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Heat Transfer in Aeropropulsion Systems

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HEAT TRANSFER IN AEROPROPULSION SYSTEMS

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ABSTRACT

An overview and perspective on aeropropulsion heat transfer is presented. A research methodology based on a growing synergism between computations and experiments is examined. The aeropropulsion heat transfer arena is identified as high Reynolds number forced convection in a highly disturbed environment subject to strong gradients, body forces, abrupt geometry changes and high three-dimensionality - all in an unsteady flow field. Numerous examples based on heat transfer to the aircraft gas turbine blade are presented to illustrate the types of heat transfer problems which are generic to aeropropulsion systems. Projections are made for the research focus of the near future in aeropropulsion heat transfer.

INTRODUCTION

The field of heat transfer in propulsion systems is really very vast. Even if one restricts the focus, as the author has, to aeropropulsion systems, the number of heat transfer related technical problems and the body of related research are overwhelming. It is necessary to select a theme or common ground, which will be useful in the context of a seminar on heat transfer problems in high technology and power engineering.

With this in mind the author has chosen to write a paper which will present an overview, or more accurately offer a perspective, on the current status of heat transfer research, applied to aeropropulsion systems, and the directions of the future. In order to do this the author will draw almost exclusively on the NASA Lewis Research Center experience, both in-house and with our contractors. There are several reasons for this. First, this is the work with which the author is most familiar. Second, the illustrations needed to support the ideas presented are readily available. Examples will be drawn from the literature where needed. In doing this there is no intention to imply that Lewis is either the only or the best source of examples, however, it is probably the only major program in the public arena. It is also important to point out here that there is no intention to provide an extensive or critical survey of the literature. The scope is too broad for that. References will be cited to illustrate a point but not to provide a guidepath in any given area. The more traditional and more focused state-of-the-art surveys provide that information.

Within the NASA sphere of interest aeropropulsion systems include both aircraft and space propulsion systems. The primary focus of aeropropulsion heat transfer research over the past 10 to 15 yr has been the aircraft gas turbine engine. Many articles, of which references 1 to 4 are examples, have discussed the technology and the technological problems of the gas turbine engine, shown typically in figure 1. For smaller general aviation aircraft a strong interest continues in internal or intermittent combustion engines (5), figure 2. The Space Shuttle Main Engine (SSME), figure 3, is the primary space propulsion system of recent interest. Although it is an excellent performer, it has experienced some durability problems (6).

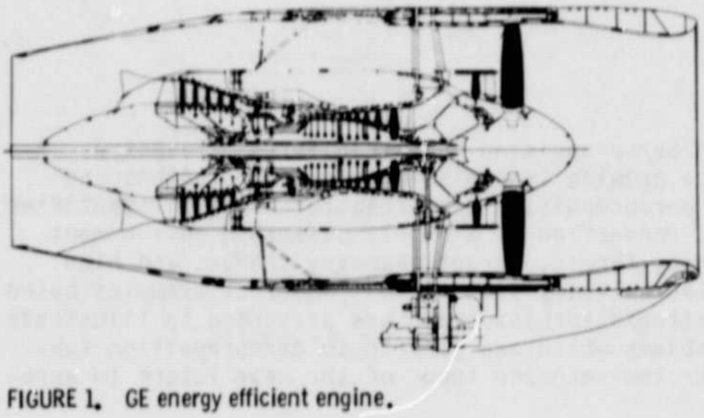

FIGURE 1. GE energy efficient engine.

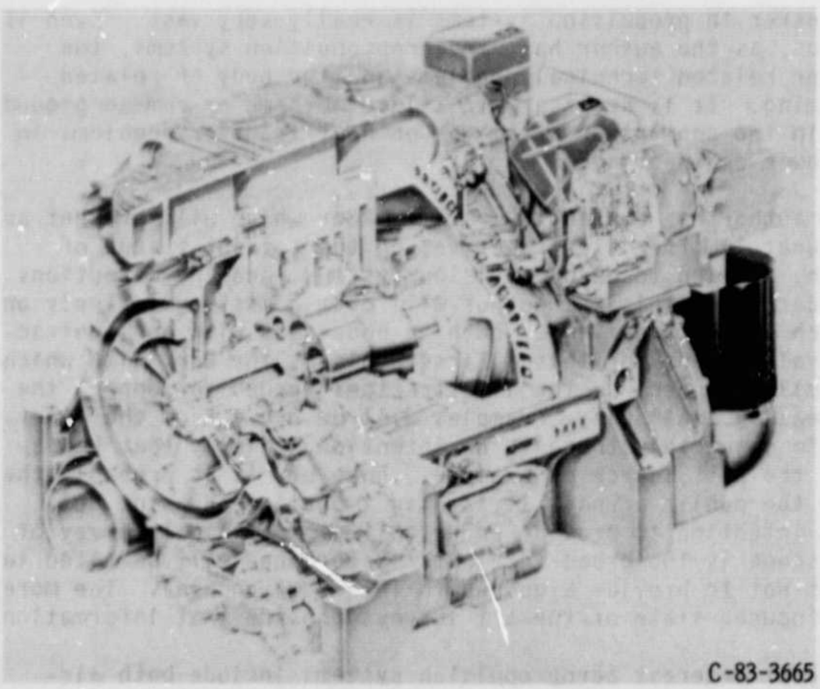

FIGURE 2. Curtiss-Wright rotary combustion engine.

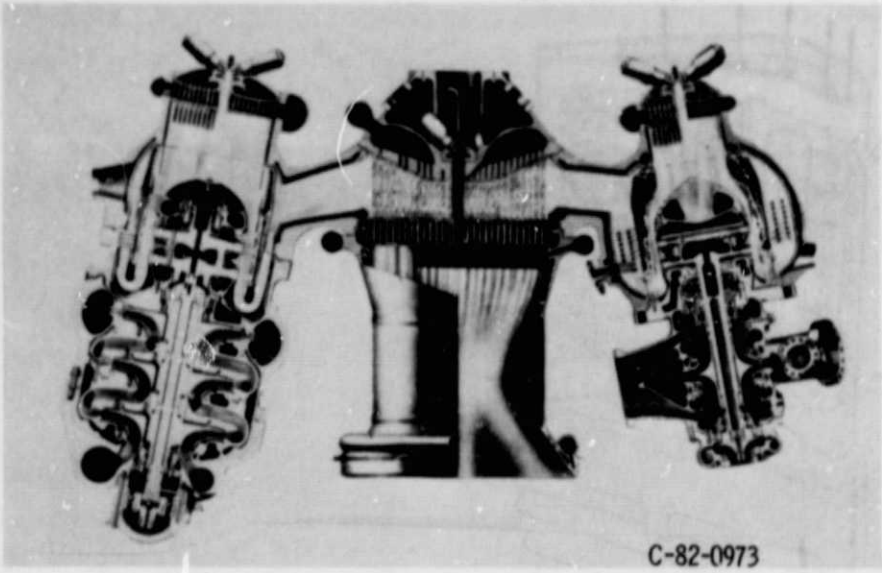

FIGURE 3. SSME powerhead component arrangement.

It is this author's opinion that we are on an exciting place on the learning curve. Our ability to make measurements and to make computations far exceeds anything that one could have imagined only a short time ago. Combining these two powerful abilities is just beginning to occur. These combined abilities are truly synergistic in that the whole created by their interactive use will be greater than the sum of their parts. It is a good time to examine heat transfer research in aeropropulsion systems.

THE COMMON THEME OF AEROPROPULSION HEAT TRANSFER

Important for research, is an understanding of the role of heat transfer in the overall design of propulsion systems. Heat transfer is not the primary function, and consequently not the primary design consideration, of a propulsion system. Heat transfer is normally viewed as a problem, a rather substantial problem at that. Because the objective of the design is always to increase propulsion efficiency there is motivation for sustained research in those areas, especially the fluid mechanics, which will result in greater performance. Because it is more problem driven, heat transfer research tends to be more uneven in intensity. When a heat transfer problem appears to be limiting a design the "research" is intense. When the problem is solved, or bypassed, the motivation to continue research in that area wanes. This is not to say that heat transfer is given little consideration in design. It is very important, especially in providing the thermal boundary conditions for stress analysis. It is just that the problem solving nature of the approach tends to make it difficult to establish a long term generic heat transfer research program. Despite this difficulty it has been possible to identify a class of heat transfer problems, important to aeropropulsion systems, which need and are receiving active research.

Propulsion systems, whether aero or otherwise, have a number of features from a heat transfer perspective which are more or less common to all such systems. This allows research to be structured along generic lines into classes of problems. It also allows one to draw general implications from research in a specific area, such as the aircraft gas turbine.

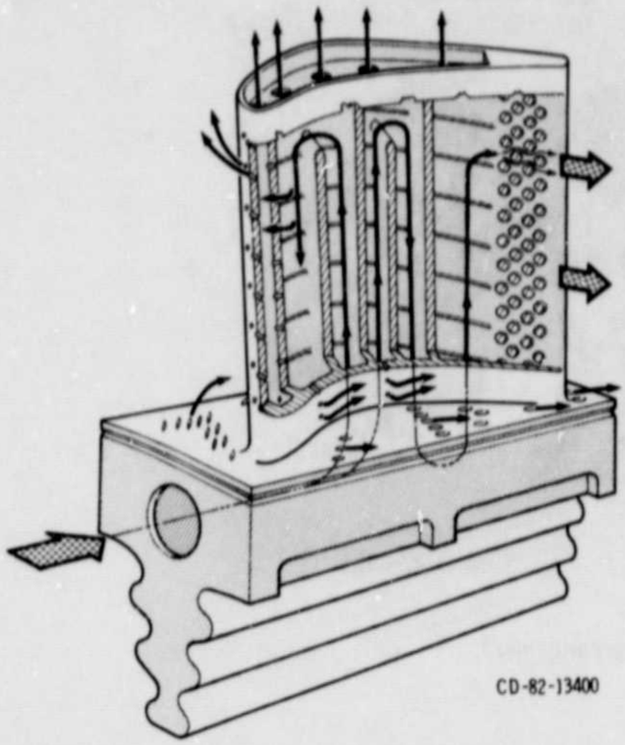

FIGURE 4. A typical cooled aircraft gas turbine blade.

The primary drivers in the design of aeropropulsion systems are performance and durability. From a heat transfer perspective the primary motivator is durability, the ability to design a propulsion system so it can perform at a desired level without premature structural failure due to high temperatures or large temperature gradients. The link between performance and durability should be obvious. In 1980, Stepka (7) made an analysis of the uncertainties associated with gas turbine airfoil heat transfer. 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. It is estimated (2) that these uncertainties could lead to an order of magnitude uncertainty in life prediction. The gas turbine community has been aggressively pursuing research programs directed at improving the ability to predict metal temperature distributions. An example of an important industry/university/government program directed towards improved durability of gas turbine engines is the NASA Hot Section Technology (HOST) program (8). The emphasis in HOST is on the ability to predict temperature and life.

And just what is it that one wishes to predict? Heat transfer research which is characteristic of aeropropulsion systems can be placed in the following technical arena: (1) forced convection, often with superimposed body forces; (2) high Reynolds number flow; (3) flows with high free-stream turbulence; (4) highly three-dimensional flow with a large regions of viscous flow; (5) abrupt geometry changes; (6) strong pressure and temperature gradients; and (7) unsteady flow fields. In addition some systems, such as the space propulsion systems, encounter strongly variable property, even two-phase, fluids. To fully analyze propulsion heat transfer it is also necessary to be able to solve the three-dimensional heat conduct problem for both steady and transient conditions. This then is the area of heat transfer research that is of interest to the aeropropulsion community.

