulent boundary-layer results of this experiment are difficult to calculate with current turbulence models.

CURVED-DUCT FACILITY



3-D LV OPTICAL SYSTEM



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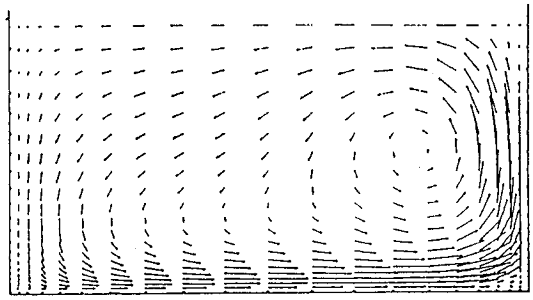
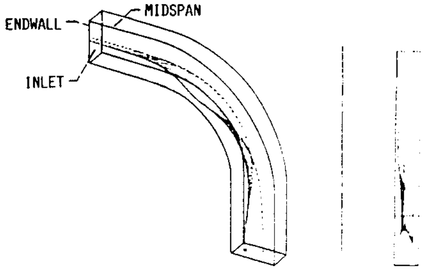
ANALYTICAL RESULTS

DUCT CROSS-FLOW PLOT P.D. THOMAS CODE

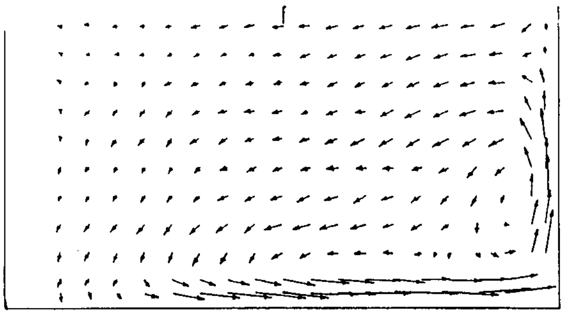


STREAM SHEET VELOCITY PATTERN THROUGH DUCT



EXPERIMENTAL RESULTS

LOW REYNOLDS NUMBER DATA



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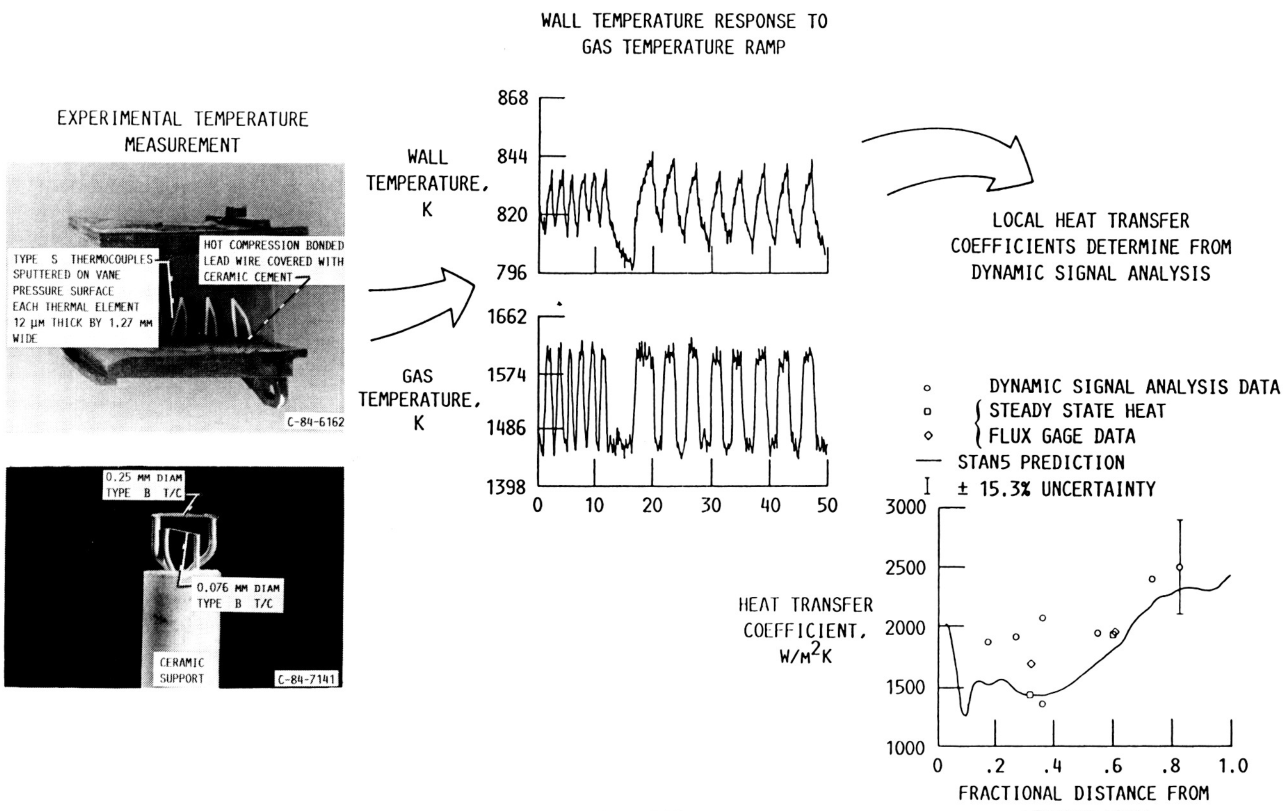
HEAT TRANSFER COEFFICIENTS IN REAL-ENGINE ENVIRONMENT

