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PROGRESS TOWARDS UNDERSTANDING AND PREDICTING CONVECTION HEAT TRANSFER IN THE TURBINE GAS PATH

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INTRODUCTION

A new era is dawning in the ability to predict convection heat transfer in the turbine gas path. We feel that the technical community now has the capability to mount a major assault on this problem, which has eluded significant progress for a long time. In this paper we hope to make a case for this bold statement by reviewing the state of the art in three major and related areas, which we believe are indispensable to the understanding and accurate prediction of turbine gas path heat transfer: configuration-specific experiments, fundamental physics and model development, and code development.

Historically, experimental work and the modeling of the physics have preceded the complex computational predictions of the phenomena. This is particularly true with respect to heat transfer. We will follow this historical approach and begin our review with the configuration-specific experiments, whose data have provided the big picture and guided both the fundamental modeling research and the code development. Following that, we will examine key modeling efforts and comment on what will be needed to incorporate them into the codes. We will then review progress and directions in the development of computer codes to predict turbine gas path heat transfer. Finally, we will cite examples and make observations on the more recent efforts to do all this work in a simultaneous, interactive, and more synergistic manner. We will conclude with an assessment of progress, suggestions for how to use the current state of the art, and recommendations for the future.

These topics will not all be treated with equal depth. The experimental work will be reviewed more globally, zooming in on detail when it is important to illustrate key physics. The modeling, on the other hand, will be discussed in more detail than the other areas because we believe that the key to a successful predictive capability lies in the modeling. Closure models will always be needed to complete the large computer codes, and the success of these codes will depend on the accuracy, reliability, range of applicability, and computational efficiency of the models. The choice of models is often dictated by the user's need to emphasize one of these criteria over the others. Accordingly, we do not anticipate a clear choice of models emerging in the near future, and we have elected to explore a fairly wide range of models in two key turbine flow physics arenas: transition and 3D endwall regions. Heat transfer code development is fairly new and will receive less depth. Here the emphasis will be on what models are used and what the codes can do, rather than on the algorithmic details of the codes.

CONFIGURATION-SPECIFIC EXPERIMENTS

Configuration-specific experiments provide a broad perspective, as well as considerable detail, on the important heat transfer physics in the turbine gas. By configuration-specific we mean experiments in which the test article is an actual turbine blade or vane profile and passage. With rare exceptions, the experiments to be cited include heat transfer. To sort out this fairly substantial body of work, we will separate the research into two major categories: rotating and nonrotating. We will also treat one important hybrid, or subcategory - the use of upstream disturbance generators to simulate wake effects in an otherwise steady experiment.

Rotating Rig Experiments

The rotating rig experiments range from continuous running tests to ones with running times on the order of milliseconds. As a general rule, the long-duration tests are best for detailed aerodynamic measurements and the short-duration tests are best for heat transfer. Recent advances in instrumentation have blurred this distinction. However, as far as the existing literature is concerned, it is rare to find both detailed aerodynamic and heat transfer data in the same experiment. Choosing between realistic operating conditions and detail is another frequent compromise. In this review the focus will be on detail, since the emphasis is on establishing a reliable predictive capability; however, one must not lose sight of the ultimate goal of predicting the behavior of the engine.

The most comprehensive research on rotating rig heat transfer has come from Dunn and coworkers (Dunn and Stoddard, 1979; Dunn and Hause, 1982; Dunn, 1984; Dunn et al., 1984a, 1984b; Dunn and Chupp, 1988; Dunn et al., 1989; Dunn, 1990) at Calspan, and Dring, Blair, and coworkers (Dring et al., 1980, 1982, 1986; Blair et al., 1989a, 1989b, 1992b) at United Technologies Research Center (UTRC).

The Calspan experiments are conducted in a shock tunnel facility, using real turbine hardware with run times of about 30 msec. They are excellent for several reasons. First, heat flux can be measured directly and with very high time resolution by using the transient thin film heat flux gage. Second, short of a real engine, they offer the closest simulation to the real world. The main limitation of these experiments is that the very short run times provide only skimpy aerodynamic data. However, the time-resolved heat flux data itself contains important aerodynamic information. Figure 1 (Dunn et al., 1989) shows a phase-locked ensemble average of the time-resolved midspan heat flux data on the suction surface. This complex behavior, when averaged out, must be modeled properly in the predictive schemes. As an example of the complex physics which must be modeled, note the heat flux peaks and valleys which occur with each blade passing. The peaks are at a level comparable to fully turbulent heat transfer, while the valleys correspond to a laminar level.

By contrast, the UTRC experiments are run in a large-scale (1.5 m diam), steady-running machine. Since the same 1-1/2 stage turbine has been used for almost all of the machine's 15-year history, a very comprehensive data base has been established. The operating medium of room-temperature air at low speed offers excellent opportunity for detailed measurements. The aerodynamic measurements by Sharma et al. (1983) and the heat transfer measurements by Blair (1992b) are excellent examples of this detail. The midspan heat transfer data taken in this turbine by Blair et al. (1989a, 1989b) are shown in Figure 2. These data summarize just about everything we know about heat transfer down the midspan plane of a turbine. The data were acquired at two inlet turbulence intensity levels, 0.5 and 9.8 percent. As might be expected, the first vane row shows a dramatic effect of inlet turbulence. (The reference for comparison throughout Figure 2 is to a boundary layer code.) The low inlet turbulence data exhibit almost completely laminar behavior, while the high turbulence data appear to be experiencing transitional behavior. There is some controversy among researchers as to whether grid generated turbulence properly models a combustor outlet; however, the trend shown in Figure 2a is believed to be correct. The data on the pressure surface were higher than turbulent prediction level. A Reynolds number effect was reported. This is an area where further analysis/modeling is needed. The rotor data (Fig. 2b) still show some free-stream turbulence effects and some transitional behavior, but a much reduced spread from that on the first vane. This has also been reported many times by Dunn. By the second vane row (Fig. 2c), all inlet turbulence effects appear washed out; however, the transitional behavior still appears. The very high heat transfer towards the suction side trailing edge was a surprise, and remains unexplained. Research is under way to investigate this.

While the UTRC experiments offer more detail, they are less realistic than the Calspan experiments. In our opinion there is no perfect experiment - each has its strengths and weaknesses. The two taken together, however, offer a commanding look into turbine heat transfer.

Other strong entries into the rotating experiment area are the short-duration (300 to 1000 msec) experiments. These fall into two classes: the isentropic light piston tunnel (ILPT), pioneered by the Oxford University team of Schultz and coworkers (Jones et al., 1978; Schultz et al., 1980), and the blowdown tunnels, pioneered by the Massachusetts Institute of Technology (MIT) team of Epstein and coworkers (Guenette et al., 1989). These facilities have the same transient heat flux measurement advantage as the shock tunnel, and they have longer run times. Coupled with new particle image velocimetry (PIV) techniques, they potentially offer the best of both worlds. If one were starting with a clean sheet of paper, these would probably be the rotating facilities of choice. This is exactly the case with the U.S Air Force (Haldeman et al., 1991), following the MIT model. We can expect to see important contributions from these facilities in the future. The midspan heat transfer reported by Guenette et al. (1989) from the MIT transonic turbine tends to agree with that of Figures 1 and 2. To date, the ILPT facilities have been used only for nonrotating and simulated wake experiments to be discussed later, but plans for development of a full turbine stage at the Royal Airforce Establishment (RAE) are under way (Harasgama and Wedlake, 1991).

Steady-running, elevated-temperature facilities, which use actual turbine hardware, have long been used by NASA and the aircraft engine companies for performance and detailed aerodynamic data. These facilities have not been used much for heat transfer because steady-state heat transfer is so difficult to measure, especially on a rotor. This may change, however, as new heat flux gages, such as reported by Guenette et al. (1989), Mancuso and Diller (1991), and Ching and O'Brien (1991), are perfected. Roelke et al. (1991) have a program underway to measure heat transfer in a cooled radial turbine.

While in general this review is limited to work which includes heat transfer measurements, some rotating experiments with only aerodynamic data are important to mention. Hodson (1984) made boundary layer velocity profile measurements with hot wires in the rotating turbine blade passage. To our knowledge, these are the only such measurements and should prove very valuable for code validation. Addison and Hodson (1990a, 1990b) also measured unsteady surface fluctuations, using hot films on the surface, to gain insight into transition in a turbine. Binder et al. (1985, 1987) have made detailed laser measurements in a cold air turbine which also should prove very valuable for code validation. Getting the right flow physics is, after all, the first requirement of a good heat transfer predictive capability. Of course, many of the heat transfer experiments, such as Dunn (1990), included unsteady pressure measurements.

Wake Simulation Experiments

A hybrid between the rotating and nonrotating experiments are the wake simulation experiments. In wake simulation facilities, either a rotating spoked wheel (Ashworth et al. 1985; O'Brien et al., 1986; O'Brien and Capp, 1989; O'Brien, 1990) or a rotating squirrel cage of bars (Pfeil et al., 1982; Bayley and Priddy, 1981; Priddy and Bayley, 1988; Schoberei, 1991), is used to produce wakes which impinge on a downstream test surface. This is where the Oxford ILPT has received extensive use. An added contribution of the turbine experiment of Guenette et al. (1989) was to verify the validity of the rotating bar simulation. They used exactly the same test blades as the Oxford group.

At Oxford a linear cascade of transonic turbine blades was heavily instrumented with thin film transient heat flux gages. The cascade was placed in the ILPT, and a spoked wheel wake generator was rotated in front of it. Schlieren pictures were also taken. The progress of the wakes and effects on heat transfer were extensively documented. Doorly and Oldfield (1985b) created a summary figure of the process (Fig. 3) which shows the progress of the wake through the cascade. As with the Calspan experiments, the heat flux levels jump back and forth between laminar and turbulent levels. Both the shock and the wake produce a distinct effect. Doorly (1988) examined the data carefully and concluded that the primary effect was a premature transition from laminar to turbulent flow. He then proposed a simple model which showed good first order agreement with data and could prove useful in making design decisions.