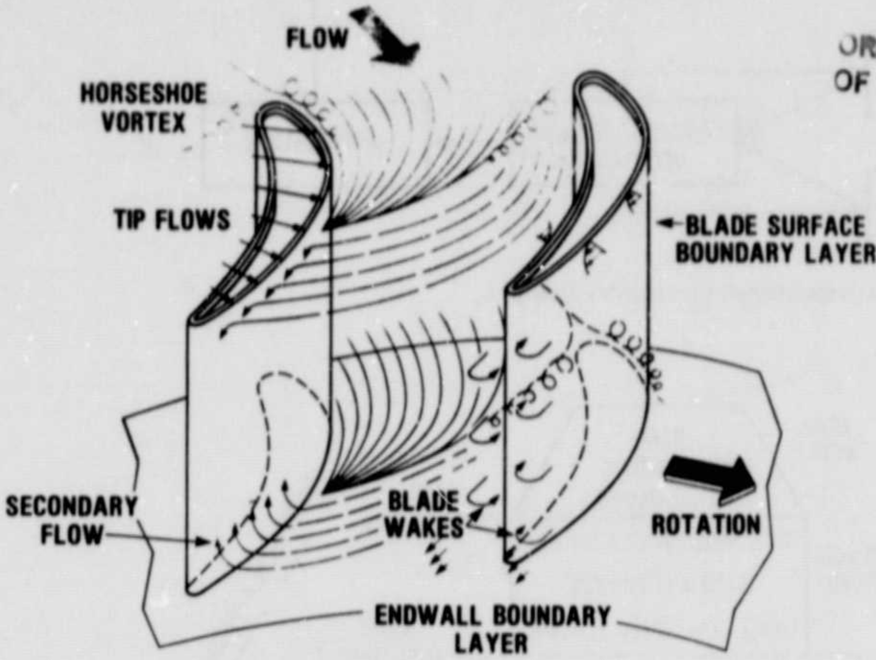

FIGURE 5. Some of the complex flow phenomena in a turbine passage.

In order to illustrate the nature and progress of research in this technical arena, this paper will zoom in on one feature, which in this authors opinion represents the common ground of aeropropulsion heat transfer, the cooled aircraft gas turbine blade. Figure 4 is an illustration of modern cooled turbine blade. It is a very complex, highly stressed, and very compact heat exchanger. The internal heat transfer paths are many, varied and complex. The "external" flow field around the airfoil, illustrated in figure 5, is equally varied and complex. One can see in these sketches the heat transfer technical arena described above. This example is chosen, of course, because of the author is familiar with the problem area, but it is also clear that it is a problem area which is generic to most propulsion systems.

PHILOSOPHY OF APPROACH

Before going into specific examples it is important to make a few comments on philosophy of approach. As said earlier, we are at a point where our ability to measure and compute quantities has taken a significant step upward. This in turn is influencing our approach to heat transfer and fluid mechanics research. Along with this increased ability has come increased complexity. This increased complexity brings increased cost in both time and money. Random experimentation and analyses of interesting problems, while still very important, are giving way to synergistic computational/experimental interactive methodologies. As illustrated in figure 6, a kind of feedback loop of interactive research is replacing isolated efforts. Because the research is becoming so complex and because the heat transfer environments in aeropropulsion systems are so hostile, it is important that a logical set of research building blocks are established to guide the programs. Figure 7 illustrates the building blocks we see to be necessary to successfully attack heat transfer research in an aircraft gas turbine.

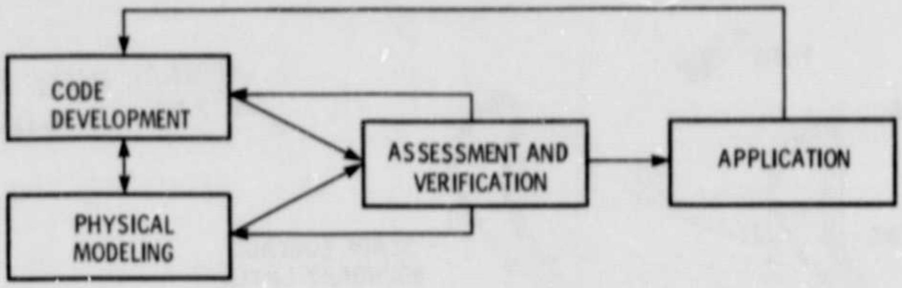

FIGURE 6. Interactive computational/experimental synergism.

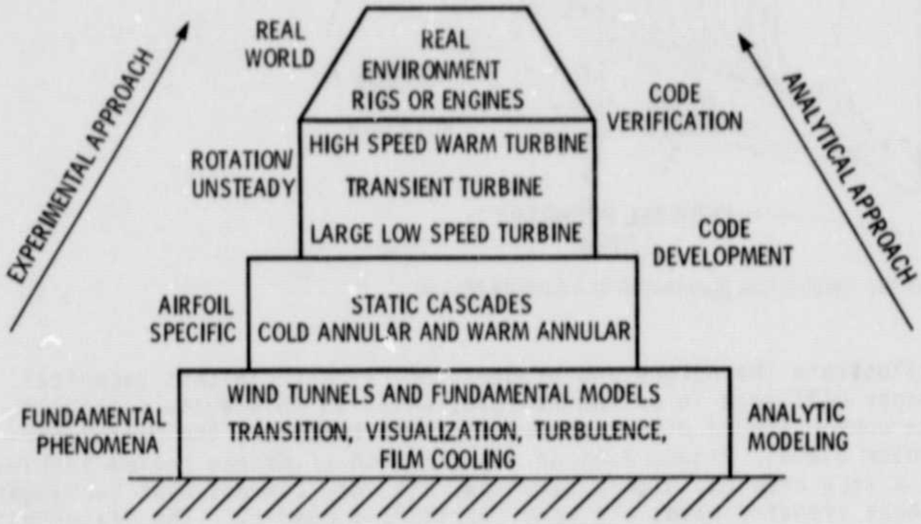

FIGURE 7. Building block approach to turbine aerothermal research.

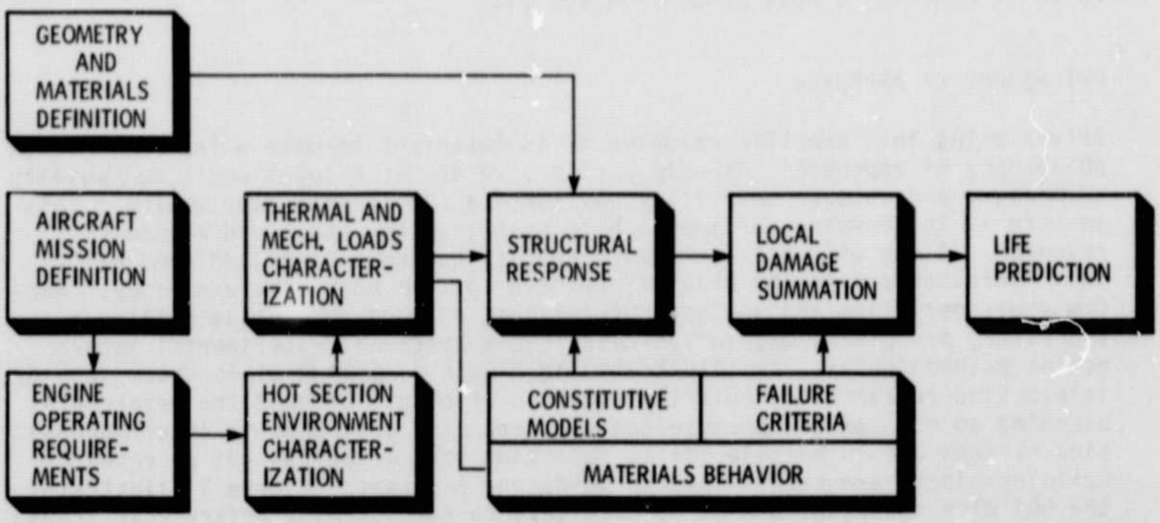

FIGURE 8. Interdisciplinary research methodology for life prediction of turbine engine hot section subcomponents.

In addition the growing need for accurate aerothermal loads predictions, as a critical first step to accurate life and durability predictions, is producing coordinated interdisciplinary research programs. The NASA HOST program (8) is such an example. NASA has a similar program (9) directed at Space Shuttle Main Engine (SSME) durability. A flow chart of the interdisciplinary HOST program is shown in figure 8. The key feature of the chart for us is that, while life prediction is the goal, thermal loads prediction is a critical first step.

One can see immediately that the computational/experimental feedback loop, the research building blocks, and the interdisciplinary flow chart are not unique to the aircraft gas turbine. They are generic to any aeropropulsion system, or for that matter any propulsion system. The specific technical problems will change slightly from system to system, although here too there is significant common ground. It is definitely possible to establish a common technical arena and establish a generic research methodology for heat transfer in aeropropulsion systems.

EXAMPLES OF CURRENT TECHNOLOGY

It is important to pause a moment and discuss the aeropropulsion heat transfer problem as an "internal fluid mechanics" problem. The flow in propulsion system passages, no matter how complex, is ultimately bounded or guided by walls and mass is conserved. The overwhelming majority of aeropropulsion heat transfer problems are internal flow problems.

Even though the flow is always internal, sometimes the communication between walls is small, say when the passage width is large compared to the local boundary layer thickness. This is especially true along mean sections of airfoils. In these cases heat transfer problems can sometimes be treated locally as though they were in an external flow field and external techniques, such as boundary layer theory, are applied. In most cases, however, the presence of the nearby walls cannot be ignored.

To avoid confusion over the word internal the following research examples will be divided into propulsion gas path heat transfer and coolant passage heat transfer. It is primarily the gas path where the external flow concepts can be applied. In addition this section on examples of current technology will discuss unsteady flows, turbulence modeling, the turbine blade as a heat exchanger, and variable property fluids. With these thoughts in mind let us return to the author's selected microcosm of aeropropulsion heat transfer technology, the cooled turbine blade, figures 4 and 5.

Propulsion Gas Path Heat Transfer

The main reason for examining the gas path separately is that it is more amenable to external aerodynamic treatment. The complex turbine passage, figure 5, is frequently broken down into simpler separate effects phenomena for research focus. The airfoil boundary layer, the airfoil/endwall intersection, and the stagnation region, for example, are each treated separately. The designer often patches these local solutions together into a design method.