Two experiments were also conducted at NASA Lewis in the high-pressure facility (Gladden et al., 1985; Gladden and Proctor, 1985; Gladden et al., 1987; Hippensteele et al., 1985). This facility was capable of testing a full-sized single-stage turbine at simulated real-engine conditions. The tests, however, were limited to combined combustor-stator experiments. One experiment examined full-coverage film-cooled stator airfoils, whereas the second experiment utilized some of the advanced instrumentation developed under the instrumentation subproject. A comparison of experimental airfoil temperatures with temperatures obtained from a typical design system showed substantial differences for the full-coverage, film-cooled airfoils and suggests that models derived from low-temperature experiments are inadequate for real-engine conditions. The advanced instrumentation tests demonstrated the capability and the challenges of measuring heat flux and time-resolved gas temperature fluctuation in a real-engine environment.

Typical results are shown in the following figure for thin film thermocouples. The dynamic gas temperature probe tested a simulated real-engine condition. A comparison is made between steady state heat flux measurements and those determined from dynamic signal analysis techniques.



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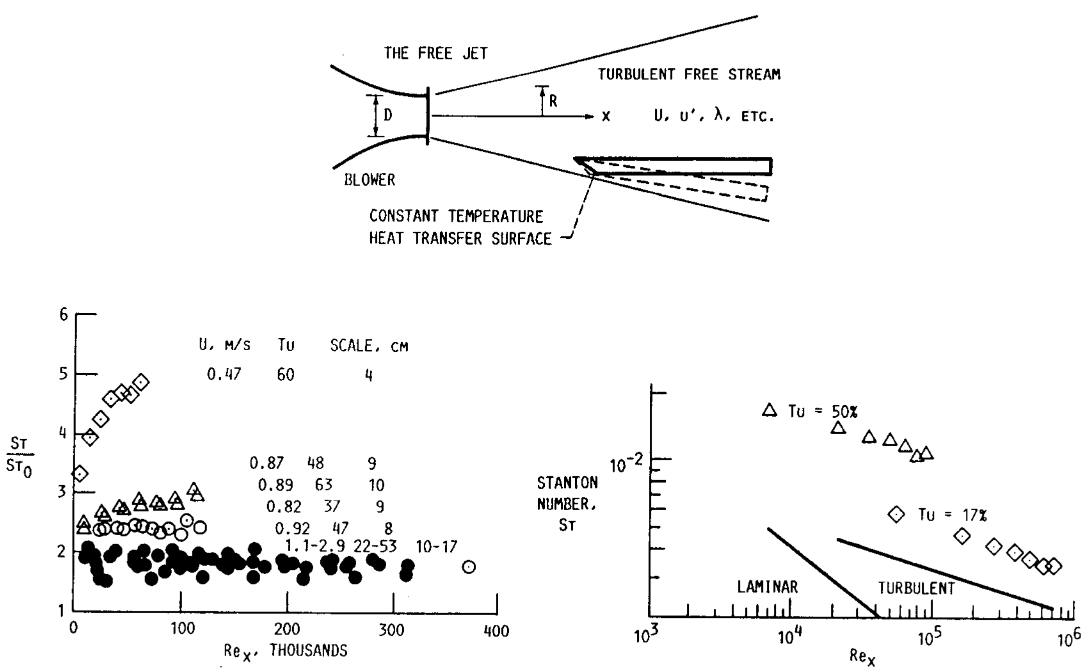
HIGH FREE-STREAM TURBULENCE EFFECTS