O'Brien and coworkers (O'Brien et al., 1986; O'Brien and Capp, 1989; O'Brien, 1990) concentrated on the stagnation region. Here again, an examination of the data in terms of a simple model may prove useful. O'Brien (1990) inserted the local unsteadiness into a standard correlation for stagnation point heat transfer in the form of an instantaneous "turbulence intensity" and found good correlation with the unsteady heat transfer data (Fig. 4). Also, O'Brien et al. (1986) used both the transient heat flux technique and a traditional steady-state technique in the same experiment with excellent agreement, helping to validate use of the transient technique. These bar-generated wake simulation experiments are relatively inexpensive, easy to run, and should produce valuable information.

In general, the rotating experiments and the wake simulation experiments have concentrated on airfoil midspan heat transfer. The Calspan experiments usually had some instrumentation near the hub and tip of the blades and vanes and also in the vane endwall region, with a few points on the blade platform. These data are in general too sparse to establish 3D contours, but will be very valuable in validating 3D codes. Recently, Blair (1992b) reported the results of a new experiment in the UTRC large, low-speed rotating rig, using both a dense array of thermocouples and liquid crystal thermography, to map the full 3D rotor blade and endwall heat transfer. The report includes a computational analysis and a comparison to the Graziani et al. (1980) data.

Cascade Experiments

The older and much more comprehensive body of literature on turbine configuration-specific heat transfer are the cascade experiments. These go back more than 30 years and have provided much of what can be described as the conventional wisdom in turbine gas path heat transfer. Instead of trying to survey it all, we have chosen to include a representative (historical and international) sampling in the References section and comment on just a few specifics that are relevant to the theme of this paper. A few of the very early works are still worthy of note and should not be overlooked. Both Wilson and Pope (1954) and Turner (1971) provide excellent detail on the midspan flow physics and heat transfer. Dyban and Kurosh (1968) ran their experiment in both a cascade and an air turbine. While the details of their experiment are sketchy, they were among the first to cite the differences between cascade and rotating rig results, showing heat transfer increases of 50 to 100 percent in the rotating rig. Sieverding (1985) has reviewed the secondary flow in turbine passages and this paper should be consulted.

A particularly important set of cascade data is the work of Langston et al. (1977) and Graziani et al. (1980). These two experiments have provided a comprehensive turbine cascade aerodynamic and heat transfer data base. Furthermore the blade profile is the same as the midspan cross section of the UTRC large, low-speed rig, which allows a comparison between cascade and rotating rig data (Blair, 1992b). Figure 5 indicates the heat transfer detail available and the important trends.

Another valuable data base is that of Hippensteele and Russell (1988) and Boyle and Russell (1990). These experiments covered a wide Reynolds number range and identified an important trend in endwall data. At low Reynolds number the lines of constant Stanton number tend to follow the streamlines, while at high Reynolds number they tend to span the passage. These results, coupled with the visual evidence provided by Gaugler and Russell (1984), make an impressive, if not very surprising, case that endwall heat transfer is truly 3D. Boundary layer analyses have little potential for success in this region. This will be discussed further in the Code Development section, and the data will be shown there.

Most of the cascade work, including that just discussed, has been performed in linear cascades, where, although the flows are 3D, the geometry is 2D. It is sometimes desirable to get information with more complex blade shapes and where stronger radial gradients exist. Thus, although more difficult, annular cascade experiments are valuable. Recent work by Wedlake et al. (1989) and Harasgama and Wedlake (1991) is an excellent example. The results, shown in Figure 6, are particularly significant, because the cascade is a highly three-dimensional modern design and is part of a larger program to make measurements in a full turbine stage.

Finally, it should be noted that the majority of the data have been acquired at or near room temperature. Very few "engine environment" data have been acquired and reported. The work of York et al. (1984) and Nealy et al. (1984) at Allison Gas Turbine and of Gladden and Yeh (1992) at NASA are exceptions. Comprehensive 3D viscous heat transfer/flow codes coupled with industry test experience should bridge that gap. It is the role of the more detailed, albeit less realistic, experiments to validate the codes and models.

FUNDAMENTAL PHYSICS AND MODEL DEVELOPMENT

The complexity of flow on a turbine blade, as influenced by geometry, local conditions of acceleration or deceleration, end wall conditions, body forces, and the unsteady nature of the flow, requires an isolation of the various physical phenomena for experimental study and modeling purposes. It is common practice to divide a turbine blade up into component parts to study and model the basic physics. For example, NASA Lewis Research Center is investigating the horseshoe vortex at the intersection of the plate and endwall, the effect of free-stream turbulence on the stagnation region heat transfer, the effect of rotor wakes, and transition from a laminar to a turbulent boundary layer. Since it would not be possible to cover all the fundamental physics and model development research, this section will detail the progress in the areas of transition and endwall heat transfer. We think that these are among the most critical areas in the prediction of convection heat transfer in the turbine gas path.

Bypass Transition Region

The bypass transition terminology used here is that of Morkovin (1978), who suggested that for laminar-to-turbulent boundary layer transition, when large disturbances exist (as in the case over a turbine), linear stability mechanisms are bypassed and finite nonlinear instabilities occur. The result is the sudden appearance of turbulent spots without the disturbance growth predicted by linear stability theory. The transition region is very important to turbine gas path heat transfer for two reasons. First, the various competing forces in the turbine gas path, such as free-stream turbulence, wakes, curvature, and acceleration, frequently result in the flow field lying between laminar and turbulent flow. Significant portions of the turbine airfoil surface can be in transitional flow. Second, the heat transfer levels associated with turbulent flow can be easily three times those of laminar flow at the same Reynolds number. Accordingly, the predictive uncertainties and the appropriate models associated with transitional flows are very important in the study of turbine gas path heat transfer. Excellent review articles of laminar-to-turbulent transition applicable to turbine heat transfer may be found in papers by Narasimha (1985), Mayle (1991), and Volino and Simon (1991).

The use of the time-averaged Navier-Stokes equations in the numerical codes requires the use of turbulence models. These models are based on the physics of flow and generally perform well for fully turbulent conditions with varying degrees of success. As Volino and Simon (1991) point out, turbulence models for the prediction of transitional flows have been less than successful. Volino and Simon, reviewing the modeling efforts with one- and two-equation models, indicated a need to include more physics in the models. Because of the anisotropic nature of transition, they suggest a potential advantage in the use of a Reynolds stress model and list the experimental quantities required for developing turbulence models which will capture the physics of bypass transition. The following is a consideration of some models with the potential to simulate the mechanisms in bypass transition and how experimental and numerical experiments are aiding their development. The turbulence models to be considered are k-ε models, intermittency models, multiscale models, and Reynolds stress models.

k-ε models. In general k-ε turbulence models used in numerical codes appear to simulate the transition governed by the transport and production of turbulence in the boundary layer. These models require a proper location of the initial profiles of k and ε to correctly predict the location of transition onset. Results with these models generally produce an underprediction of transition length (Rodi and Scheuerer, 1985b). Using empirical correlations, Schmidt and Patankar (1988) modified the turbulent production term of the differential turbulent kinetic equation to make predictions consistent with experiment, as shown in Figure 7. This work, and the work of Stephens and Crawford (1990), demonstrate the sensitivity of the prediction of the onset of transition to the location at which calculations are started. Simon and Stephens (1991) suggest, for free-stream turbulence levels less than 5 percent, that calculations begin at the critical Reynolds number for linear stability growth. Furthermore, models which have been designed for and calibrated with fully developed turbulent flows may not be adequate. Such has been found to be the case for the K.Y. Chien turbulence model which produces a premature start of transition (Stephens and Crawford, 1990) due to a damping function dependence on the boundary layer normal distance. In the work of Stephens and Crawford it was determined that the two-equation turbulence models which perform best in predicting transition have a damping function which is dependent on the turbulent Reynolds number. Improved models have a damping function dependence on both the turbulent Reynolds number and the boundary layer normal distance (Chen, 1990). In general k-ε models do a respectable job of simulating bypass transition. Improvements to these models will require greater knowledge of the physics of transition. Experiments and direct numerical simulations (DNS) are being performed to achieve this end.

The experiments of Suder et al.(1988) produced some valuable insights on the mechanisms of bypass transition. Single hot-wire measurements of a boundary layer on a flat plate undergoing transition indicate that turbulence spots begin at a maximum boundary layer turbulence level of 3.5 percent regardless of the path (high or low free-stream turbulence) to transition. The intermittency at this point according to Suder's data is on the order of 0.03. Using Suder's criterion of 3.5 percent on the experimental results of Kuan and Wang (1989) results in a momentum Reynolds number transition number of 249 compared to an experimental value of 297 for zero intermittency. Sharma et al. (1982) simulated the flow on the convex side of an airfoil with a pressure gradient distribution on a flat plate. He determined that the onset of transition, as defined by an intermittency of 0.1, occurs when the streamwise boundary layer turbulence level reached a threshold value of three times the friction velocity. The data of Suder confirm this conclusion for an intermittency of 0.1.

In Figure 8 the boundary layer disturbance growth, as measured by a DNS calculation by Rai and Moin (1991) and the k-ε calculated maximum turbulence intensity in the boundary layer, is presented for the case of zero pressure gradient and 2.6-percent free-stream turbulence. Suder's criterion when applied to Figure 8 produces a transition value consistent with the numerical results of Simon and Stephens (1991). They use the criterion of minimum coefficient of friction for the onset of transition and assume this to occur at zero intermittency. Figure 8 shows how the k-ε model captures the nonlinear growth which produces the first sign of turbulent spot formation. This example points out the power of numerical experiments to increase understanding of transition physics and to aid in the testing and development of transition models. The data base produced from numerical experiments such as Rai and Moin (1991) will be invaluable.

Intermittency models. The experimental work of Sohn et al. (1991), Kuan and Wang (1989), Arnal et al. (1978), Kim and Simon (1991), and Kim et al. (1989) all demonstrate, via a conditional sampling approach, that the transition region cannot be described by a combination of Blasius and fully turbulent boundary layer profiles. This puts into question the approach of transition modeling based on intermittency weighting of the "nonturbulent" and turbulent spot zones first proposed by Dhawan and Narasimha (1958). The results of Sohn et al. indicate that the nonturbulent zone starts with a Blasius velocity profile at low intermittency and deviates from this profile with increasing intermittency. Conversely, the turbulent spot zone becomes more like a fully developed turbulent velocity profile as the intermittency increases. These effects are shown in Figure 9. These results suggest that conditioned average techniques rather than global time averages in turbulence models would better describe the physics of transition. The use of conditioned averaging techniques for the turbulent spots and the laminar-like fluid surrounding the spots in a k-ε model by Vancoille and Dick (1988) resulted in good agreement between experiment and prediction of the turbulence intensity profiles. Simon and Stephens (1991) derived conditioned energy equations and used a modified Vancoille and Dick approach to show the potential of this approach in predicting bypass transition heat transfer, as shown in Figure 10.