There is probably no better place to start than with the flat plate boundary layer. Of particular interest in propulsion heat transfer is the laminar-turbulent transition region. Recently Gaugler (10), using the STAN5 boundary layer code (11), examined the laminar-turbulent transition region of several

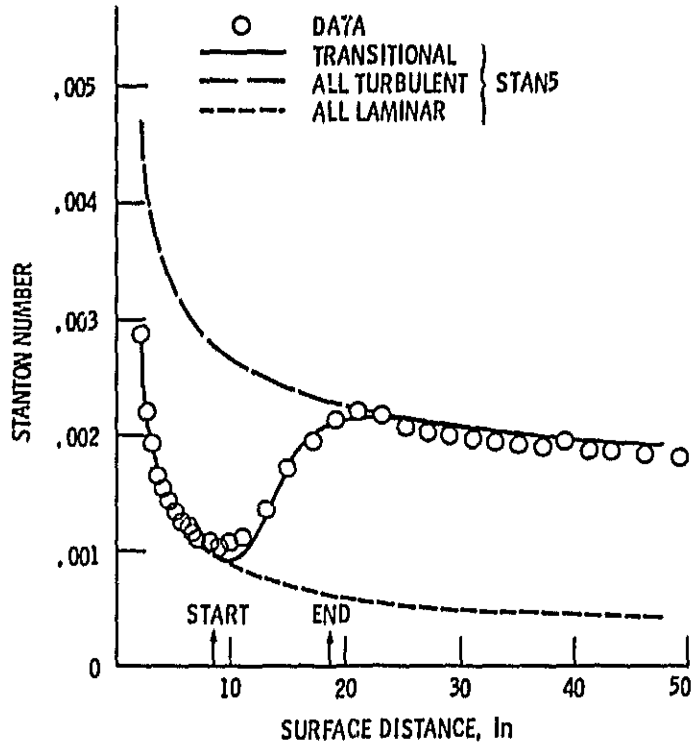

FIGURE 9. Data and prediction of flat plate heat transfer.

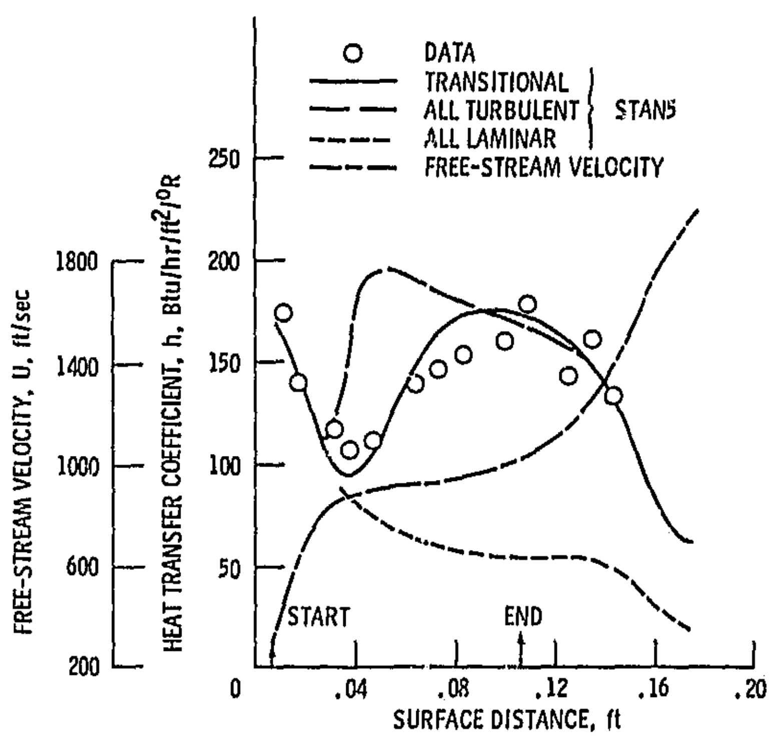

FIGURE 10. Heat transfer coefficient as a function of surface length. turbine vane suction surface.

airfoils. Using the very fine experimental flat plate data of Blair (12) as a reference, Gaugler showed that the ability to predict flat plate transitioning heat transfer is well in hand, figure 9. Heat transfer to airfoils is another matter. Figure 10 shows the Lander airfoil experimental data (13), which has been in the literature for some time now. In order to correlate it, as well as shown, Gaugler (10) had to manipulate STAN5 considerably. Note, for example, that transition was started in the code well before the heat transfer data would suggest it should have been. Despite the high turbulence (18.7 percent), the strong acceleration competes with it, as the boundary layer develops, and transition occupies fully half the blade. These types of strong competing forces are not uncommon in aeropropulsion systems.

Another effect important to airfoil heat transfer is curvature. Since curvature and free stream pressure almost always go together in the propulsion gas path, these effects are difficult to separate. Fundamental research on the heat transfer effects of curvature without pressure gradient has been conducted at Stanford (14, 15). The heat transfer data, shown in figure 11, indicate a significant reduction in heat transfer relative to the flat plate due to curvature. This, of course, was not unexpected, since convex curvature should be expected to produce a thicker boundary layer. The surprise was that the recovery to flat plate levels in the downstream straight section was much slower than expected. The research of Simon and Moffat (14) also included the effects of acceleration. The follow-on work (15) included film cooling.

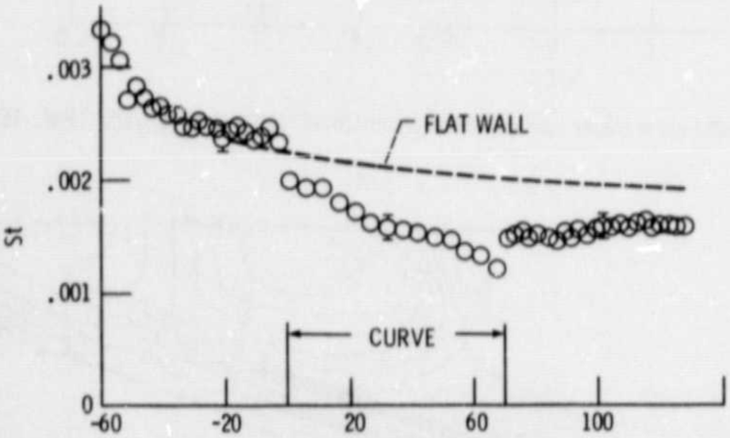

FIGURE 11. The effect of streamwise convex curvature on turbulent boundary layer heat transfer-the baseline case. (Ref. 14.)

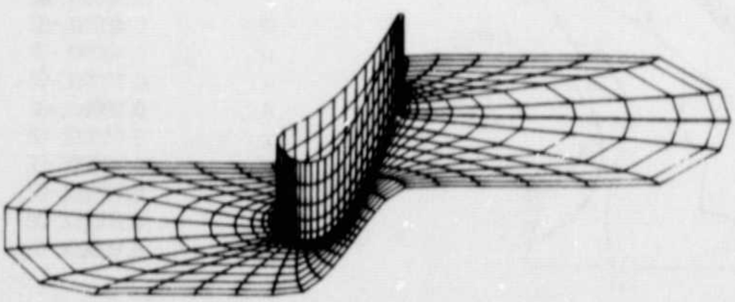

FIGURE 12. Typical O-grid meshes required to compute turbine flows.

Even though boundary layer analyses provide important insight, the long term will require something much more sophisticated than boundary layer codes, and efforts are well underway. Figure 12, is an example of a grid used in the MINT code (16), a full three-dimensional Navier-Stokes solver with heat transfer. Heat transfer calculations along a vane midspan are compared to data in figure 13. The transition start was forced but the rest of the calculation shows fine agreement. This work was done under the HOST program (8).

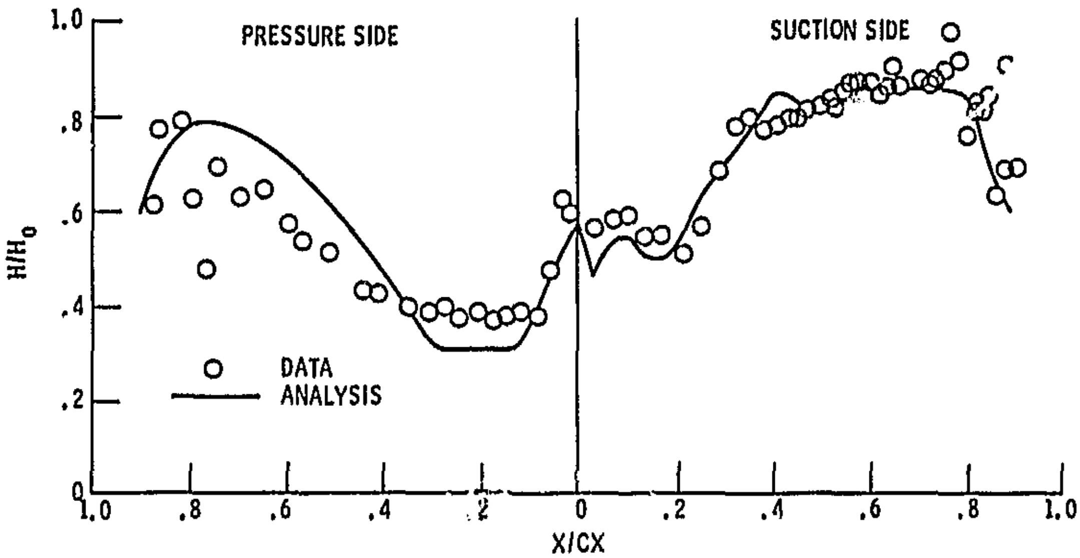

FIGURE 13. Calculation of turbine airfoil heat transfer using a three-dimensional Navier-Stokes code. (Ref. 16).

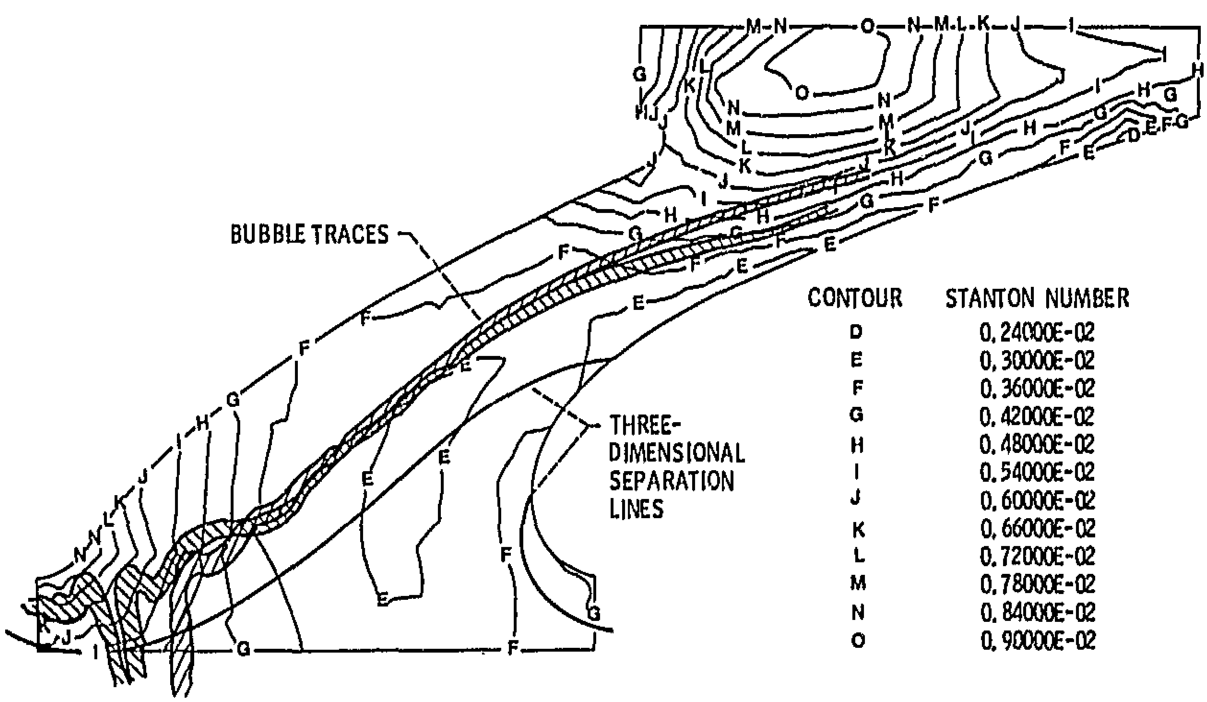

FIGURE 14. Turbine vane endwall Stanton numbers w... flow visualization results superimposed.

