REVIEW AND ASSESSMENT OF THE DATABASE AND NUMERICAL MODELING FOR TURBINE HEAT TRANSFER

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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 and to assess and improve the analytical methods used to predict the flow and heat transfer in high-temperature gas turbines. At the time the HOST project was initiated, an across-the-board improvement in turbine design technology was needed. A building-block approach was utilized and the research ranged from the study of fundamental phenomena and modeling to experiments in simulated real engine environments. Experimental research accounted for approximately 75 percent of the funding while the analytical efforts were approximately 25 percent. A healthy government/industry/university partnership, with industry providing almost half of the research, was created to advance the turbine heat transfer design technology base.

NOMENCLATURE

- $B_x$: airfoil axial chord
- $C$: blade tip gap
- $C_X$: axial flow speed
- $D$: jet diameter/blade tip cavity depth
- $d$: coolant channel hydraulic diameter
- $H$: heat transfer coefficient
- $H_o$: reference heat transfer coefficient
- $M_2$: stator exit Mach number
- $Nu$: Nusselt number
- $Nu_o$: reference Nusselt number
- $P_C$: coolant pressure
- $P_t$: gas stream pressure
- $R$: radius
- $Re_2$: stator exit Reynolds number
- $Re_X$: local Reynolds number
- $T_C$: coolant temperature
- $T_G$: gas stream temperature
- $T_w$: airfoil temperature
- $Tu$: turbulence intensity
- $S$: surface distance
- $St$: Stanton number
- $St_o$: reference Stanton number
- $U$: gas stream velocity
- $U_m$: rotor wheel speed
- $U_w$: moving surface velocity
- $u'$: instantaneous velocity
- $V$: coolant velocity
- $W$: blade tip cavity width
- $X$: axial length
- $\theta$: angle between mean velocity and major tip cavity axis
- $\lambda$: length scale
- $\Omega$: rotational velocity
INTRODUCTION

Improved performance of aircraft gas turbine engines is typically accompanied by increased cycle pressure ratio and combustor exit gas temperature. The hot-section components of these turbojet/turbofan engines are subjected to severe aerothermal loads during the mission flight profile. Meeting the design goals of high cycle efficiency, increased durability of the hot-section components, and lower operating costs requires a multidisciplinary approach. Turbine Heat Transfer was one of the six disciplines addressed in the multidisciplinary Hot Section Technology (HOST) Project.

When the HOST Project was originally being planned, Stepka (1980), one of the originators of the project, performed an uncertainty analysis on the ability to predict turbine airfoil temperatures. He estimated that the current ability to predict metal temperature in an operating engine was within 100 K and that by testing prototypes this could be refined to within 50 K. He also suggested that the uncertainty in heat flux was on the order of 100 K. These levels of uncertainty in metal temperature can contribute to an order of magnitude uncertainty in component life.

A typical cooled aircraft gas turbine blade is illustrated in Fig. 1, showing the intricate internal flow passages and the variety of heat transfer mechanisms at work. These include: impingement cooling, serpentine passages with turbulator surfaces, and pin fins, all in very short (i.e., entrance length) distances and subject to strong rotational forces. In addition, since most blades are film cooled, the internal mass balance is a variable. The complexity of the external flow field over the turbine blade is illustrated in Fig. 2. Heat transfer in the external flow field is characterized by: high Reynolds number forced convection with rotation, high free-stream turbulence, strong pressure and temperature gradients, surface curvature, and an unsteady flow field. In addition, most important, the internal and external surface heat transfer coefficients are coupled through the metal walls. In fact, the turbine airfoil is a very compact, very complex, and very efficient heat exchanger. This feature is particularly important in a durability program, such as HOST, where the real focus is on the thermal stresses and fatigue of the airfoil.

Thus, in the HOST Turbine Heat Transfer Subproject it was important to conduct research attention to both the internal and external surfaces of the turbine airfoil.