Stanford University has conducted a systematic study of the physical phenomena that affect heat transfer in turbine airfoil passages. Their recent experimental research has been concerned with high free-stream turbulence intensity and a large turbulence scale that might be representative of combustor exit phenomena. A schematic of their free jet test facility and typical results are shown in this figure. Data are measured on a constant temperature flat plate located at a specified radial and axial distance from the jet exit centerline. These data, presented as Stanton number ratios, indicate that heat transfer augmentation can be as high as 5X at a high value of free-stream turbulence intensity but only 3X if the length scale is changed. These results suggest that the designer must know a great deal more about the aerodynamic behavior of the flow field in order to successfully predict the thermal performance of the turbine components.



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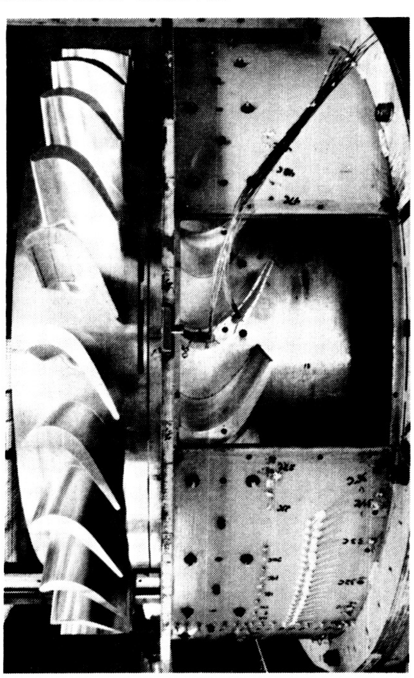
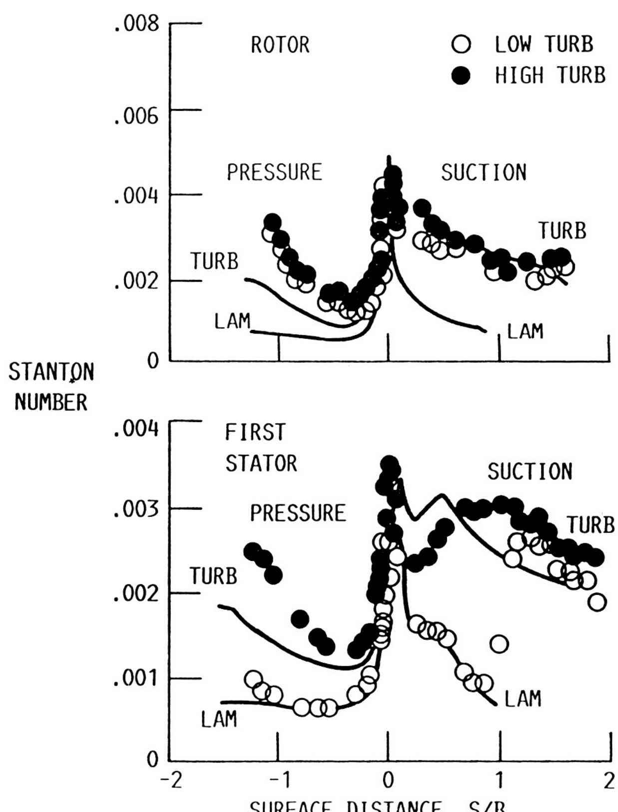
In the rotating reference frame, experimental aerodynamic and heat transfer measurements were made in the large, low-speed turbine at the United Technologies Research Center (Dring et al., 1986a; Dring et al., 1986b; Dring et al., 1986c; Dring et al., 1987; Blair et al., 1988a; Blair et al., 1988b). Single-stage data with both high and low-inlet turbulence were taken in phase I. The second phase examined a one and one-half stage turbine and focused on the second vane row. Under phase III, aerodynamic quantities such as interrow time-averaged and rms values of velocity, flow angle, inlet turbulence, and surface pressure distributions were measured. A photograph of the test facility is shown in the following figure. Typical heat transfer data for both the first stator and rotor are also shown. These data show that an increase of inlet turbulence has a substantial impact on the first stator heat transfer. However, the impact on the rotor heat transfer is minimal. These data are also compared with Stanton numbers calculated by a boundary-layer code and the assumption that the boundary layer was either laminar (LAM) or fully turbulent (TURB). These assumptions generally bracketed the data on the suction surface of both the stator and the rotor. However, the heat transfer on the pressure surface, especially for the high-turbulence case, was generally above even fully turbulent levels on both airfoils. Pressure surfaces have traditionally received less attention than suction surfaces. The high heat transfer on the pressure surface is not readily explainable and calls for additional research, especially modeling, on pressure surfaces.