Multiscale models. The recent work of Volino and Simon (1991) applied quadrant and octant analysis to experimental data to analyze the differences in structure between turbulent and transitional flows. They found differences in transition and fully turbulent flows, which they believe are due to incomplete development of the turbulence in the transition region. They state that transitional flows are dominated by large-scale eddies because of the incomplete development of the cascade of energy from large to small scales. They indicate that this suggests the need for incorporating additional scales into transition models such as the standard k-ε model. Such a modified k-ε model would, for example, have a k equation for the large scales and one for the small scales. This is consistent with the experimental results of Blair (1983), whose power-spectral-density measurements indicated that the ratio of turbulent dissipation to production increased through transition. He used this information to explain the high turbulent kinetic energy (TKE) values near transition onset, which may be caused by an incomplete development of energy cascade. The development and implementation of a multiscale model for transition would appear to have much merit. Such a model might also capture the effect of length scale on transition that Suder et al. (1988) and others have found experimentally.

Reynolds stress models. The laboratory experiments of Sohn et al. (1991) and Sharma et al. (1982) and the numerical experiments of Rai and Moin (1991) indicate that a large level of anisotropy exists in a transitioning boundary layer, as seen in Figure 11. This suggests the use of a Reynolds stress type of turbulence model for a more exact accounting of all the stresses. The k-ε model assumes isotropic turbulence and is therefore limited in providing information on boundary layer stresses. In the field of transition modeling, Reynolds stress modeling is a new area of work and there is little to report to date. However, the need to examine the anisotropic nature of transition exists and, at the very least, should be used to evaluate simpler models. On the other hand, as the experimental and numerical results indicate, the stress in the streamwise direction has the greatest growth during transition. This may partially explain the success of the k-ε models.

At this juncture of transition models it appears that the k-ε and k-ω models are the most practical for effective bypass transition calculations. However, use of these models requires proper attention to the transition region. Conditioned averaged techniques and a greater knowledge of the growth of nonlinear disturbances in the boundary layer will be required. Such information will permit the proper implementation of the initial profiles for k and ε.

3D Endwall Region

The 3D endwall region, formed by the intersection of the blade/vane with the hub, is an important heat transfer region. At this intersection a "horseshoe" vortex is formed. The result is a secondary flow that greatly influences the heat transfer at the endwall and at the vane suction surface.

The flow visualization work of Gaugler and Russell (1980) using neutrally buoyant, helium-filled bubbles documents well the nature and path of the vortex flow. They superposed their visual results on the data of York et al. (1984) in the same geometry cascade, as shown in Figure 12. The high Stanton number gradients near the entrance to the cascade appear to be along the vortex path. The experimental documentation of heat transfer by workers such as Blair (1974), Graziani et al. (1980) (cf. Fig. 5), and Goldstein and Spores (1988) also shows that the result of endwall secondary flows is unwanted heat transfer augmentation at the endwall and airfoil suction surface. The effect of such secondary flows on heat transfer can be expected to be even more pronounced on modern gas turbines because the smaller blade aspect ratio permits a greater portion of the blade to be influenced by secondary flows. Such a complex heat transfer phenomenon is best studied by methods which allow for detail surface mapping of the heat transfer as has been done by using the liquid crystal technique. Hippensteele and Russell (1988) used this technique to find a Reynolds number effect on the passage endwall heat transfer pattern and an increase in the Stanton number with an increase in the Reynolds number. This work was extended by Boyle and Russell (1990) to include the effect of the inlet boundary layer. It was determined in this effort that the pattern of the Stanton number contour lines was not affected by changes in the thickness of the inlet boundary layer. However, the thickness of the boundary layer did affect the level of the Stanton number. It is clear that the complex nature of the endwall heat transfer requires a greater understanding of the flow physics for the development of turbulence models that can be used in 3D numerical codes.

Unlike the situation in the preceding section (transition region), there are few "simple" heat transfer experiments to capture the basic endwall mechanisms, which need to be modeled. There are some fluid mechanics experiments, but little heat transfer. One notable experiment is the work of Abrahamson and Eaton (1991). In this study a two dimensional boundary layer was made three dimensional by introducing a wedge obstruction and making measurements of the heat transfer. The heat transfer results of Abrahamson and Eaton are consistent with the near wall turbulence measurements of Anderson and Eaton (1989), who noted that the turbulent shear stresses were suppressed. Abrahamson and Eaton hypothesize on the basis of their experimental results that the near wall region for their 3D boundary layer was dominated by two dimensional transport mechanisms. This insight has some value in conjunction with the more extensive research conducted in cascades to investigate basic endwall heat transfer mechanisms. Thus, the discussion of these cascade experiments which began in the previous section continues, now with the focus on modeling.

Reynolds stress models. Bradshaw (1972) recommends the Reynolds stress turbulence model for complex three dimensional flows rather than models based on the eddy viscosity principle (e.g., k-ε or Baldwin-Lomax) are worth considering for complex three dimensional turbulent flows. He states that "the simple behavior of eddy viscosity and mixing length in simple thin shear layers is not maintained in more complicated cases like three dimensional flow, multiple shear layers or flows with significant extra rates of strain." This view that Reynolds stress transport models have the greatest potential for complex flows is also held by many researchers involved in the development of turbulence models, including Launder et al. (1975), Donaldson (1971), Hanjalić and Launder (1972), and Lakshminarayana (1986). However, applications of second-order turbulence closure models have been mainly limited to momentum transport processes with little work in applications related to heat transfer. Their applicability for heat transfer requires further investigation.

Launder and Samaraweera (1979) included turbulent heat flux transport equations as part of a second-order turbulence closure approach to predicting heat transfer in free shears and boundary layers. However, in the near wall region where molecular transport becomes more important they used a wall function approach that required experimental information. It would be better and more consistent to have a low Reynolds number version of the Reynolds stress turbulence model, as in the case of two-equation turbulence models, to predict the near wall momentum and thermal behavior. Such a low Reynolds number model was developed by Hanjalić and Launder (1976), although this early model did not use the full set of transport equations like the model of Shih and Mansour (1990). This newer model, when compared with the DNS results of Kim et al. (1987), performs very well in predicting the behavior of the near wall turbulence and the flow field. As indicated previously, little work has been done in using the second-order approach for heat transfer predictions, and no work appears to have been done in the endwall region using this model. Perhaps this reflects the additional level of difficulty in obtaining accurate numerical predictions. Despite these concerns, to date those who have applied turbulence models for the calculation of endwall heat transfer rates have used models based on the eddy viscosity concept.

k-ε models. The k-ε or two-equation turbulence model assumes the turbulence to be isotropic. Despite the k-ε model inconsistency with the anisotropic nature of the endwall turbulence, the k-ε model has been found useful for three dimensional numerical analyses. Hah (1989) used a 3D Navier-Stokes code with a low-Reynolds-number version of a two-equation model to predict the heat transfer near the endwall of a turbine blade row. This permitted him to include effects of turbulence and transition from a laminar to turbulent boundary layer using a turbulence model of Chien (1982). As noted previously in the Bypass Transition section, this model produces transition too soon, a result that Hah reported. Hah reports good comparisons of his numerical predictions with the experimental data (Fig. 13a) of Graziani et al. (1980) for the endwall of a turbine blade cascade. This is shown in Figure 13b. Choi and Knight (1988) used this experimental data base to compare with their 3D numerical code predictions. Their code uses the q-ω two-equation turbulence model. Agreement with the experiment was found to be good, as shown in Figure 13c. The possible reasons for the apparent success of low-Reynolds-number, two-equation turbulence models may be found in some ideas expressed by Launder et al. (1984). Launder states that "velocity gradients normal to a rigid boundary are so steep that, with exception of flow near spinning surfaces, the low-Reynolds-number region can usually be regarded as in simple shear." He further states that streamwise convective transport effects are of secondary significance, suggesting that Boussinesg viscosity models will do the job of turbulence modeling as one nears the wall. He goes on to explain how, in what may be a compensating error, the calculation of an incorrect length scale can result in the correct overall heat and momentum transfer resistance. This occurs even though the predicted boundary layer profiles may not correspond exactly to the data. He recommends that improved near-wall length scale predictions be incorporated. This recommendation is being addressed by such efforts as that of Shih and Mansour (1990).

Baldwin-Lomax model. The above comments help to explain the apparent success of 3D Navier-Stokes codes that use mixing-length models. Such models cannot account for the history and transport effects of turbulence. Chima and Yokota (1988) present results of a 3D Navier-Stokes code that uses the Baldwin-Lomax model for a horseshoe vortex created on a flat plate by a circular cylinder normal to the plate. Comparisons with experiment show excellent agreement for flow and pressure contours. This approach is extended by Ameri and Arnone (1991) to include heat transfer for the endwall of a linear turbine cascade. The objective of this work was to explore the ability of the Baldwin-Lomax model in a 3D Navier-Stokes code to predict heat transfer. Numerical results were compared to the data of Graziani et al. (1980) and were found to be good, especially in the endwall region. This is partly attributed to the fully turbulent nature of the flow in that region, as shown in Figure 13d. Since mixing-length models require corrections for pressure gradient, modifications were recommended for the model to improve the heat transfer results in the regions with large pressure gradient. The model also does not comprehend transition behavior on the blade and requires a transition criterion to be invoked. While the comparisons of the approach of Hah (k-ε model), Choi and Knight (q-ω model), and Ameri and Arnone (Baldwin-Lomax) with the experimental data of Graziani (Fig. 13), reveal individual differences, the encouraging result is that they all capture the right trends. To give additional credibility to the use of a mixing-length approach, it is worth noting that Anderson and Eaton (1989) used the Rotta (1979) T-mixing-length model to get reasonable predictions of the experimental shear stresses. This model permits an anisotropic eddy viscosity.

"Wall-function" type modeling. Launder et al. (1984) describe wall function methods by which the inner, low-Reynolds-number, layer may be described by one-dimensional near-wall solutions. Such methods have long been in use and would obviate the need to compute a numerical solution all the way to the wall, where high velocity and temperature gradients require about 50 percent of the grid points. However, the assumptions made in developing these traditional one-dimensional wall functions may not be applicable to complex three dimensional flows.