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 increasing both the size and quality of the data base was essential. It was further recognized that HOST could not address this goal alone, that HOST could be a sufficient catalyst and provided a sufficient forum to make this goal one that all of the partners; government, industry and universities; would find obtainable and worth pursuing.

This paper outlines the program directed at these goals. The paper will delineate progress towards the goals by reporting example results from each of the various research activities. It will summarize the major accomplishments and will make some observations on future needs.

TURBINE HEAT TRANSFER SUBPROJECT

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 of developing a new reference approach to turbine heat transfer, as shown in Fig. 3. The research was focused on modeling fundamental phenomena and exploring the effects of various research activities. The research program covered most of the research activities. It will summarize the major accomplishments and will make some observations on future needs.

EXPRESSMENTAL DATABASE

The experimental part of the Turbine Heat Transfer Subproject consisted of six (6) large experiments and three (3) of somewhat more modest scope and was structured to address the phenomena identified in Figs. 1 and 2. The majority of the large experiments were conducted in a stationary frame of reference and three (3) were conducted in a rotating frame of reference.

Stationary Reference

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; 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...
gas temperature fluctuation in a real-engine
environment subproject. A comparison of experimental air-
flows with a relatively thin inlet boundary layer and
thicker inlet boundary layer and higher free-stream tur-
bulence. Typical experimental results of this research
are shown in Fig. 5. A typical cascade configuration is shown in the photograph (Fig. 5(a)).
Two-dimensional midspan heat transfer coefficients and static pressure distributions were measured on the cen-
tral airfoil of the three-vane cascade. Nonfilm-cooled data are shown in Fig. 5(b) where the boundary layer
transition is clearly identified as a function of Reynolds number on the suction surface. Figure 5(c)
shows the effect on heat transfer in the downstream
recovery region to the addition of showerhead film cool-
ing. Data are presented as a Stanton number reduction.
A detrimental effect is noted in the boundary layer
transition region of the suction surface to the addition
mass at the leading edge. Figure 5(d) shows a strong
dependence on "gill-region" film cooling which is con-
sistent with experience. However, when combining
showerhead with gill-region film cooling more mass addi-
tion 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 mod-
ern airfoils. It went beyond the traditional effective-
ness correlations to provide actual heat transfer data. It
should provide a valuable baseline for emerging anal-
ysis codes.

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 utilized to represent airfoil passage
curvature without the complexity of the horseshoe
vortex. These data consist of simultaneous three-
dimensional mean and fluctuating components of
velocity through the duct and compliment similar data
in the literature. A schematic of the test facility
and the three-dimensional laser velocimeter are shown
in Fig. 6. 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 tur-
bulence. Typical experimental results of this research
are shown in Fig. 6. The vector plot of cross-flow vel-
ocities clearly shows the development of a vortex in the
duct corner near the low pressure surface. The analyt-
cal results will be mentioned in the Viscous Flow
Analysis section. These data provide a comprehensive
benchmark to verify codes at realistic flow conditions.

Two experiments were also conducted at NASA Lewis
in the high-pressure facility (Gladden et al., 1985a;
Gladden et al., 1985b; Gladden et al., 1987; Hippen-
steile et al., 1985). This facility was capable of
testing a full-sized single-stage turbine at simulated
real engine conditions. The tests, however, were lim-
ited to combined combustor/stator experiments. One
experiment examined full-coverage film-cooled stator
airfoils, while the second experiment utilized some of
the advanced instrumentation developed under the instru-
mentation subproject. A comparison of experimental air-
foil 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-turbulence 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 Fig. 7 for thin film
thermocouples and 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

Stanford University has conducted a systematic
study of the physical phenomena that affect heat trans-
fer in turbine airfoil passages. Their recent experi-
mental research has been concerned with high free-stream
turbulence and high Reynolds number. One of the
most significant findings was that turbulent film cooling
is inefficient with high turbulence intensity and large scale. This
might be representative of combustor exit phenomena. A
schematic of their free jet test facility and typical
results are shown in Fig. 8. Data are measured on a
custom temperature flat plate located at a specified
eradial 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.