LARGE-SCALE ROTATING RIG 1-1/2 STAGE TURBINE CONFIGURATION FIRST VANE AND ROTOR CASE REMOVED



HIGH REYNOLD'S NUMBER: 65-PERCENT GAP



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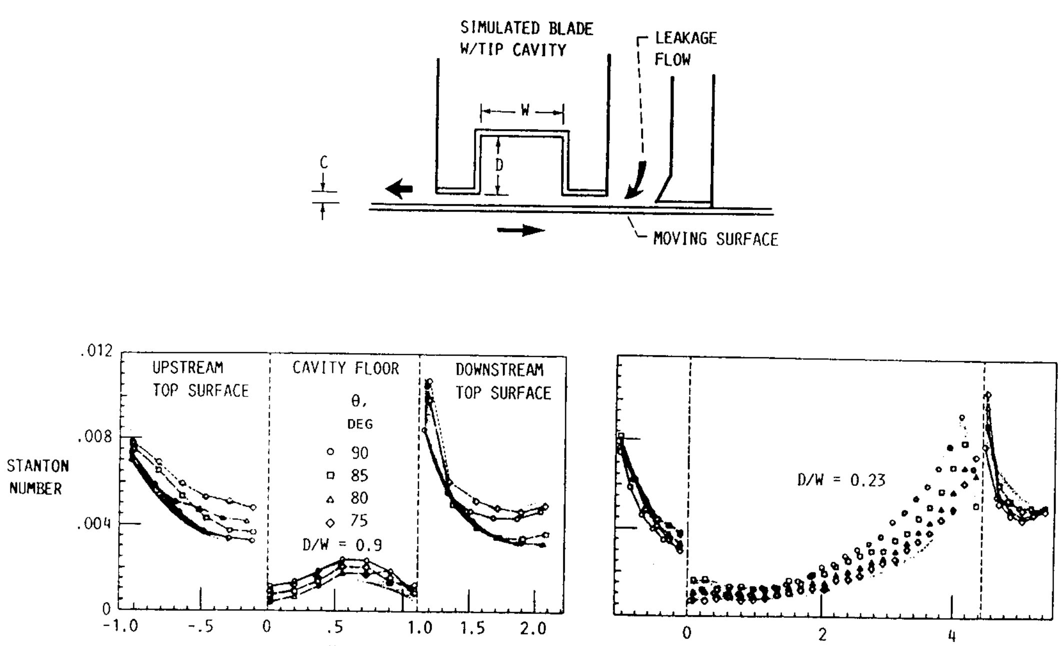
TIP REGION HEAT TRANSFER

The tip region of rotor blades is often a critical region and an area that suffers substantial damage from the high-temperature environment. Arizona State University has experimentally modeled the blade tip cavity region and determined heat transfer rates by a mass transfer analogy with naphthylene (Chyu et al., 1987). A schematic of the test is shown in the following figure.

The blade tip cavity is a stationary model and the relative velocity of the shroud is represented by a moving surface at a specified gap spacing from the blade. Stanton number results for two different cavity aspect ratios are also shown. The heat transfer on the surfaces next to the shroud are little changed by the aspect ratio, which is not surprising. However, the heat transfer to the floor of the cavity is increased significantly on the downstream portion at the lower aspect ratio. Also shown in the figures is the flow angle effect on heat transfer. Because the airfoil turns at the tip, the cavity will be at different angles of attack to the mean crossflow direction. The data shows a minimal effect at an aspect ratio of 0.9 and a substantial effect at an aspect ratio of 0.23. This dataset is really quite a new addition to a traditionally neglected area and shows that with careful datasets and analyses one can obtain an optimal design for tip cavities.