An area of importance that will surely require a full three-dimensional code is the intersection between two surfaces, such as the airfoil/endwall. Some time ago a significant body of heat transfer and flow data were generated by Allison Gas Turbine (17). The Stanton number contours shown in figure 14 reveal a very complex heat transfer pattern. Superimposed on figure 14 is the locus of the horseshoe vortex, as determined visually by Gaugler and Russell (18), using helium filled soap bubbles, as shown in figure 15. The high Stanton numbers near the leading edge fall right under the horseshoe vortex. Also superimposed on figure 14 is the three-dimensional separation line, as determined by ink dot traces on the endwall and shown on figure 16. In addition work is currently underway, using liquid crystal techniques, to further refine this complex heat transfer region. This combination of carefully acquired local heat transfer data and flow visualization have provided an excellent data base to the code developer and should provide considerable guidance as to what features the code must model. This is an area where simplistic modeling has not been adequate and the data clearly lead the analysis.

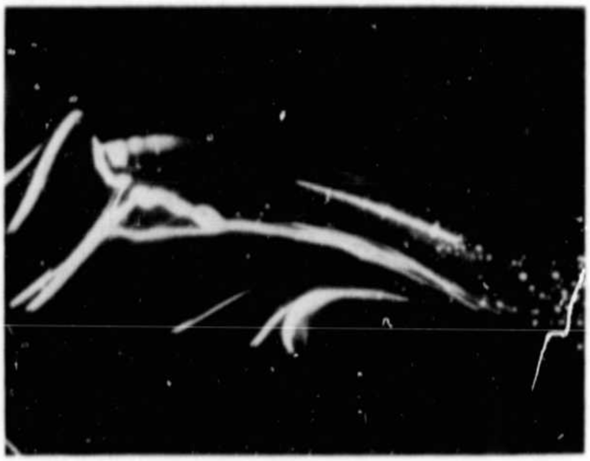

FIGURE 15. Neutrally buoyant, helium-filled, soap bubble traces in the endwall boundary layer.

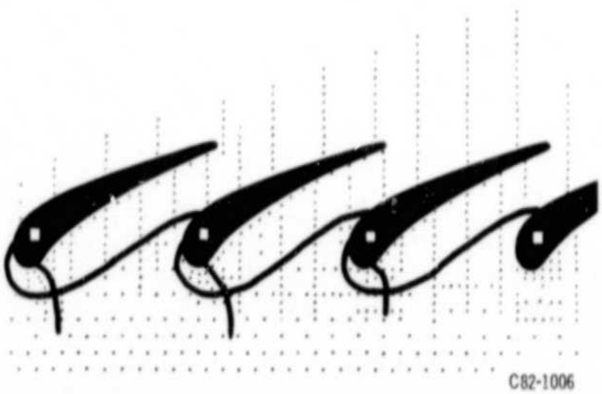

FIGURE 16. Ink dot flow visualization of the end wall surface secondary flows.

Stagnation regions are important regions wherever they occur in propulsion systems, because they are high heat transfer regions. On the turbine blade it is the leading edge. These are usually circular or near circular. Thus studies of heat transfer to circular cylinders are valuable. Figures 17 and 18 taken from a study by VanFossen and Simoneau (19) show wire wake turbulence and consequent heat transfer from a circular cylinder. Using a combination of hot wire anemometry, smoke wire visualization, and liquid crystals, they showed that the high heat transfer in the stagnation region occurred between, not under, the vortex pairs formed on the leading edge. They concluded that any proper model should show that fluid is being convected from the free-stream to the surface by the vortex pairs.

An important challenge to the computational/experimental methodology is the presence of highly localized surface heat transfer phenomena, such as discreet hole film cooling used in advanced cooling concepts. The big flow codes are

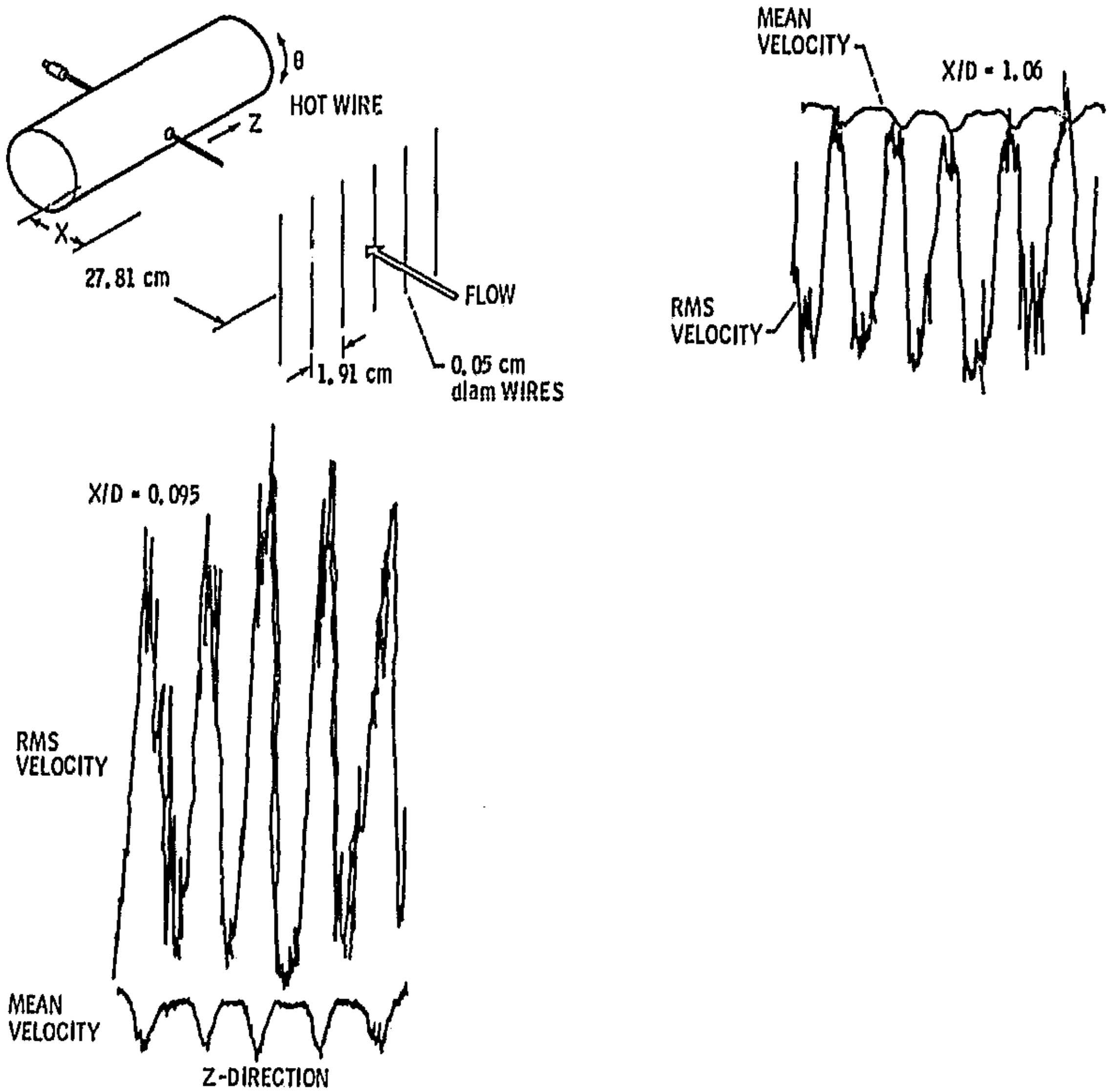

FIGURE 17. Spanwise traverses of a hot wire near the cylinder stagnation point. (NOTE: Abscissa of RMS and mean velocity plots offset slightly due to pen offset on x-yy' recorder.)

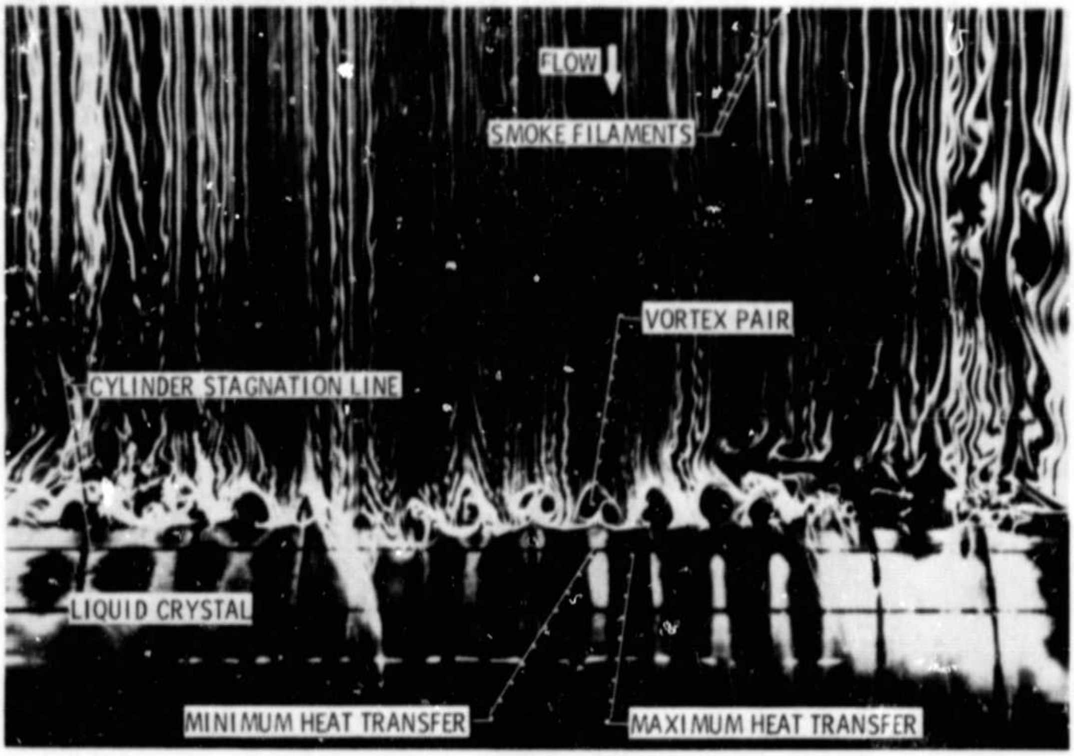

FIGURE 18. Combined thermal and flow visualization of cylinder in cross flow.