A better approach is to develop solutions for three dimensional near-wall layers which reflect the physics of such flows. Work of this nature was done by Goldberg and Reshotko (1984) and Degani and Walker (1989,1990). Goldberg and Reshotko performed a three dimensional asymptotic analysis for high-Reynolds-number turbulent boundary layers and developed solutions for three dimensional law-of-the-wall and law-of-the-wake models for the pressure-driven part of the turbomachinery endwall flow. The results compare well with experimental velocity values and their direction in the wall region. They concluded that the flow in the wall layer is two dimensional and in the direction of the wall shear stress.

An asymptotic expansion approach was used by Walker et al. (1986) to develop wall functions for two-dimensional turbulent flows, taking into consideration the coherent structure of the near-wall flow. This approach was extended to three dimensional flows for cases of no heat transfer and heat transfer by Degani and Walker (1989,1990). In their asymptotic analysis, terms were included which took into account the effect of pressure gradient. This resulted in the conclusion that second-order effects of pressure gradient are not, in general, negligible and will cause the velocity and shear stress profile to skew significantly. The authors state that this is more in line with the experimental evidence. This is contrary to the conclusions of Goldberg and Reshotko. In their application of the asymptotic approach for predicting heat transfer, Degani and Walker (1990) used profiles developed by Walker et al. (1986) for the inner layer velocity and enthalpy. They compared their computed results of turbulent boundary layer in a plane of symmetry for a cylinder normal to a flat plate with the computations to the wall of a three dimensional Navier-Stokes code that uses a Cebeci-Smith eddy viscosity model with constant Prandtl number. While there is little difference in the results of the two approaches, we believe that their wall function method will give more realistic results for heat transfer with pressure gradients.

This survey of turbulence models for endwall heat transfer code calculations leads us to conclude that for practical, accurate calculations at the end wall the best choice for the present is a low-Reynolds-number, k-ε or k-ω model.

CODE DEVELOPMENT

As stated earlier, convective heat transfer predictive capability in the turbine gas path has traditionally lagged behind the fluid mechanics predictive capability. This is still true. Although 3D Navier-Stokes codes are beginning to enter the aero design decision-making process, they are not yet a part of the heat transfer design decisions.

For many years heat transfer design decisions were made on the basis of empirical correlations, coupled with industry proprietary test data. In the 1970's, with the introduction of the Patankar and Spalding (1972) method and the highly popular STAN5 (Crawford and Kays, 1976) boundary layer code, turbine gas path heat transfer prediction took on a new dimension. Presently, 3D Navier-Stokes codes with heat transfer are beginning to emerge. We will discuss the boundary layer methods and the Navier-Stokes codes and leave the empirical methods to history. Before leaving them, however, one comment is in order - simplicity is good. If you have a reliable correlation that covers the range of interest, then use it.

The use of advanced computational methods to analyze, and ultimately predict, turbine gas path heat transfer really began with the introduction of the STAN5 boundary layer code by Crawford and Kays (1976). STAN5, based on the Patankar and Spalding (1972) method, is a highly modularized, finite-difference computer code which was designed to predict heat transfer through a flat plate boundary layer. Over the years it has been continually modified and upgraded, particularly with respect to new turbulence/transition models. In addition to being a predictive tool, it has been a test bed for exploring new models (cf. Bypass Transition Region). Crawford (1985) has continued to maintain STAN5 in the form of a code called TEXSTAN. Members of the aeropropulsion industry have modified it and incorporated it into their design and analysis schemes. These codes are not often published, but one example can be found in a paper by Zerkle and Lounsbury (1989). This code allows for local free-stream velocity distributions, which can be supplied empirically or through coupling it with an aero analysis. One popular technique is to combine boundary layer codes with the quasi-3D Euler analyses of Katsanis and NcNally (1977) in what has become known as the MTSB code described by Boyle et al. (1984). This code is particularly popular, because the Katsanis codes have been part of industry design systems for a long time and industry is comfortable with them. Although advanced modeling is beginning to enter predictive codes, the present standard for design and analysis is primarily algebraic mixing models and empirical transition models. The use of k-ε models in these codes is just beginning to emerge.

Another reason the boundary layer codes are popular is that they are computationally efficient when compared with the Navier-Stokes codes. This is because they are parabolic and they focus on a very small physical space in a large flow field. This in turn allows for the very high grid resolution computations necessary for some heat transfer calculations. This is particularly true in the airfoil midspan region where the flow is nearly two dimensional and laminar-turbulent transition is one of the major flow features. Figure 14, taken from Zerkle and Lounsbury (1989), illustrates both the strength and weakness of such methods. The calculations, using a k-ε turbulence model, agree well with data over most of the region, but are very sensitive to free-stream turbulence in the transition region and miss the last two data points. When transition is less of an issue, the sensitivity to free-stream turbulence is less and the prediction is better. An obvious problem with these methods is starting the calculation on turbine airfoils, since it is basically a flat plate calculation. Most codes have some starting scheme built into them. To examine this problem and to explore the use of Navier-Stokes analyses, Boyle (1990) used the thin layer quasi-3D Navier-Stokes code of Chima and Yokota (1988) in an extensive investigation of various computational models, compared to several datasets. One example from Boyle's work, using the rotor data of Blair et al. (1989a) for comparison, is shown in Figure 15. The same type of behavior as was seen by Zerkle and Lounsbury (1989) with the boundary layer code is seen here. In fact, one of the conclusions that can be drawn from Boyle's work is that the turbulence models developed in flat plate experiments and with boundary layer analyses can be extrapolated to the Navier-Stokes codes. They appear to work equally well, or equally poorly. This is important, because it suggests that the large body of work done on flat plates and simple 2D channels remains valuable. It also suggests that boundary layer analyses can yield valuable insight, at least in the important midspan region. In the endwall region, not surprisingly, boundary layer codes are much less successful. Since the experiments show that the flow in this region is truly three dimensional and the outer flow field has major significance, one would expect this type of flow to be beyond the range of boundary layer analyses. These analyses can be made to work, as per the example of Anderson (1987), but the effort to get the edge condition correct is so complex that one wonders if it is worth the effort. The incorporation of 3D "wall functions" into the Navier-Stokes codes might be more practical.

Choi and Knight (1988) also showed good three-dimensional results on the blade surface, as shown in Figure 16. The subtle, but important, differences between experiment and computation are somewhat masked by the scale of the figure. The same transition sensitivity at midspan, as discussed throughout, is present in Figure 16. The focus here should be on the ability to capture the three dimensionality. Choi and Knight (1991a) have explored the transition calculations in a recent paper.

The endwall region is where the 3D Navier-Stokes code will be most needed and where the investment will be most productive. Furthermore, transition is less of a factor in this region, lessening the need for some of the very high resolution turbulence models. This discussion was started in the preceding section and continues here. Probably the longest term effort to develop 3D Navier-Stokes codes with heat transfer has been by Knight and Choi (Knight and Choi, 1987; Choi and Knight, 1988, 1991a, 1991b), using the q-ω model, and by Hah (Hah, 1984, 1989; Hah and Selva, 1991), using the k-ε model. Both have compared their work to the Graziani et al. (1980) experiment with generally good results, as shown in Figure 13. A number of heat transfer codes have used the Baldwin-Lomax algebraic turbulence model, popular with the turbine aerodynamicists. The results of Ameri and Arnone (1991), using this model, are also shown in Figure 13. Dorney and Davis (1991) performed similar analyses using their 3D Navier-Stokes code. In general, the results with Baldwin-Lomax are qualitatively good, but not as good as those using the two-equation models. In response to these shortcomings, Chima et al. (1992) have recently made a substantial revision to the Baldwin-Lomax turbulence model and have examined the Reynolds number dependance reported by Boyle and Russell (1990), as shown in Figure 17. The major trends are captured and the actual level of heat transfer predicted is quite good, especially in the high-Reynolds-number case.

A very popular 3D Navier-Stokes code among the turbine aerodynamicists is the Dawes (1988) code; however, to date very little work has been done with it for heat transfer. Vogel (1991) has modified the Dawes code for heat transfer and has included film cooling. Also, Dawes (1992) has recently added heat transfer to his code, albeit for a coolant side problem. These efforts should be followed for future progress.

It is encouraging, and maybe just a bit surprising, that the 3D Navier-Stokes codes are doing so well. Two things seem to favor success. First, turbine flows are strongly pressure driven and, despite strong secondary flows, the main flow direction is almost always well established. Second, the ability to predict heat transfer accurately is greatly enhanced by getting the local free-stream total temperature correct. The codes seem to be able to do this well.

Up to this point every computational effort that has been discussed has been a steady-state analysis of an isolated blade row. Yet, recalling Figure 1, what we really have at work is a very complex time-dependent phenomenon. We have already cited long-standing evidence that the results in a turbine are different from the isolated blade row. Ultimately it is this unsteadiness that must be modeled and properly accounted for in the analyses. This can be done by using a time-accurate solution or by using a properly averaged time-averaged solution. At this time there are very few analyses of either type which treat heat transfer. Part of the work of Dring et al. (1986) included an unsteady boundary layer analysis of their heat transfer data. Tran and Taulbee (1991) conducted an unsteady Euler/boundary layer analyses of the Dunn (1990) unsteady heat transfer data with some success.

There are a number of fine efforts which attack the flow physics. Getting the flow physics correct, especially the total temperature distribution, is probably the major portion of the battle, so we will comment on these efforts. The time-accurate turbine flow field analyses have been led by the efforts of Rai (1989a, 1989b), Rai and Madavan (1990), and Rao and Delaney (1990). Rai modified the UTRC turbine geometry slightly to create four-rotor/three-stator periodicity and then compared their unsteady pressure calculations to the experiment of Dring et al. (1982) with quite favorable results. The results were also compared with the turbine exit total pressure contours measured by Butler et al. (1986) with qualitatively similar results. As part of a joint program between Allison Gas Turbine and Calspan, supported by the U.S. Air Force (Dunn 1990), a transonic turbine with an exact three-rotor/two-stator periodicity was constructed and tested. The results appear to support the time-accurate pressure analyses of Rao and Delaney (1990), although some questions exist. Their analysis of the blade unsteady pressure (Fig. 18), if supported by continuing research, has important implications for future predictive capability. The results indicate that time-average of the unsteady behavior may not be the same as a steady calculation. This is an early result that will have to be watched. In addition, heat transfer results from this turbine should appear in the future.