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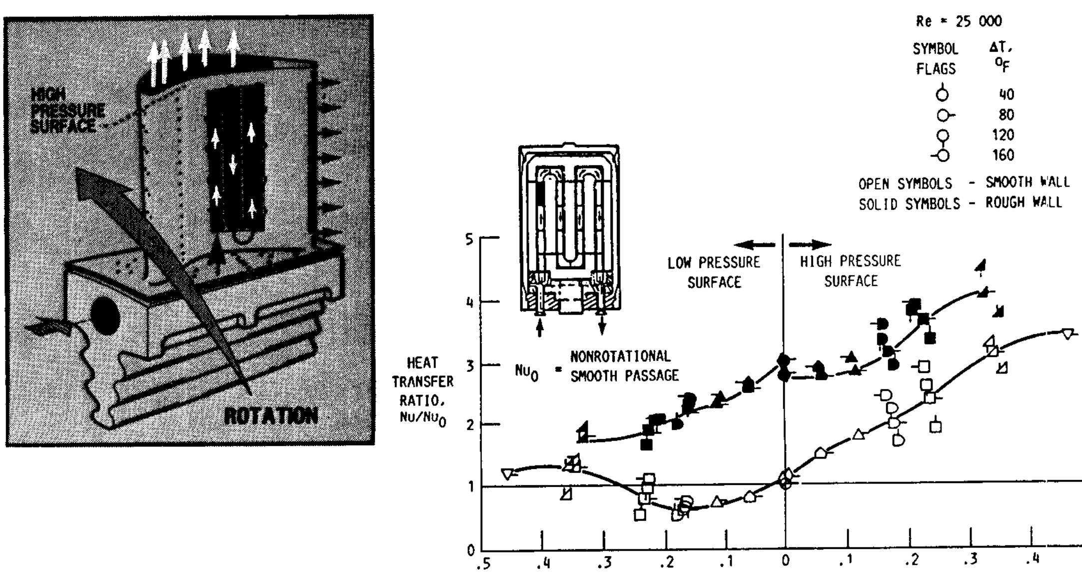
ROUGH-WALL HEAT TRANSFER WITH ROTATION

Coolant passage heat-transfer and flow measurements in a rotating reference frame were also obtained at Pratt & Whitney Aircraft/United Technologies Research Center (Kopper, 1984; Sturgess and Datta, 1987; Lord et al., 1987). Experimental data were obtained for smooth-wall serpentine passages and for serpentine passages with skewed and normal turbulators. The flow and rotation conditions were typical of those found in actual engines. This was a very realistic experiment. Data for both the smooth-wall and skewed turbulator passages are shown in this figure for radial outflow, representing only a tiny fraction of the total data involved in this very complex flow. Both datasets are shown correlated with the rotation number except for high rotation numbers on the high pressure surface. This is an area that requires additional research to understand and model the physical phenomena occurring in these passages.



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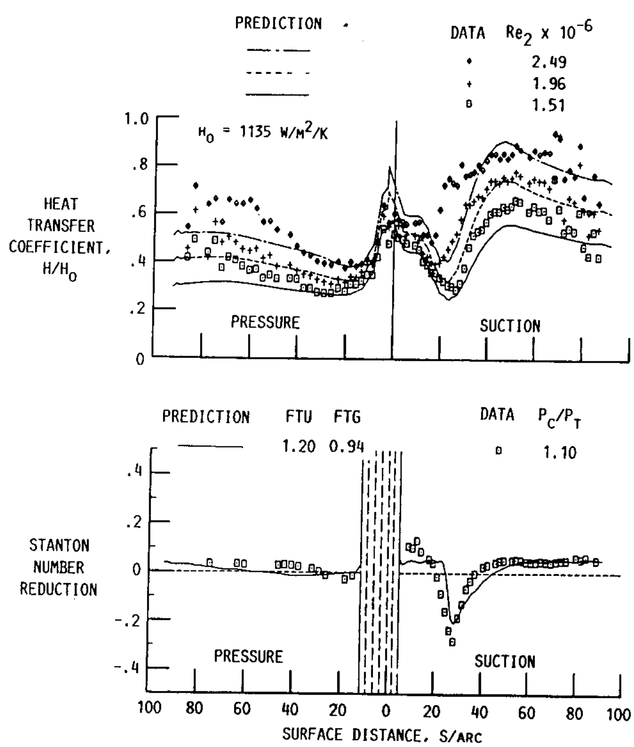
BOUNDARY-LAYER ANALYSIS