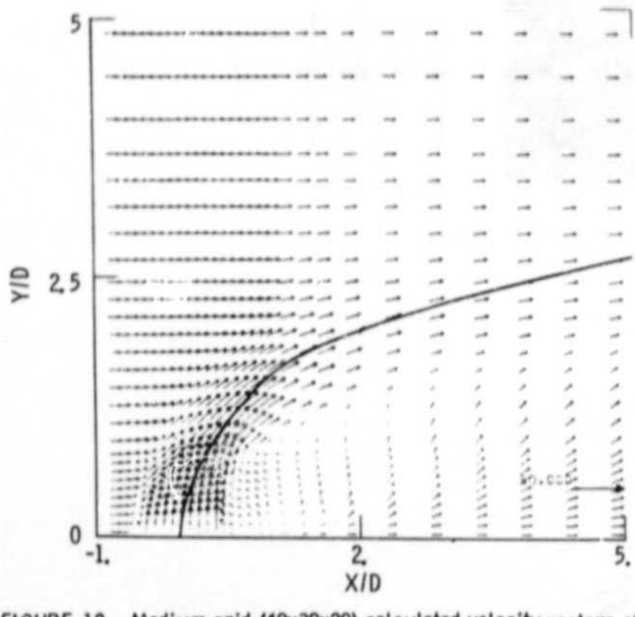

FIGURE 19. Medium grid (40x30x20) calculated velocity vectors of single, free jet flow field. Shown is the x-y plane throught the jet centerline with the solid line indicating empirical, trajectory correlation.

not likely to ever place more than a few grid points in the region of a film cooling hole, and yet the flow is really quite complex. This complexity is illustrated in figure 19 for some recent calculations by Claus (20) for a 90° jet. Calculations by Patankar (21) show similar complexity. Film cooling is a much studied subject (22) but the focus has been primarily on correlating cooling effectiveness. Work by Papell (23) on the effectiveness and by Simon and Ciacone (24) on the jet trajectory, shown in figures 20 and 21, for various hole shapes, indicates that modeling the region of flow near a film cooling hole will be very complex. If by simply shaping the hole one can control the jet trajectory, then the computational detail must be quite complex. It is hoped that research on the nature of the flow field and heat transfer, coupled with detailed analyses, will lead to analytic models, which will allow the

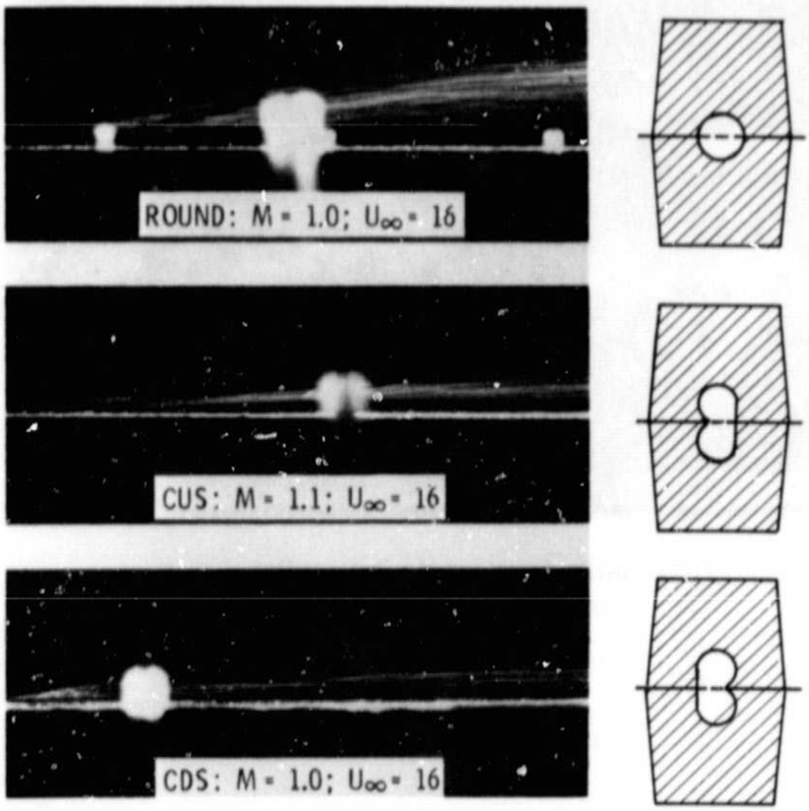

FIGURE 20. Flow visualization of film cooling jet trajectories.

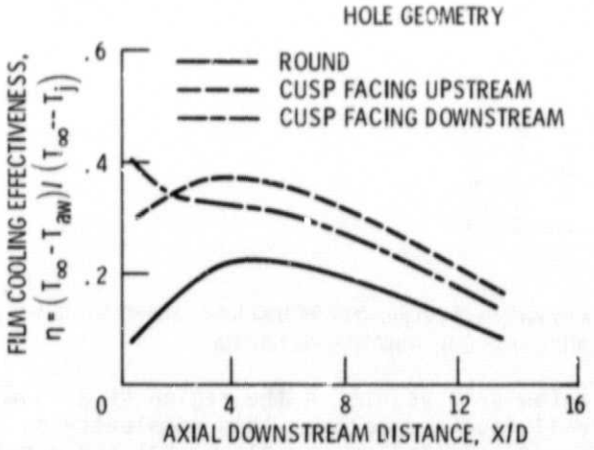

FIGURE 21. Centerline film cooling effectiveness as a function of axial distance, M = 1.0.

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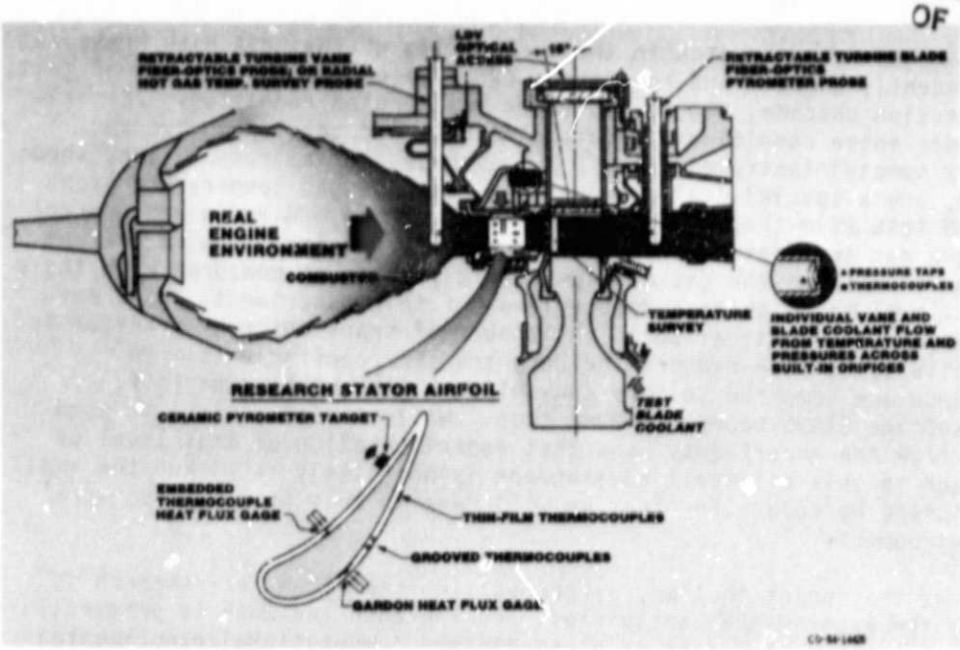


FIGURE 22. Hot section cascade rig.

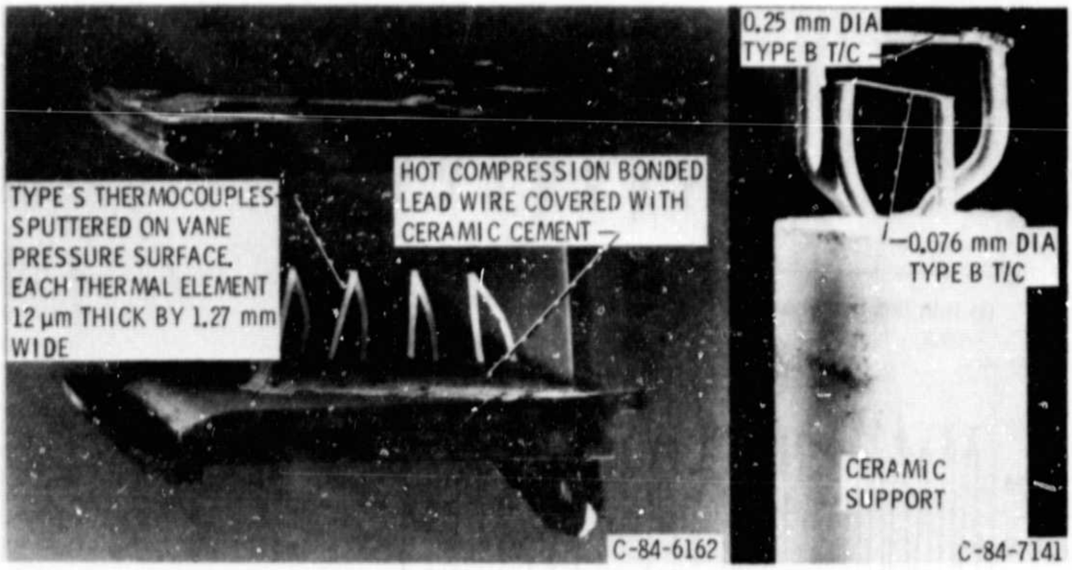
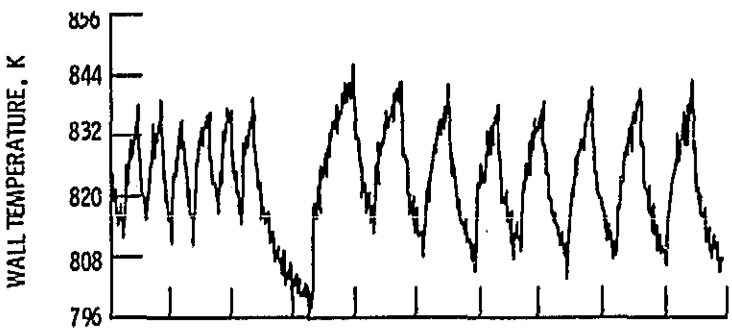


FIGURE 23. High temperature, high response heat transfer instrumentation.

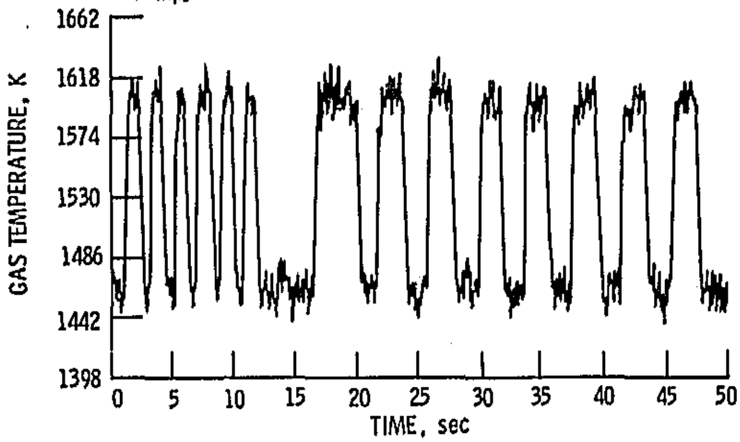
complex codes to compute near a film cooling hole with minimal grid points. Meanwhile the designers must rely heavily on condition specific data, such as shown in figure 21.