Another approach to understanding and modeling the unsteady flow physics of the turbine has been developed by Adamczyk et al. (1990). The idea set forth by Adamczyk (1985) is to break the flow field variables down into a quadruple decomposition. The instantaneous axial velocity, for example, contains an average term, a random unsteadiness term, a blade-passing unsteadiness term, and an unequal-blade-count unsteadiness term. Operations similar to Reynolds averaging are performed on the terms in these equations. Needless to say, this yields a huge number of terms to be modeled, and a program is under way to do that. Early results, modeling just a few terms (Adamczyk et al., 1990), are very encouraging.

In summary, the computational approach should be to use the level of sophistication needed to reliably predict the gas path region of interest. In the truly 3D regions, such as endwalls, this probably means 3D Navier-Stokes. Early results in these regions are encouraging. Along the midspan transition is a major issue. Thus, high resolution and sophisticated modeling will probably be needed. However, the computation may not necessarily need a 3D Navier-Stokes code. A boundary layer approach, zonally imbedded in a bigger code (Euler or Navier-Stokes; quasi-3D or full 3D) may do well. Other regions, such as stagnation regions or film cooling hole regions, may still find wall functions or correlations, embedded in the codes, to be the best approach.

INTERACTIVE MODEL FOR DEVELOPING PREDICTIVE CAPABILITY

We started this paper (see the Introduction) with a brief reference to a model for developing a convective heat transfer predictive capability in the turbine gas path. At this point we would like to expand on it. It is our opinion that the technical community has at its disposal very sophisticated computational and experimental tools with which to attack the very complex problems associated with the advanced design of modern aeropropulsion systems. (This can also be said of many other complex heat transfer systems.) It is also our opinion that in order to use these tools effectively to achieve an advanced capability, they must be used in a synergistic, interactive manner. This has not been the history. Traditionally, the research has been done in a more sequential manner in which the computational analyses have been compared to previously acquired data, or vice versa. The comparisons, cited earlier, of all the recent 3D Navier-Stokes heat transfer computational analyses with the experiments of Langston et al. (1977) and Graziani et al. (1980) are excellent examples of this type of sequential approach at its best.

What will be needed in the future is an approach where the computational and experimental teams are working interactively, feeding the results of their work back and forth to make the most of both the experiment and the analysis. The modeling must be an integral part of this process. Unfortunately, at present there are very few heat transfer examples of this model at work, at least in the turbine heat transfer arena. The work reported by Guenette et al. (1989) is a good beginning in this type of approach.

In aerodynamics there are a number of fine examples of computational and experimental interaction and the readers are directed to them. The work reported by Leylok and Wisler (1991) from research done in the General Electric large, low-speed axial compressor is a good example. A recent paper by Hathaway et al. (1992) is probably the best example of the model at work. Changes in the experiment design and procedure were made as a result of the analyses, and changes in the analyses were made as a result of the experiment. The effects of the one on the other were then evaluated. The work cited earlier of Dunn (1990), working with Rao and Delaney (1990), is also a good example. So too is the tie between the research in the UTRC large, low-speed turbine (Dring, Blair, and coworkers (Dring et al., 1980, 1982; Blair et al., 1989a, 1989b, 1992b)) and Rai et al. (Rai, 1989a, 1989b; Rai and Dring, 1990) and Adamczyk et al. (Adamczyk, 1985; Adamczyk et al., 1990). More recently, the Rai code has been used by Rai and Dring (1990) and Dorney et al. (1990) to analyze simulated combustor generated inlet temperature distortions and hot streak migrations through the same machine.

The ties to UTRC and the Calspan research are particularly noteworthy for this paper, because they deal with turbines and have a long tradition of heat transfer measurements. Future programs include plans for a more interactive research with the developing heat transfer codes. The work reported by Blair (1992b) shows the beginning of this effort. The work of Guenette et al. (1989) at MIT has already been mentioned and it is continuing. The turbine facility reported by Wedlake et al. (1989) and Harasgama and Wedlake (1991) for a turbine annular cascade at RAE is being expanded to a full stage and is expected to be more closely coupled to the heat transfer code development. A new and larger blowdown facility, built on the MIT model, has just been brought on line at Wright Patterson Air Force Base (Haldeman et al., 1991), with plans for substantial flow field and heat transfer measurements on real turbine hardware, coupled with computational analyses.

Another effort is just beginning at NASA in a newly constructed transonic cascade facility, described by Verhoff et al. (1992). The machine was originally designed using the MTSB code (Boyle et al., 1984). Subsequently the design was analyzed using the 3D Navier-Stokes codes of Ameri and Arnone (1991) and Chima et al. (1992). This led to design modifications. One example of the calculations from Ameri and Arnone (1991) is shown in Figures 19. The cascade is also being analyzed with the code of Hah and Selva (1991). The cascade is now operational, and the blade coordinates have been distributed to approximately two dozen researchers internationally. Plans include periodic workshops with the involved turbine heat transfer community to review and evaluate both the computational and experimental progress.

CONCLUDING REMARKS

By examining the literature and drawing on our own experience, we have attempted to provide a critical examination of the state of the art in the prediction of convective heat transfer in the turbine gas path. Configuration-specific experiments, fundamental physics and model development, and heat transfer code development were all examined for their status and impact on establishing a capability. Although we cited a substantial body of literature, it was not our intention to perform a comprehensive literature survey, but rather to build a story and provide some insight.

From this experience we feel able to draw some conclusions about the present state of the art in turbine gas path convective heat transfer and to offer some suggestions for the future.

1. The present state of the art in the prediction of turbine gas path convective heat transfer is advancing rapidly.

2. The present standard for turbine heat transfer prediction is a two-dimensional boundary layer code embedded in a quasi-3D Euler code.

   a. The turbulence modeling relies heavily on algebraic mixing-length models with some use of k-ε modeling.

   b. Transition predictions are largely empirical, based on models developed on flat plates.

3. A truly reliable three-dimensional predictive capability is not yet in hand; however, the tools to put such a capability in place are at hand.

   a. The necessary heat transfer codes are under development and showing good progress.

   b. The proper modeling efforts are under way and substantial progress is being made.

   c. There are numerous fine configuration-specific experiments, which are yielding very impressive turbine heat transfer results.

4. Fundamental physics and model development is showing significant progress on several fronts.

   a. Both laboratory and numerical experiments have yielded significant insight into the key physics, such as laminar-turbulent transition, associated with turbine heat transfer.

   b. New models, particularly k-ε models which have been specially tailored to a particular class of problems, are showing promise, at least for meaningful near-term analyses.

   c. The evaluation of models, such as mixing-length and k-ε, in full 3D codes is growing and offering valuable information. This trend is expected to continue.

5. The stage is set for the integration of this research into a synergistic, interactive model to build a comprehensive three-dimensional turbine gas path heat transfer predictive capability.

At the present time the recommendations for design analyses of turbine gas path convective heat transfer can be separated into two categories: midspan heat transfer and endwall heat transfer.

The midspan region can be defined as the middle 50 to 75 percent of the vane/blade span. It is the region where the endwall boundary layer has little or no influence. The flow is nearly two dimensional or "quasi" three dimensional. The flow can be characterized either by combination Euler/boundary layer codes, such as MTSB, or by Navier-Stokes codes. Care must be taken to have very good modeling for laminar-turbulent transition in the turbine, where transition is subject to many external forces. Good prediction of transition will generally require both sophisticated turbulence modeling and high resolution near the walls. Thin layer or parabolized solutions near the wall should work, since the flows are strongly pressure driven and nearly two dimensional. In summary, the midspan region is one where the flow field should be relatively easy to characterize and the modeling is the issue.

In the endwall region the flow field needs to be characterized well, and the full 3D Navier-Stokes code is the recommended choice for computation. On the other hand, while the turbulence must be modeled, reasonable heat transfer results are not nearly so dependent on the modeling, as they are in transition. Even though the physics are very complex and simple models should not be expected to work, they do a fairly decent job. Mixing-length models, for example, can be made to work. The models of choice, however, are the two-equation (k-ε or q-ω) models. These form an effective compromise between capturing the physics and computational efficiency. They do a better job than the mixing-length models and definitely will help the turbine heat transfer engineer made good design decisions.

What about the future? Where should we be going in our research? First of all, it is our position that for steady-state heat transfer predictive capability we are already into the future. All of the right pieces are in place to make a major assault on turbine gas path heat transfer.

Of course, the list of recommendations for the future could be very long. We will resist the urge to provide laundry lists and just make a few suggestions. First, we strongly believe that experimental/modeling/computational synergism needs to become the accepted way of doing business. It is neither research efficient nor cost effective for everyone to do their own thing, and then try to fit it together. For example, the modeling efforts are getting more and more sophisticated, as are the computational efforts. However, the integration of models into codes frequently remains rather primitive. Code developers use the simplest models that will work in theirs codes, while modelers keep developing models without regard to how they will impact a huge computation of a complex problem. It should be emphasized that this operational model does not have to exist in one organization. The people who can contribute the best, wherever they are, should do the work - just not in isolation.

Second, the key has been, is now, and will continue to be understanding the fundamental physics and modeling it properly. The look to the future needs to emphasize the fundamentals in the more complex problems, that is, get off the flat plate!

Finally, the next real frontier, which we have already engaged, is the unsteady flow physics inherent in turbomachinery. Identifying the key unsteady flow physics and modeling it in very complex geometries is the agenda for the future and will surely occupy the rest of the 1990's.