The STAN5 boundary-layer code (Crawford and Kay, 1976) (which was developed on NASA contract at Stanford University in the mid-1970's) was modified by Allison Gas Turbine Division to define starting points and transition length of turbulent flow to accommodate their data, with and without film cooling, as well as data in the literature. Specific recommendations were made to improve turbine airfoil heat transfer modeling used in the boundary-layer analysis. These recommendations address the boundary conditions, the initial condition specification, including both velocity and thermal profiles, and modifications of conventional zero-order turbulence models. The results of these improvements are shown in the following figure, where the start of transition and its extent on the suction surface are reasonably well characterized. For the case of showerhead film cooling, two empirical coefficients were used to modify the free-stream turbulence intensity and the gas stream enthalpy boundary conditions and to permit a representative prediction of the Stanton number reduction in the recovery region. Boundary-layer methods can be used for midspan analysis; however they require a realistic data base to provide the coefficients needed for proper reference.



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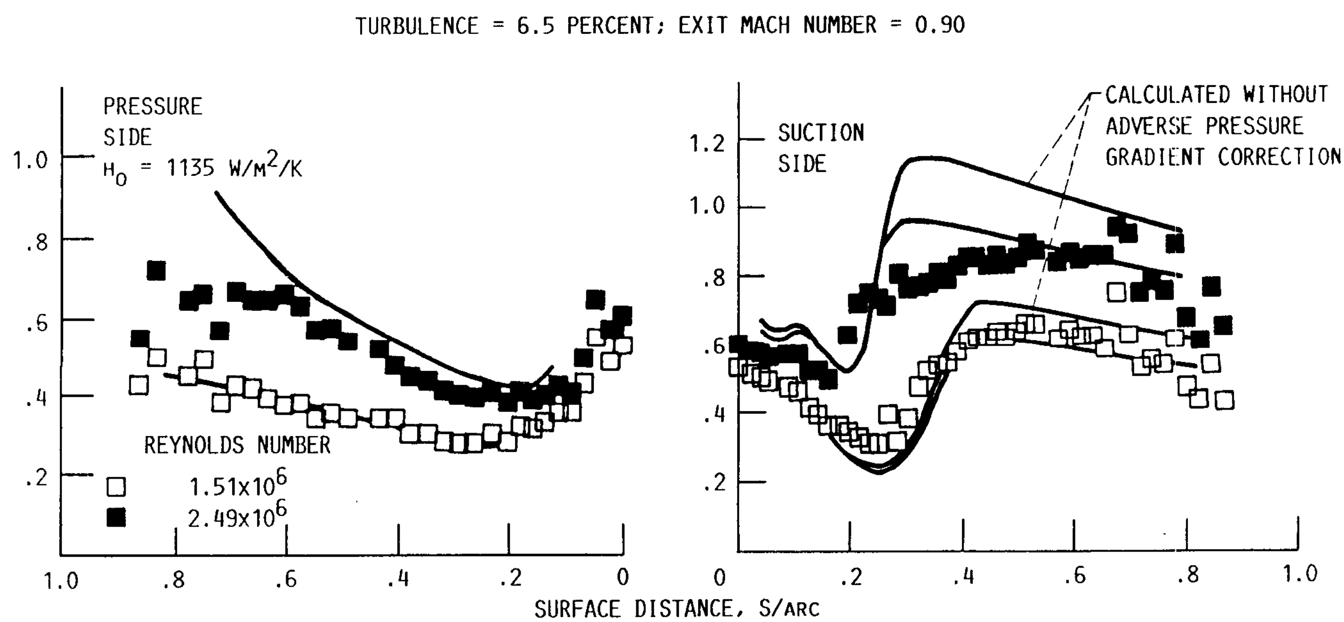
TURBULENCE MODELING

A fundamental study on numerical turbulence modeling, directed specifically at the airfoil in the turbine environment, was conducted at the University of Minnesota. A modified form of the Lam-Bremhorst low-Reynolds-number k-e turbulence model was developed to predict transitional boundary-layer flows under conditions characteristic of gas turbine blades (Schmidt and Patankar, 1987) including both free-stream turbulence and pressure gradients.