All of the examples discussed so far have been drawn from the lower tiers of the building blocks. Aeropropulsion research is also being carried out at the higher levels as well. Most of the engine companies and some research labs have rotating rigs and heated rigs which more closely approach the real world. Some of these will be discussed in the section on unsteadiness. Here we will draw some examples from research in the turbine leg of the NASA High Pressure Facility. Recently Gladden and co-workers (25, 26) conducted a series of tests in the hot section cascade, figure 22, under real engine conditions. Experimentation under these conditions is very difficult and very expensive and requires very special instrumentation. Two examples of instrumentation, shown in figure 23, are a special dual element high response gas temperature probe and sputtered thin film thermocouples on a vane surface. Gladden and Proctor (26) created a gas temperature transient by ramping the fuel flow to the combustor. Figure 24 shows the gas and surface responses, as measured with these instruments. Note the high temperature level of this experiment. By a correlation analysis and application of the theory of transient heat transfer in a semi-infinite solid they deduced the heat transfer coefficients. In figure 25 these are compared to more conventional instrumentation (c.f. figure 22) and the STAN5 boundary layer code. While the comparison is good one can see from the uncertainty band that experimentation at this level of complexity and in this difficult environment is not likely to pickup the small nuances exhibited by code. For that we will have to rely on data from more friendly environments.

In general, at this point in time, aeropropulsion heat transfer research is being led by the experimental activities. Furthermore the work is primarily problem driven, rather than part of a coordinated computational/experimental methodology. This interactive methodology is coming, but it has not arrived.



(a) Thin film thermocouple (TTFIO) response to gas temperature ramp.



(b) Gas temperature ramp measured by the 0.025 cm element of dual - element probe.

FIGURE 24. Typical time histories of gas and wall temperatures during 2 and 4 second ramp cycles. Reynolds number=1.2×10^6.

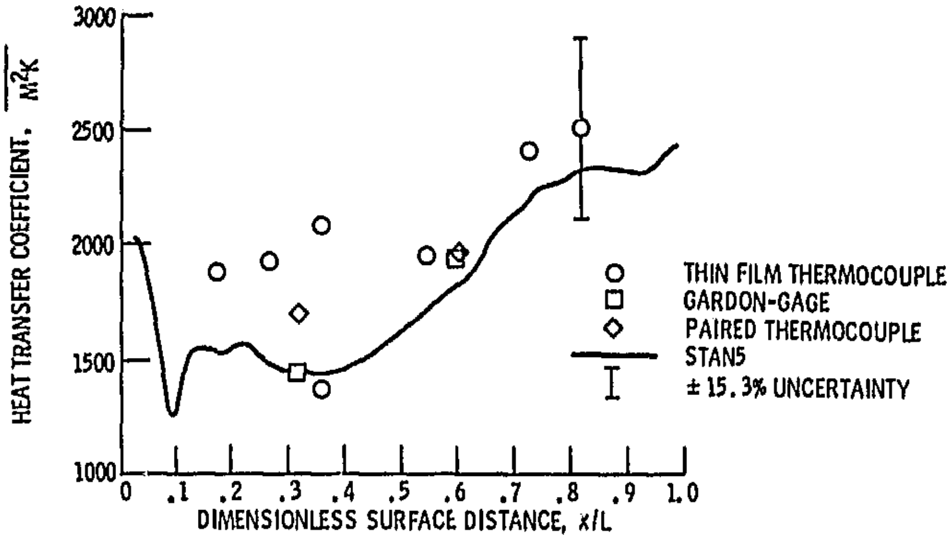


FIGURE 25. Experimental heat transfer coefficient on the airfoil pressure surface compared with STAN 5. Reynolds number = 1.20×10^6.

This is not to say that there is no computational activity. There is currently a considerable effort in internal computational fluid mechanics (27-29); however, at present it is primarily directed at flow field calculations with little emphasis on heat transfer.

One exception to this statement may be in the area of duct flow calculations. Aeropropulsion systems are full of short and weird shaped transition ducts which connect one component to another. These ducts often have complex flows and are usually not amendable to boundary layer methods. As a result three-dimensional viscous flow codes for ducts have been under development for some time now. Some of these ducts are downstream of the combustion chamber and are exposed to the hot gases. Anderson (30) recently defined a set of complex exhaust ducts in need of heat transfer research. An example is shown in figure 26. Using the PEPSI-G code (31), he computed the viscous flow field.

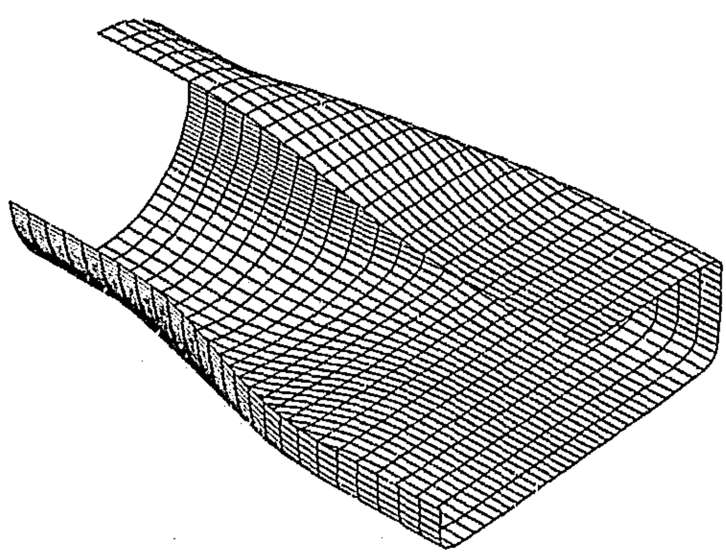


FIGURE 26. Typical engine exhaust nozzle transition duct.

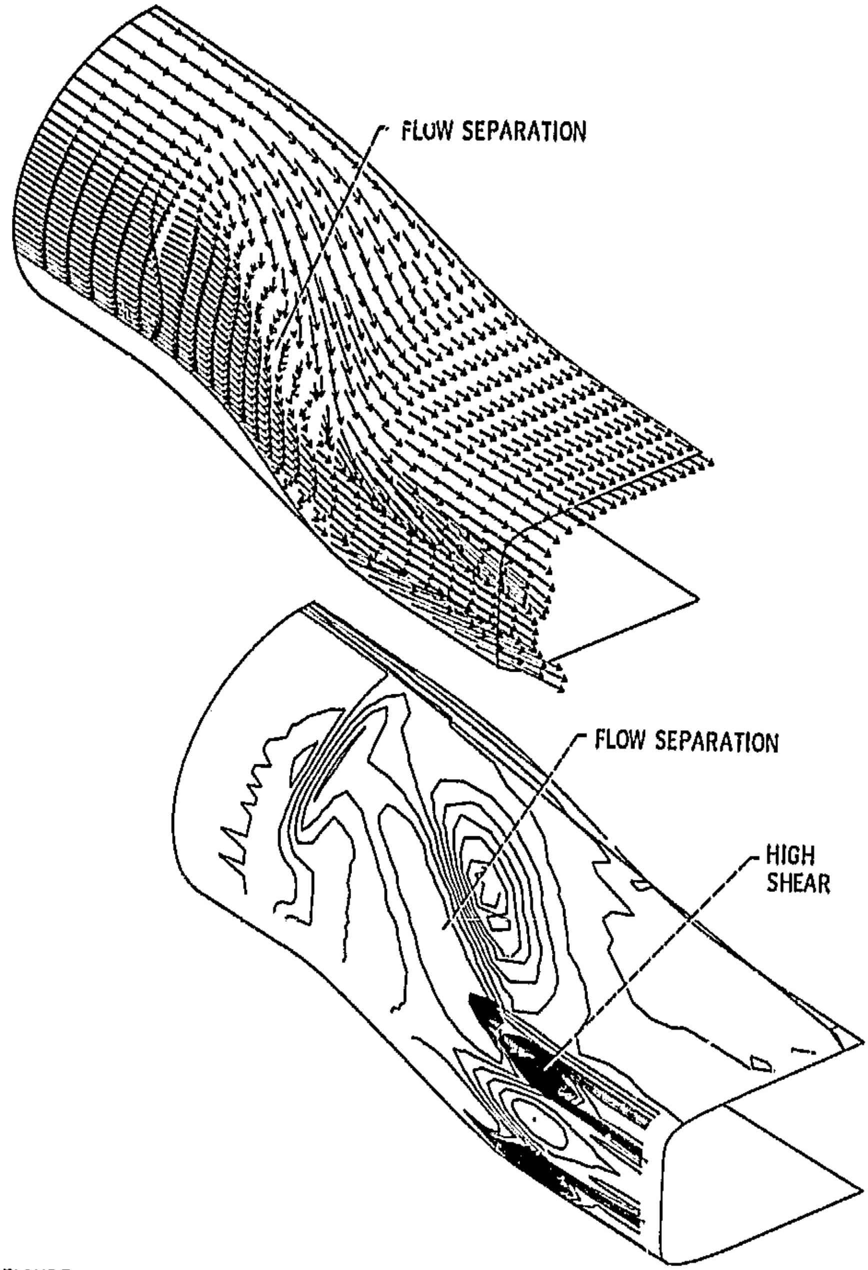


FIGURE 27. Computed near wall velocity vectors and surface shear stress in a transition duct.

Figure 27 shows the near wall velocity vectors and surface shear. The high shear areas can be expected to be high heat transfer areas. The energy equation is currently being added to the PEPSI-G code and an experimental heat transfer and flow program is being initiated. It is expected that this program will follow the computational/experimental feedback shown in figure 6.

Coolant Passage Heat Transfer

In the aeropropulsion gas path minimizing pressure loss is directly related to performance, so every attempt is made to keep surfaces smooth and gradual. This is not quite so true in the cooling passages, where space and high local heat transfer are the premiums. Return for a moment to figure 4, the sketch of a cooled turbine blade. The variety and complexity of the coolant flow passages are obvious. They contain serpentine passages with turbulence promoting trip strips, impingement cooling, and turbulence pins near the trailing edge, just to mention a few schemes. While the focus is on the turbine blade, similar cooling passages exist in many different types of engines. This leads to a body of research that is very geometry specific and heavily dependent on experimentation and the correlation of data. Yeh and Stepka (32) offer a good survey on coolant passage heat transfer.

There are very few flow codes directed at heat transfer in internal passages. The TEACH code, developed by Patankar and Spalding (33) is one example that has been used for many years for computing heat transfer in coolant passages. Unfortunately, coolant passages are frequently so complex that grid resolution is a real problem and the codes are receiving only limited use. More often one must rely on correlation, as in the following examples.

The small pedestals at the trailing edge of an airfoil serve two purposes. They are both a structural element and a heat transfer promoter. Although they are often called pin fins, they are frequently not truly extended surfaces, since they often cover more surface than they add. They are turbulence promoters. VanFossen (34) found that by defining an effective heat transfer coefficient based on wetted areas, the data could be correlated in standard fashion. The results, shown on figure 28, show an increase in heat transfer, falling between plain surfaces and true fins. Of course, this method yields only average results.