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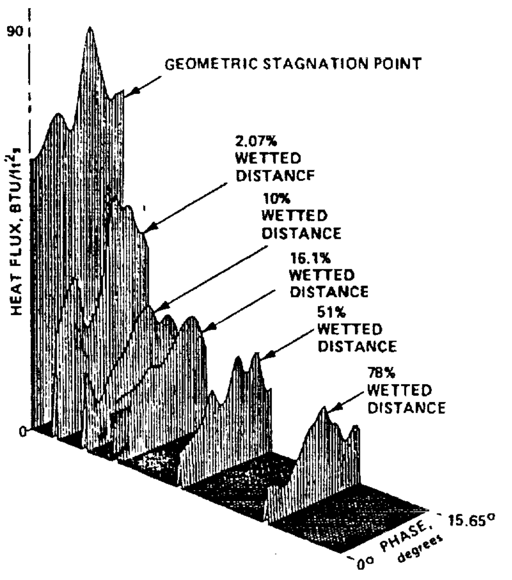
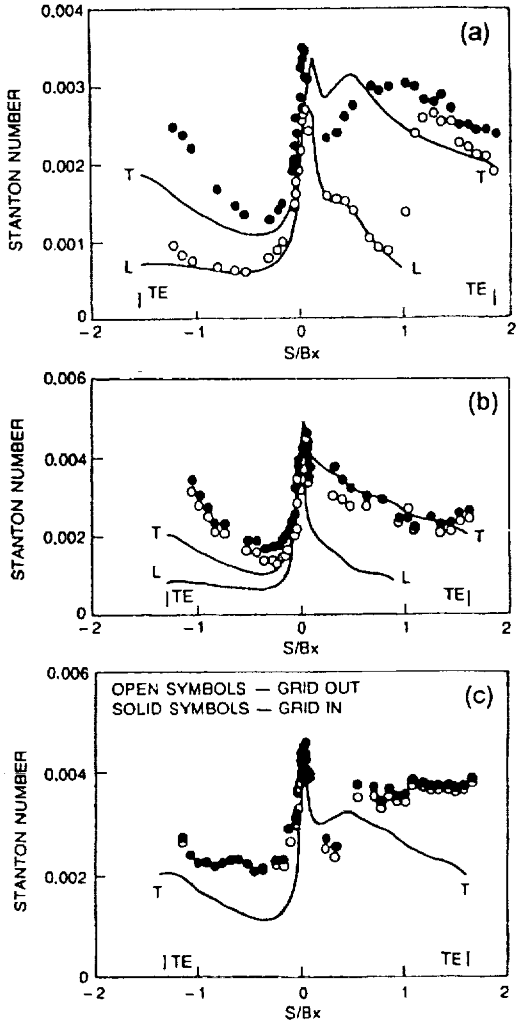


PHASE-RESOLVED CONTOUR PLOT OF HEAT-FLUX DISTRIBUTION ON BLADE SUCTION SURFACE

FIGURE 1. Phase-resolved contour plot of heat-flux distribution on actual turbine hardware suction surface, operating in a shock tunnel (Dunn et al., 1989). Used with permission from the American Society of Mechanical Engineers.



(a) First stator.
(b) Rotor.
(c) Second stator.

FIGURE 2. Midspan heat transfer distributions in a large, low-speed turbine, subject to high and low free-stream turbulence (Blair et al., 1989a, 1989b). Used with permission from the American Society of Mechanical Engineers.

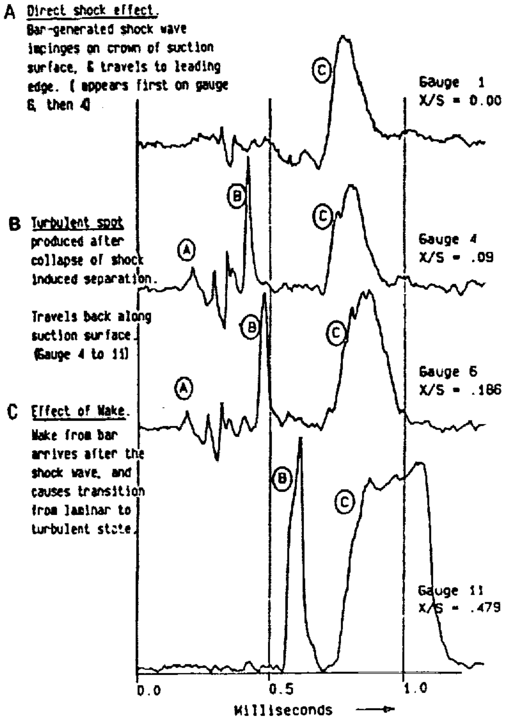


FIGURE 3. Summary of the progression of effects of passing wakes and shocks on heat transfer from a turbine airfoil suction surface (Doorly and Oldfield, 1985b). Used with permission from the American Society of Mechanical Engineers.

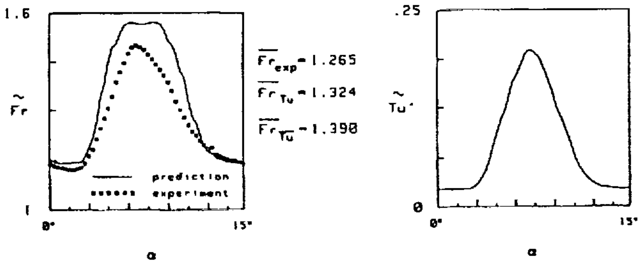


FIGURE 4. Results of using local unsteadiness as a variable to predict stagnation point heat transfer behind a passing wake (O'Brien, 1990).

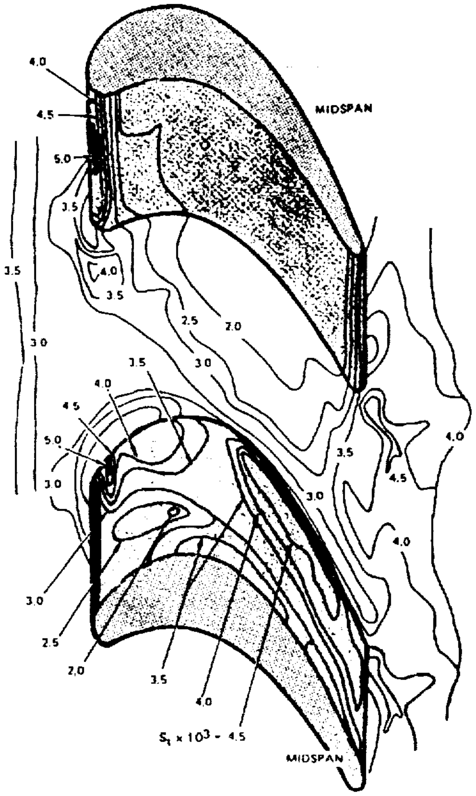


FIGURE 5. Heat transfer (Stanton number) distribution on the endwall and airfoil surfaces in a turbine cascade (Graziani et al., 1980). Used with permission from the American Society of Mechanical Engineers.

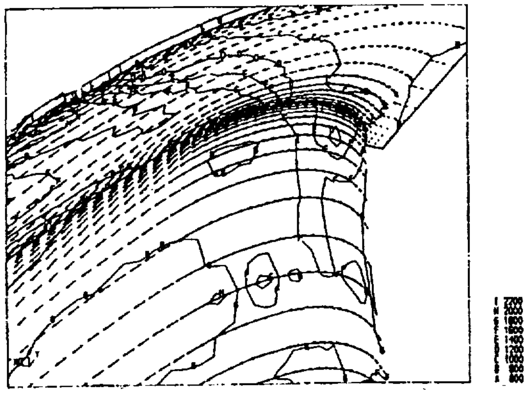


FIGURE 6. Endwall and vane suction surface heat transfer contours and velocity vectors in a full annular cascade of modern airfoil design (Harasgama and Wedlake, 1991). Used with permission from the American Society of Mechanical Engineers.

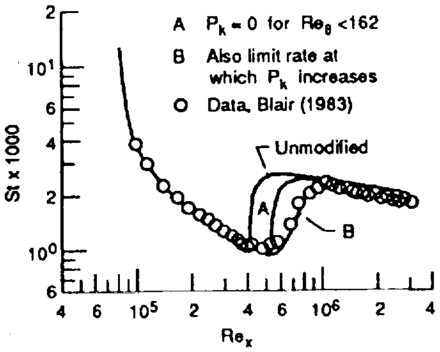


FIGURE 7. Effect of production term modifications to the k-ϵ model in the transition region (Schmidt and Patankar, 1988).

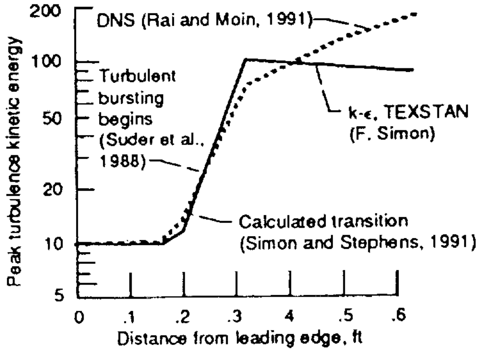
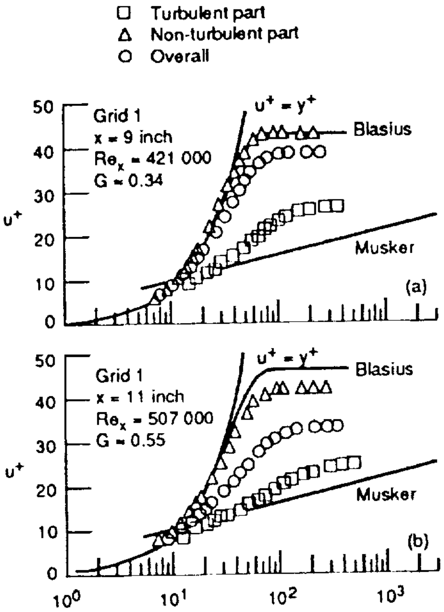


FIGURE 8. Comparison of computed disturbance energy from computations based on a k-ϵ model and on direct numerical simulation (DNS) for bypass transition (Simon and Stephens, 1991; Rai and Moin, 1991).



(a) Intermittency, 0.34.
(b) Intermittency, 0.55.

FIGURE 9. Conditionally sampled velocity profiles in a transitioning boundary layer, subject to 1 percent free-stream turbulence (Sohn et al., 1991).