Prior to the advent of the HOST program, Arizona
State University was pursuing a systematic study of
impingement heat transfer with cross-flow characteristic of
turbine airfoil cooling schemes. The work was ini-
tially sponsored by the NASA Lewis grant and was
subsequently funded by the HOST program. The results of this
research are summarized in Florschuetz et al. (1982a),
Florschuetz et al. (1982b), Florschuetz et al. (1982c),
Florschuetz et al. (1983), Richards et al. (1984),
Florschuetz et al. (1984), Florschuetz et al. (1987),
Florschuetz et al. (1985), Florschuetz et al. (1984).
In addition to the many transfer correlation experiments,
this research also investigated the effects of various jet-
flow to crossflow ratios and differences between the
jet-flow and the cross-flow temperature. Correlatfons
were developed for both inline rows of impingement jets
and staggered arrays of jets but without an initial
cross-flow. The effects of cross-flow and temperature
differences were then determined relative to the base
correlations.

Rotating Reference
In the rotating reference frame, experimental aero-
dynamic and heat transfer measurements were made in the
large, low-speed turbine at the United Technologies
Research Center (Dring et al., 1987; Dring et al.,
1986a; Dring et al., 1986b; Dring et al., 1986c; Blair
et al., 1988; Blair et al., 1988). 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 II 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
Fig. 9. 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
ANALYTICAL TOOLS

The analytic parts of the turbine heat transfer subproject are characterized by efforts to adapt existing codes and analyses to turbine heat transfer. In general, these codes and analyses were well established before HOST became involved; however, the applications were restricted to simple geometries. The results of this effort indicate that the code is qualitatively adequate for simple geometries. For more complex cases, more work is required.

Boundary Layer Analysis

The STANS boundary layer code (Crawford et al., 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 are made to improve turbine airfoil heat transfer modeling utilizing a boundary layer analysis. These recommendations address the boundary conditions, initial condition specification, and modifications of conventional zero order turbulence models. The results of these improvements are shown in Fig. 12 where the start of transition and its extent on the suction surface are reasonably well characterized. For the case of shower head film cooling, two empirical coefficients were utilized to modify the free-stream turbulence intensity and the gas stream enthalpy boundary conditions and 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.

In another boundary layer code effort United Technologies Research Center assessed the applicability of its three-dimensional boundary layer code to calculate heat transfer total pressure loss and streamline flow patterns in turbine passages. The results indicate a strong pressure gradient on the suction surface over the fully turbulent value is predicted reasonably well. In addition, an adverse pressure gradient correction is utilized, the suction surface heat transfer data is also predicted reasonably well.

Finally, 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-Brehmhorst low-Reynolds-number k-e turbulence model was developed to predict transitional boundary layer flows under conditions characteristic of gas turbine blades (Schmidt et al., 1987) including both free-stream turbulence and pressure gradient.

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 in Fig. 13. 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 utilized, the suction surface heat transfer data is also predicted reasonably well.

This was a reasonably good beginning to establishing 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.

Viscous Flow Analysis

The three-dimensional Navier-Stokes TEACH code has been modified by Pratt & Whitney for application to internal passages and to incorporate rotational terms. The modified code has been delivered to NASA Lewis and testing is ongoing. The geometric model is currently being made for internal passages. The results of this effort indicate that the code is qualitatively adequate for simple geometries. For geometries of practical interest, much work remains to be done to bring the internal passage computational codes up to the level of proficiency of the free-stream codes. For the external airfoil surface important analytic progress is being made. However, the model for internal passages is still primitive. The internal problem is substantially more complex.

A fully elliptic three-dimensional Navier-Stokes code has been under development at Scientific Research
with both free-stream turbulence and pressure gradients. The heat transfer predictions from the MINT code are shown in Fig. 14 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 calculation.