Another area that has been approached by a data correlation method is impingement cooling. Correlations based on data, such as one by Kercher and Tabakoff (35) are in wide use. Research by Florrschuetz et al., (36), shows that, while average correlations can be established, large swings in local heat transfer occur between the holes, figure 29. This was nicely demonstrated by use of the liquid crystal method of Hippensteele and Russell (37), as shown in figure 30. Impingement cooling is to the coolant passages what film cooling is to the gas path. Both flows yield highly local complex phenomena that provide a real resolution problem to codes. This type of nonuniform thermal load is important to stress analysis. Some very good analytic modeling will be needed to resolve this properly.

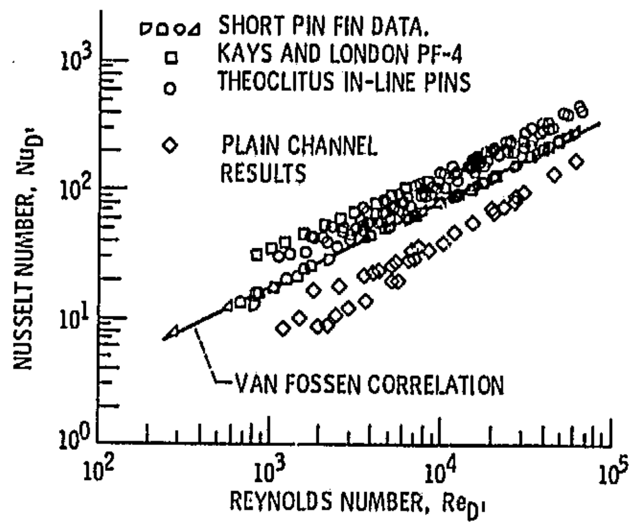


FIGURE 28. Comparison of short pin fin data with long pin data and plain channel data.

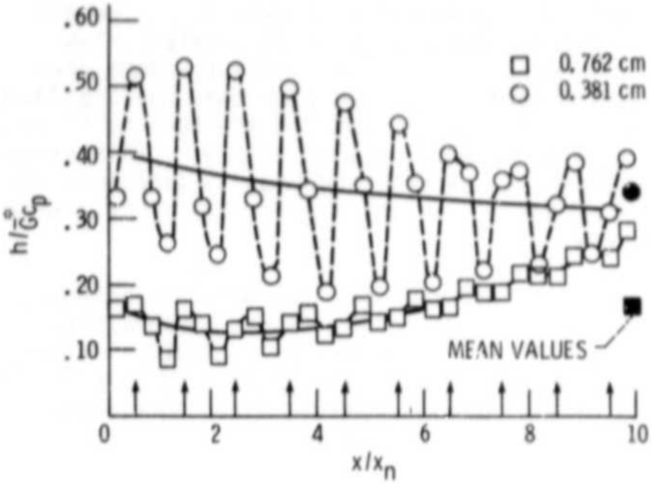


FIGURE 29. Effect of hole diameter on chordwise periodic variations, smoothed profiles, and mean values of heat transfer coefficient for fixed $\bar{G}^{\circ}$ – inline hole pattern for impingement cooling. (Ref. 3)

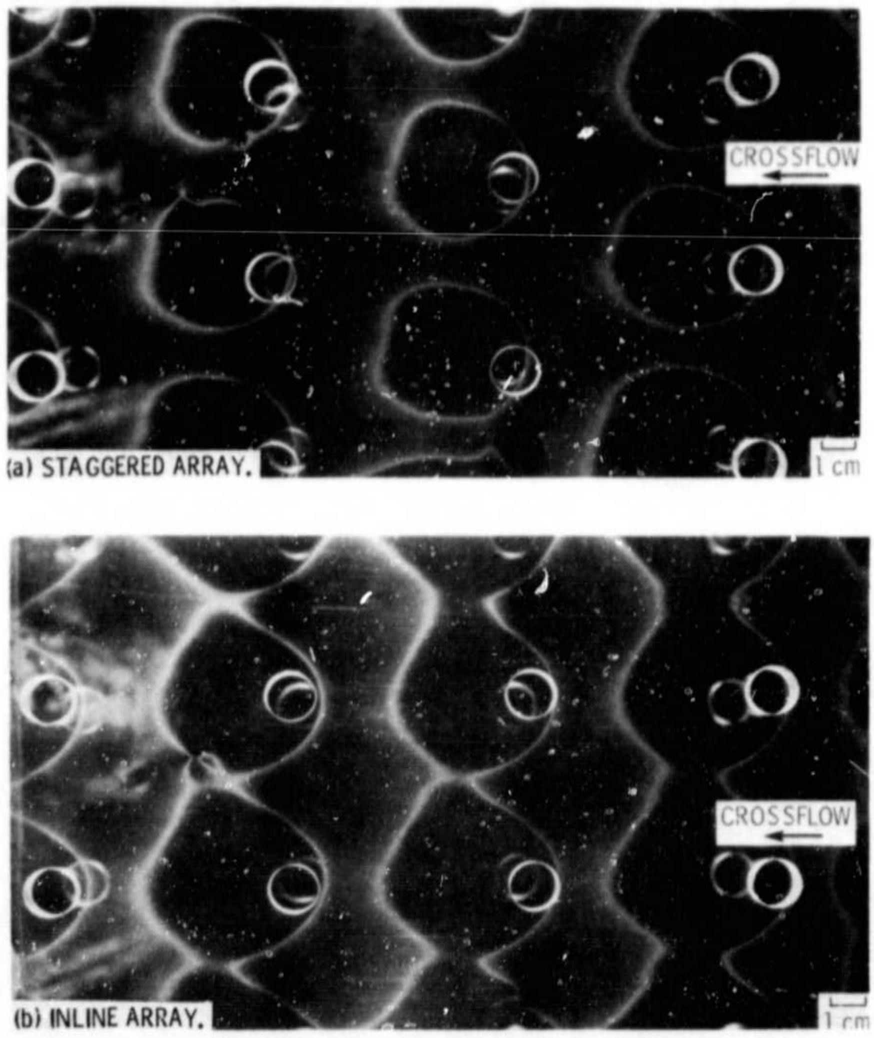


FIGURE 30. Impingement cooling heat transfer visualization with liquid crystals.

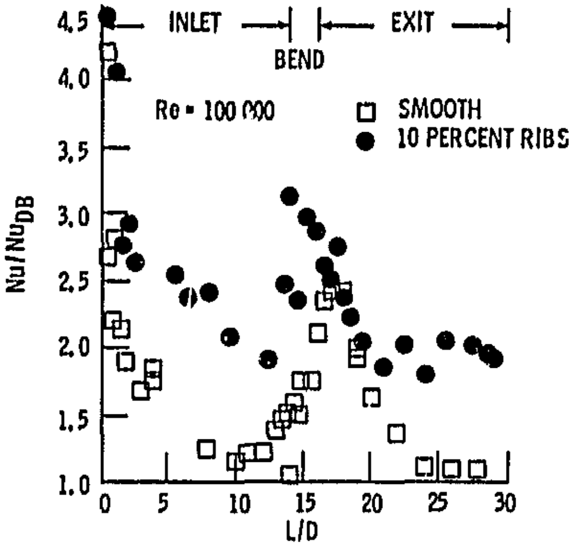


FIGURE 31. Effect of turbulence generating ribs on heat transfer in a serpentine internal coolant passage.

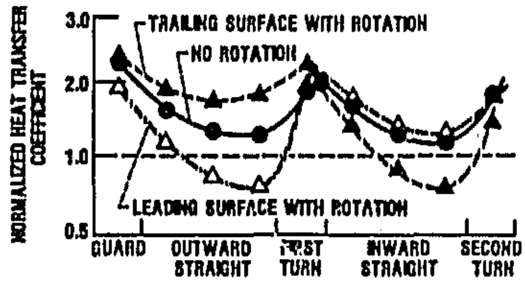


FIGURE 32. Effect of rotation on coolant passage heat transfer.

The serpentine or multipass configuration, as shown in figure 4, is typical of advanced airfoil cooling concepts. The data of Boyle (38) are shown on figure 31 for this type of configuration. They are for a square passage that flows in one direction then abruptly turns back 180°. The results show a strong entrance effect which is barely leveled off when the turn arrives and a new "entrance" seems to appear. The addition of turbulating strips or ribs shifts the heat transfer up almost uniformly over the whole passage.

The coolant passages are generally thought to be more sensitive to rotational effects than the propulsion gas path flow field. Some recent data being generated in the HOST program (39), shown in figure 32, would support that idea. These data for a rotating multipass channel show significant variations across the passage as a result of rotation. Full details will be available in about two years. A recent experiment by Epstein (40) shows the effects of rotation on a leading edge impingement cooled passage.

Unsteady Flow Field Heat Transfer

Except for a rocket nozzle most aeropropulsion systems transfer their power with moving parts. Even the SSME has two turbines in the gas path. Thus, in the normal mode of operation the propulsion gas path is an unsteady flow field. The treatment of the flow unsteadiness, especially its effect on heat transfer, is relatively new. It promises to be an exciting and challenging research field. At the moment the experimental work is leading the analytic, however some interesting analyses are beginning to emerge.

Most of the early unsteady flow work has been aerodynamic in nature and directed at aeroelastic phenomena, such as component blade flutter. Recently, however, the attention as turned to wakes and wake propagation through turbomachinery. Recent papers by Hodson (41) and Binder et al., (42) have focused on the behavior of wakes in turbine rotors. Work on wakes is also underway at NASA (43). All of this will be important to the heat transfer community. Of particular interest is the work of Dring et al., (44). They instrumented the rotor blade surface with high response pressure sensors and thin film sensors.

A typical unsteady surface pressure and thin film response for a suction surface gauge is shown in figure 33. The passing of the upstream vane is marked on the figure. The superposition of the boundary layer turbulence on the flow unsteadiness can be seen in the data. The challenge will be to separate the two and evaluate their effect, if any, on heat transfer.

Efforts to look at the heat transfer are already well underway. In fact, with respect to unsteady work an interesting phenomenon is occurring. In steady state experiments surface heat transfer is frequently the last thing measured. The measurements are difficult and by nature usually quite intrusive. Knowing the surface heat transfer does not help much in describing the flow field. As a result, in the steady state the initial effort, both experimentally and analytically, focuses on the flow field. Only after this is done do we turn our attention to surface phenomena. By contrast in unsteady flow the measurement of surface heat transfer can tell one something of the nature of flow. Anyone who has worked with hot wire anemometry knows this. The thin film measurements shown in figure 33 are heat transfer based. In addition unsteady heat transfer can be determined in a less intrusive manner than steady. All of this has combined to make heat transfer a primary measurement in unsteady flow fields and the heat transfer data is evolving as rapidly as the flow field data. A welcome and exciting development.

The unsteady flow field heat transfer work divides into two categories; the effect of unsteady flows on steady heat transfer (i.e., time-averaged) and the unsteady heat transfer itself (i.e., time-resolved). The work of Dring et al., (44), Simoneau et al., (45) and Gladden and Proctor (26) are examples of the former. We will discuss the latter in a little more detail.