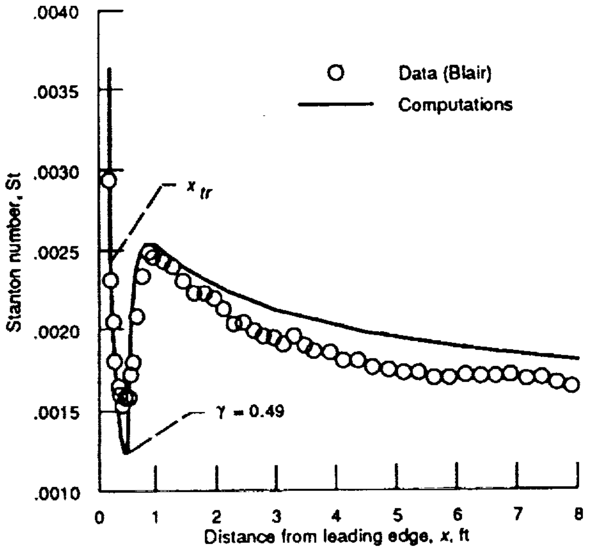


FIGURE 10. Comparison of intermittency based k-ε model prediction to the transitioning heat transferdata of Blair (1983) at a free-stream turbulence of 2.8 percent (Simon and Stephens, 1991).

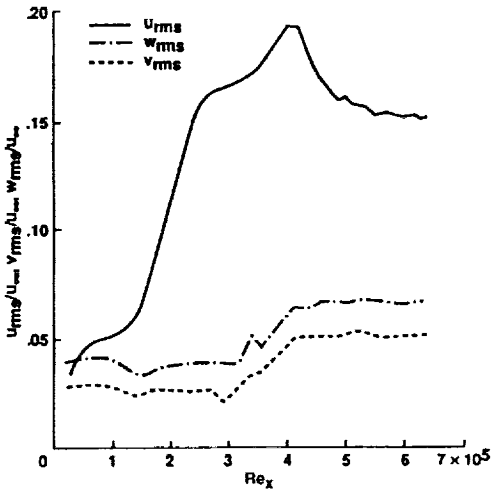


FIGURE 11. Calculation of peak turbulence intensities in a transitioning boundary layer, using direct numerical simulation (DNS) methods (Rai and Moin, 1991).

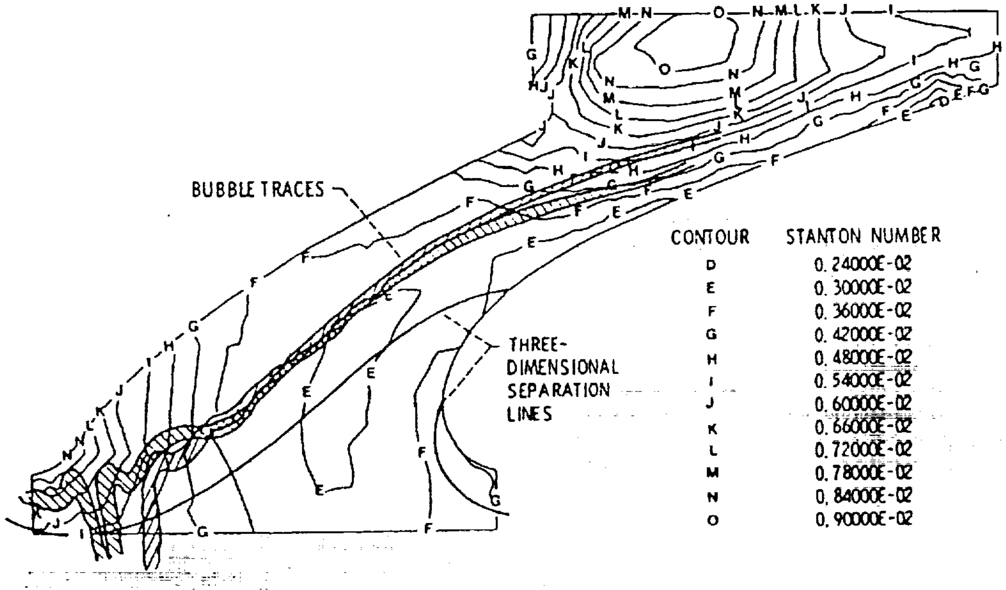
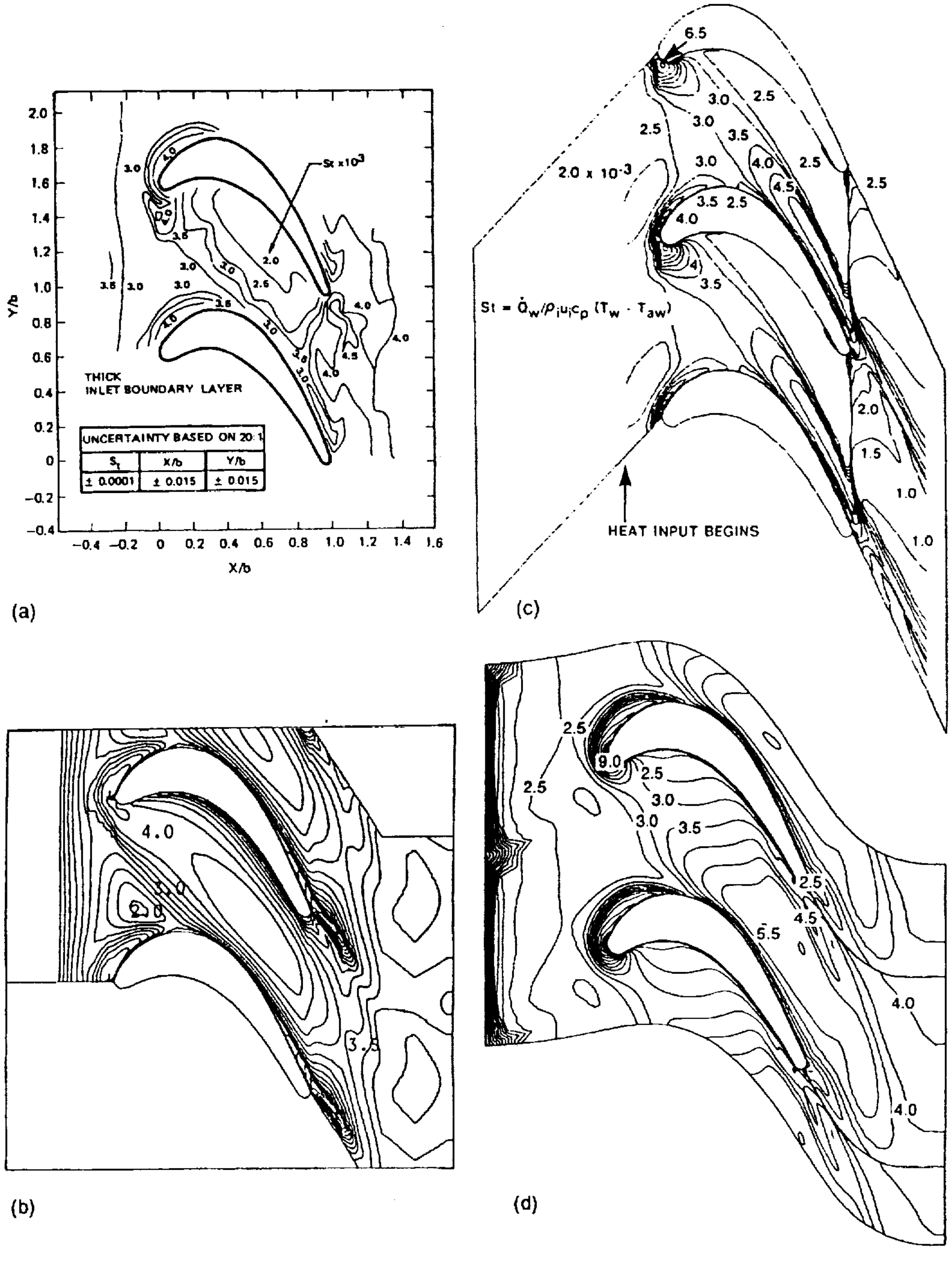


FIGURE 12. Superposition of flow visualization results on endwall heat transfer data of York et al. (1984) (Gaugler and Russell, 1984).



UNCERTAINTY BASED ON 20:1		
S_t	X/b	Y/b
± 0.0001	± 0.015	± 0.015

(a) Experimental data (Graziani et al., 1980). Used with permission from the American Society of Mechanical Engineers.

(b) k-ϵ model (Hah, 1989). Copyright © 1989 American Institute of Aeronautics and Astronautics. Used with permission.

(c) q-ω model (Choi and Knight, 1988). Copyright © 1988 American Institute of Aeronautics and Astronautics. Used with permission.

(d) Baldwin-Lomax mixing-length model (Ameri and Arnone, 1991).

FIGURE 13. Comparison of the use of various turbulence models in full 3D Navier-Stokes calculations of endwall heat transfer data of a turbine blade cascade.

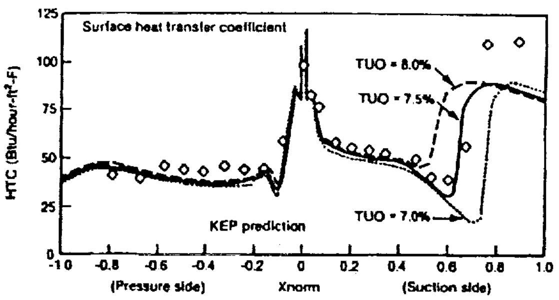


FIGURE 14. Application of boundary layer analysis, using a k-ϵ turbulence model, to turbine airfoil midspan heat transfer (Zerkle and Lounsbury, 1989). Copyright © 1989 American Institute of Aeronautics and Astronautics. Used with permission.