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 in Fig. 6 where a vector plot of the cross-flow velocities are 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.

CONCLUDING REMARKS

Since this paper is an overview of the Turbine Heat Transfer aspects of the HOST program it has been presented as a cataloging and summarizing of the various activities. More importantly, the HOST program should be viewed as a catalyst bringing together the gas turbine community and building a technology momentum to carry advanced propulsion systems into the future. Specifically, the HOST Turbine Heat Transfer Subproject can point to the following accomplishments.

1. The impact of axial spacing and inlet turbulence on heat transfer and aerodynamics throughout the stator-rotor-stator of a stage and one-half axial turbine was measured. High-turbulence and post-transitional effects on the pressure surface of both stator and rotor can cause the Stanton number to be greater than the fully turbulent value.

2. Reynolds number, Mach number, curvature, and wall-to-gas temperature effects on boundary layer transition and heat transfer were determined for a stator airfoil.

3. Showerhead and "gill-region" film-cooling were shown to have both beneficial and adverse effects on the recovery region heat transfer at simulated engine conditions which depended on specific operating conditions.

4. Heat Transfer in both smooth-wall and turbulated-wall serpentine rotating coolant passages were correlated with a rotation number for the low-pressure surface. The high-pressure surface heat transfer was not well correlated.

5. Blade tip cavity heat transfer was shown to be strongly dependent on the cavity aspect ratio and angle-of-attack to blade tip flow direction.

6. Heat transfer measurements in high-turbulence intensity flow fields, simulating combustor exit phenomena, shows augmentation rates of 3X to 5X depending on the length scale of the turbulence.

7. Improved definition of the initial conditions and boundary conditions which are applicable to turbine airfoils was successful in improving the prediction of airflow heat transfer for a wide range of geometries using the STANS boundary layer code.

8. The Lam-Bremhorst low-Reynolds number k-e turbulence model was modified to also improve the predictions of airflow heat transfer under transitional flows with both free-stream turbulence and pressure gradients.

9. A fully elliptic Navier-Stokes code was developed for turbine airfoils and includes turbulence modeling, an energy equation and improved user friendliness. Propulsion predictions for hypersonic vehicles where the overall thermal management and design of the vehicle and the propulsion system become an integrated interactive entity. We now have, or are developing, tremendous analytical capabilities with which one can attack these very complex technology issues.

LOOK TO THE FUTURE

Many recent studies have been made to assess the 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, single-stage-to-orbit or subsonic transport, the issues for the designer are improved fuel efficiency, high thrust-to-weight, 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, etc. The issues to be addressed and the technology advances required to provide the aeropropulsion systems of the 21st century are quite challenging.

REFERENCES


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\(^a\)Experiment and analysis in the same contract.
\(^b\)Work done under two separate contracts.

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FIGURE 1. - TYPICAL COOLED AIRCRAFT GAS TURBINE BLADE. SEE TABLE I FOR DESCRIPTION OF NUMBERED FLOW PHENOMENA.

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CURVED-DUCT FACILITY

3-D LV OPTICAL SYSTEM

DUCT CROSS-FLOW PLOT P.D. THOMAS CODE
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Lewis Research Center.
THE FREE JET
TURBULENT FREE STREAM

BLower

CONSTANT TEMPERATURE
HEAT TRANSFER SURFACE

U, W/S
Tu SCALE, CM

0.47 60 4
0.87 48 9
0.89 63 10
0.82 37 9
0.92 47 8
1.1-1.2 22-53 10-17

Rex, THOUSANDS

ST/ST0

ST

Tu = 50%

Tu = 17%

LAMINAR
TURBULENT

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STANTON NUMBER

UPSTREAM CAVITY FLOOR

LEAKAGE FLOW

MOVING SURFACE

STANTON NUMBER

HIGH REYNOLDS NUMBER SIMULATED GAP, C2 = 0.74
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CD-87-29102

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