The purpose was to extend previous work on turbulence modeling to apply the model to transitional flows with both free-stream turbulence and pressure gradients. The results of the effort are compared with the experimental data of Allison Gas Turbine Division. The augmentation of heat transfer on the pressure surface over the fully turbulent value is predicted reasonably well. In addition, when an adverse pressure gradient correction is used, the suction surface heat transfer data is also predicted reasonably well.

This research established a methodology for moving away from the heavy dependence on empirical constants. Although boundary-layer methods will never solve the whole problem, they will always remain important analytic tools.



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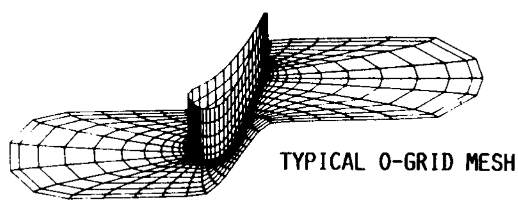
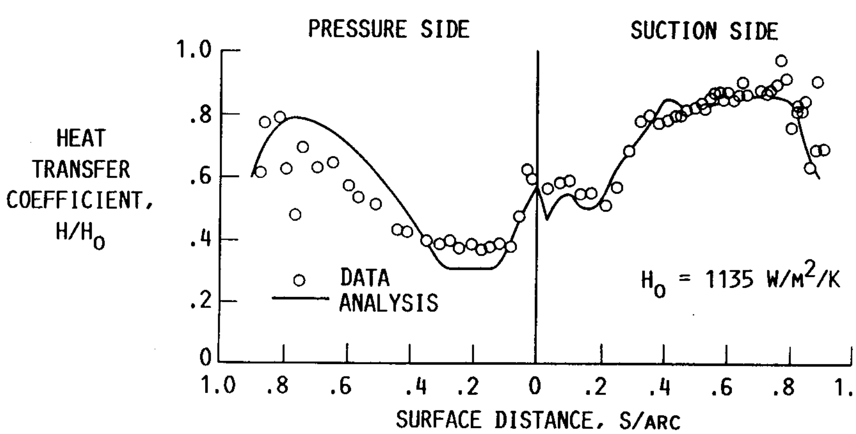
VISCOUS FLOW ANALYSIS

A fully elliptic, three-dimensional Navier-Stokes code has been under development at Scientific Research Associates (SRA) for many years. This code was primarily directed at inlets and nozzles. SRA, Inc., has modified the code for turbine applications (Weinberg et al., 1985). This includes grid work for turbine airfoils, adding an energy equation and turbulence modeling, and improved user friendliness. The heat transfer predictions from the MINT code are shown compared to the data from the Allison Gas Turbine research. The analytical-experimental data comparison is good, however, the location of boundary-layer transition was specified for the analytical solution.





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LOOK TO THE FUTURE

Many recent studies have been made to assess aeropropulsion technology requirements into the 21st century. The consensus seems to suggest that significant technology advances are required to meet the goals of the future. Whether the goals are high-speed sustained flight vehicle, single-stage-to-orbit transport, or subsonic transport, the issues for the designer are improved fuel efficiency, high thrust-to-weight ratio vehicle, improved component performance while maintaining component durability, and reduced operating and maintenance costs. These issues will only serve to increase the opportunities available to the researcher in aerothermal loads and structures analysis. The verifiable predictions of unsteady flowfields with significant secondary flow phenomena and coupled thermal-velocity profiles is a fertile research area. Very little progress has been made to date in applying CFD techniques to the intricate and complex coolant channels required in the hot-section components. With the expected advances in high-temperature materials, the components with significant aerothermal loads problems will expand beyond the airfoils and combustor liners to shrouds, rims, seals, bearings, compressor blading, ducting, nozzles, and other turbine components. The issues to be addressed and the technology advances required to provide the aeropropulsion systems of the 21st century are quite challenging.

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