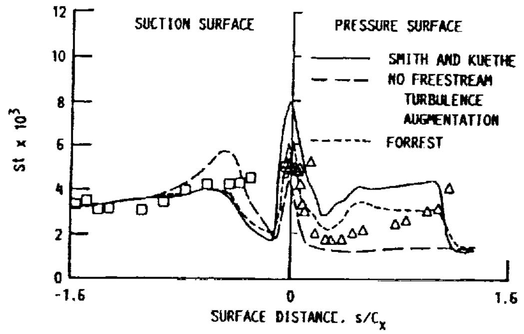
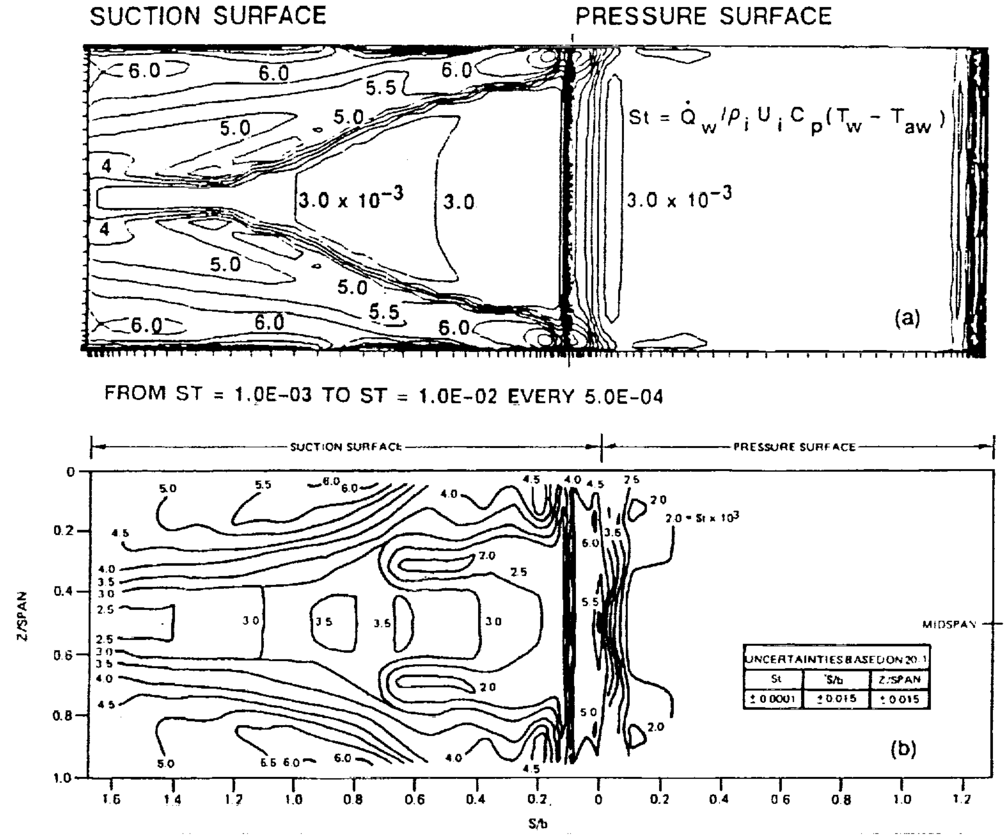


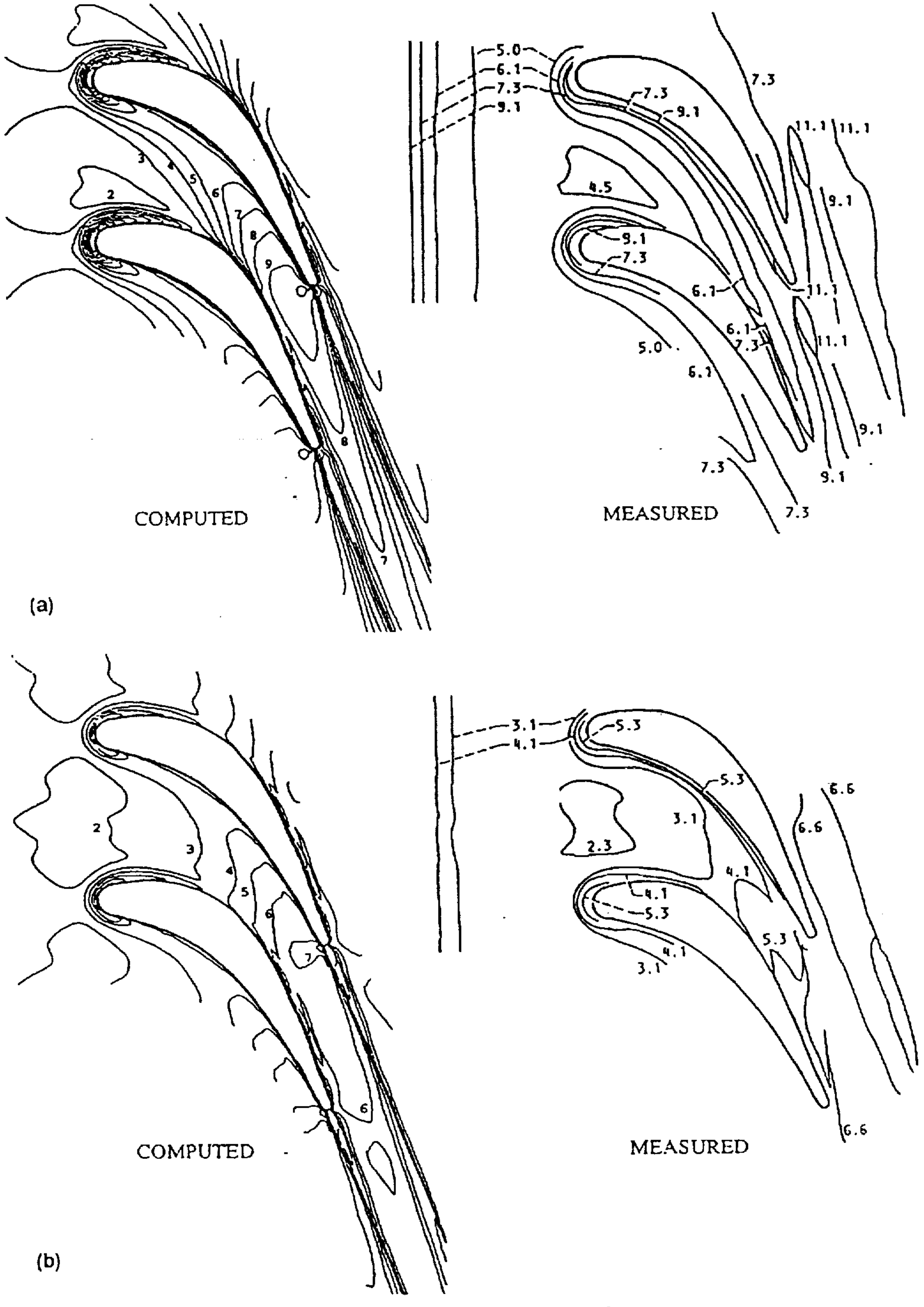
FIGURE 15. Comparison of various turbulence models developed from flat plate data applied to turbine data of Blair et al. (1989a, 1989b), using a quasi-3D Navier-Stokes code (Boyle, 1990).



(a) Experimental data (Graziani et al., 1980). Used with permission from the American Society of Mechanical Engineers.

(b) Calculation (Choi and Knight, 1988). Copyright © 1988 American Institute of Aeronautics and Astronautics. Used with permission.

FIGURE 16. Comparison of full 3D Navier-Stokes code, using a q-ω turbulence model, to turbine cascade heat transfer data.



(a) Low Reynolds number (78,000).
(b) High Reynolds number (490,000).

FIGURE 17. Comparison of full 3D Navier-Stokes calculation, using a new modified Baldwin-Lomax mixing-length model, to endwall data of Boyle and Russell (1990) (Chima et al., 1992).

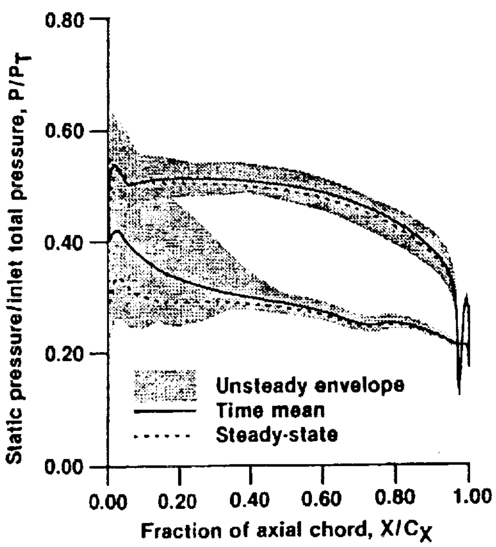


FIGURE 18. Rotor/stator interaction calculations, using a time-accurate Euler solver (Rao and Delaney, 1990). Copyright © 1990 American Institute of Aeronautics and Astronautics. Used with permission.

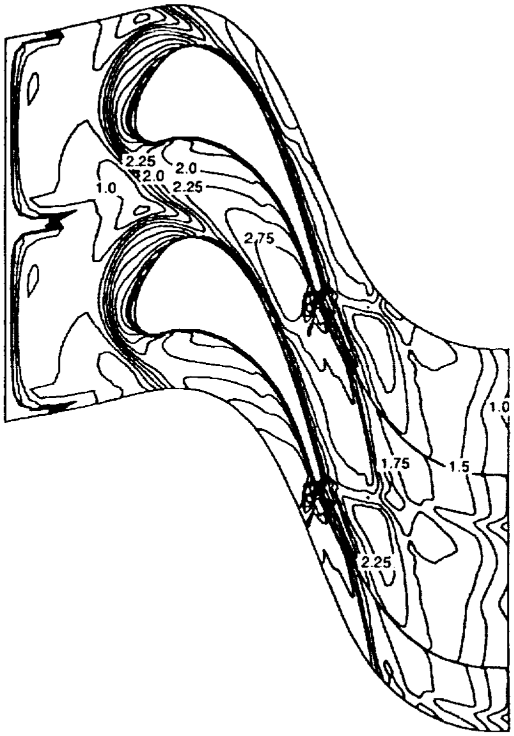


FIGURE 19. Calculations of endwall region heat transfer high-work, high-turning transonic turbine blade cascade, using 3D Navier-Stokes code (Ameri and Arnone, 1991).

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13. ABSTRACT ***(Maximum 200 words)***

A new era is dawning in the ability to predict convection heat transfer in the turbine gas path. We feel that the technical community now has the capability to mount a major assault on this problem, which has eluded significant progress for a long time. In this paper we hope to make a case for this bold statement by reviewing the state of the art in three major and related areas, which we believe are indispensable to the understanding and accurate prediction of turbine gas path heat transfer: configuration-specific experiments, fundamental physics and model development, and code development. We begin our review with the configuration-specific experiments, whose data have provided the big picture and guided both the fundamental modeling research and the code development. Following that, we will examine key modeling efforts and comment on what will be needed to incorporate them into the codes. We will then review progress and directions in the development of computer codes to predict turbine gas path heat transfer. Finally, we will cite examples and make observations on the more recent efforts to do all this work in a simultaneous, interactive, and more synergistic manner. We will conclude with an assessment of progress, suggestions for how to use the current state of the art, and recommendations for the future.

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