Propulsion related unsteady heat transfer is being studied in both rotating machines and in simulations. The experimental facilities range from shock tunnels to short duration tunnels to steady running rigs. Dunn (46, 47) has installed a full single stage turbine in a shock tunnel. He instruments the surfaces with thin film sensors and reduces the data employing a transient heat conduction analysis for a step change in heat transfer on a semi-infinite solid. The test times are about 30 ms. A typical heat transfer trace is shown in figure 34. The wake passing time is marked. In this environment, without ensemble averaging on the wake event, it is hard to tell if there is a specific wake related heat transfer or not. At Oxford University (48, 49) a light piston short duration tunnel is used. The test time is about an order of magnitude greater, 300 ms. This allows time for some flow field measurements. The rotor is simulated by a spoked wheel of small rods passing in front of a linear

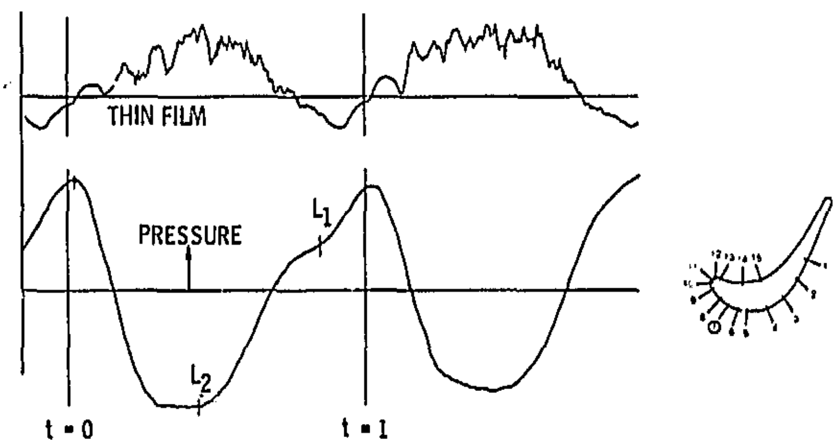


FIGURE 33. Rotor pressure and thin film data on the suction surface of a rotating blade. (Ref. 44.)

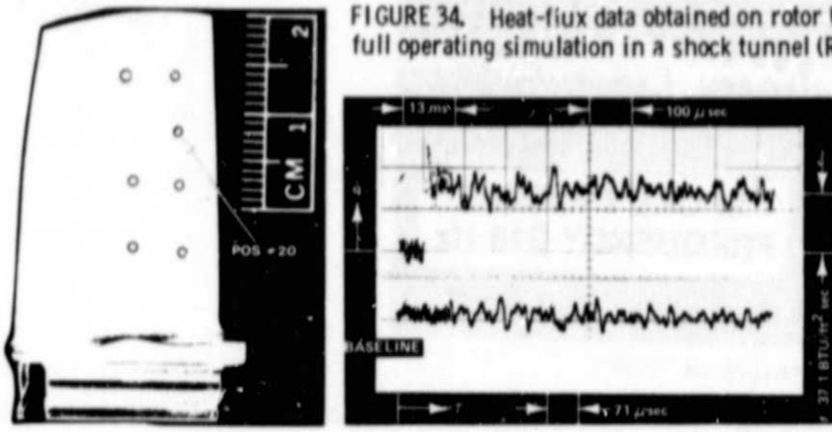


FIGURE 34. Heat-flux data obtained on rotor blade suction surface at full operating simulation in a shock tunnel (Ref. 47).

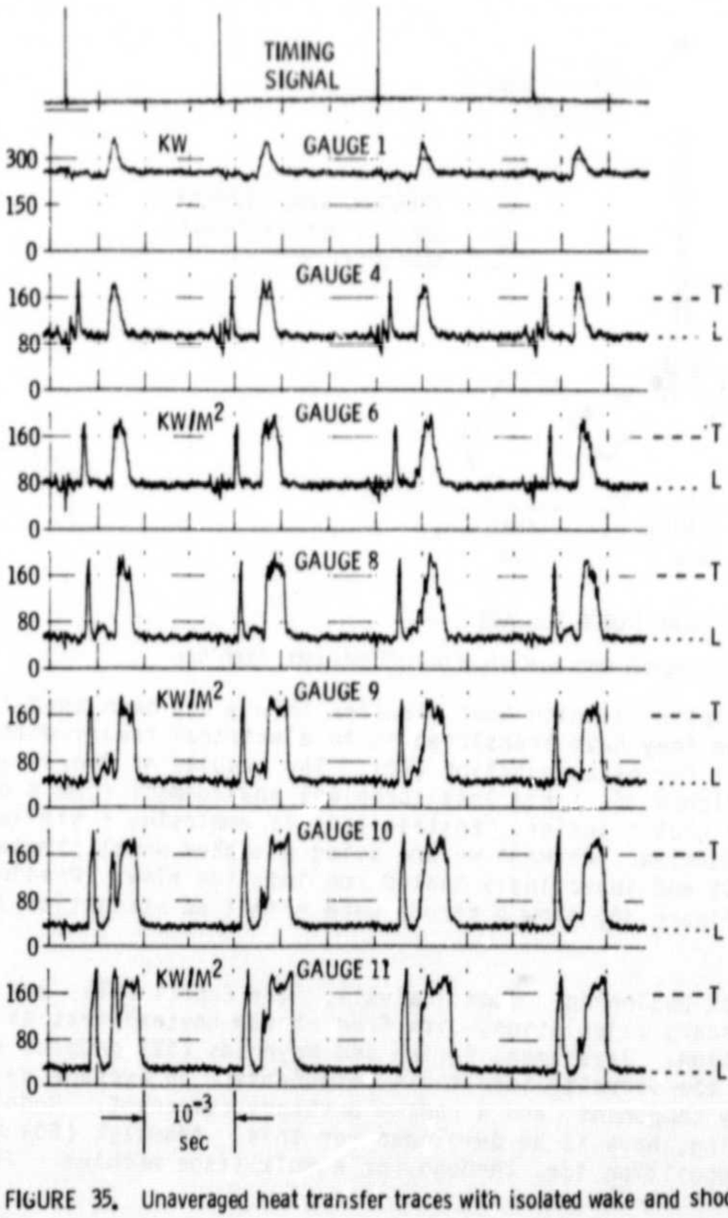


FIGURE 35. Unaveraged heat transfer traces with isolated wake and shockwave passing (two 0.9 mm-dia-bars). (Ref. 48.)

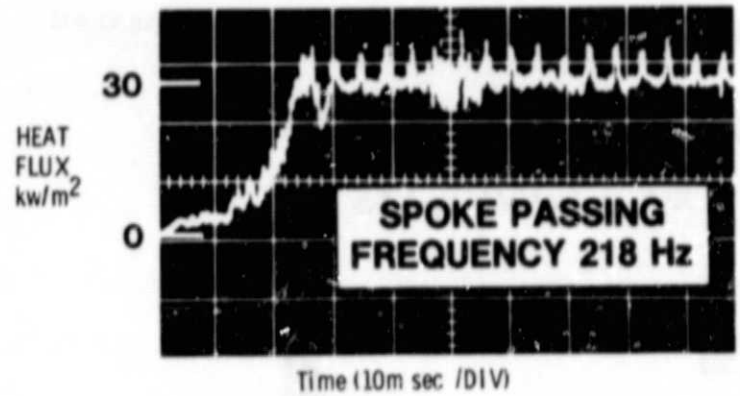


FIGURE 36. Instantaneous surface heat flux along the stagnation line of a circular cylinder in the wake of a spoked rotor. (Re=75,000 and S=0.19)

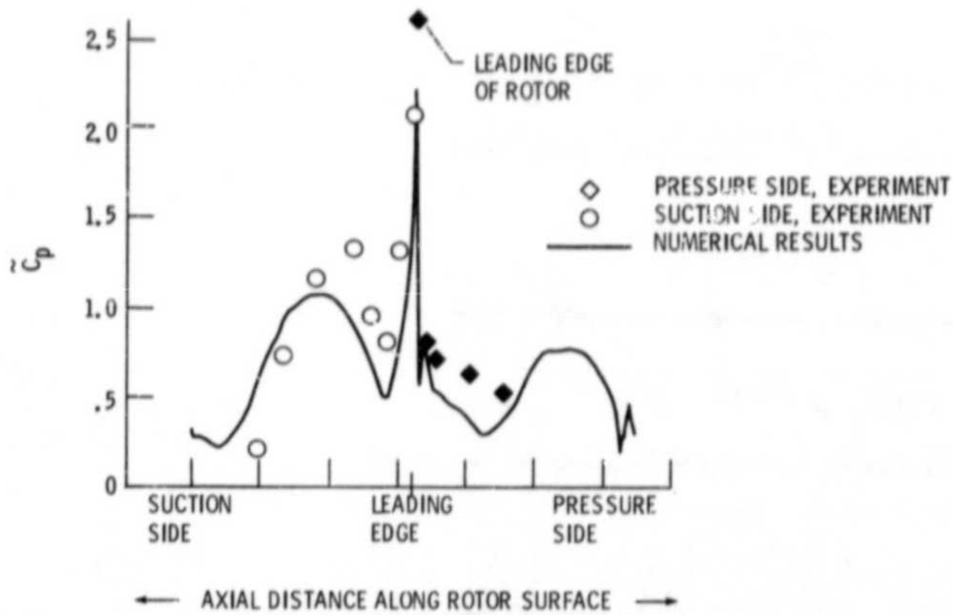


FIGURE 37. Results of an unsteady computer code analysis of Dring's data (44). (Ref. 54).

cascade. The same semi-infinite solid heat transfer theory has been used for a long time at Oxford and they have translated it to electrical theory with an electronic analog circuit for data reduction (48). The results of Doorly and Oldfield (48) shown in figure 35, for a less turbulent environment show a dramatic effect of wakes on heat transfer. Epstein (50) is employing a similar approach in a blowdown turbine. At NASA we are using a spoked wheel simulator in a steady flow rig (45) and injecting a heated rod into the flow. Preliminary results, shown in figure 36, show a strong wake effect on stagnation line heat transfer.

Analytic efforts are just beginning. Some analysts, like Cebeci (51), are performing unsteady boundary calculations with free stream unsteadiness as the unsteady boundary condition. Jayaraman, Parikh and Reynolds (52) propose a triple decomposition of the velocity into three components: an average velocity, a periodic unsteady component, and a random unsteady component. Models, such as Reynolds averaging, have to be developed for this. Adamczyk (53) has carried the triple decomposition idea through for a multistage machine. The computational community is beginning to attack the problem. A variety of very complex grid schemes are being proposed. A patched zonal approach proposed by Rai (54) shows considerable promise. He has attempted to compute Dring's rotor data (44) with impressive results, as shown in figure 37.

Turbulence Modeling

This paper will not attempt a review of the vast and complex subject of turbulence modeling. However, a few remarks in the context of aeropropulsion heat transfer are appropriate. There are excellent surveys on turbulence modeling by Hirata, et al. (55), Rodi (56), and Spalding (57). Most readers will be familiar with these reviews. A recent review by Nallasamy (58) will be of interest, because it directs a critical review at applications to internal flow.

A large debate exists today in the computational community on the value and direction of turbulence modeling. The positions range from persons who say that the details of turbulence modeling have little effect on flow field calculations, as long as one accounts for turbulence, to those who say that one can never properly account for turbulence and that the time dependent Navier-Stokes equations should be solved directly. For this paper we will try to narrow the focus substantially and discuss turbulence only as it effects heat transfer.

The two important distinguishing features of heat transfer are that heat transfer is a wall related phenomena and that it is a flux, dependent on knowing gradients. The same, of course, can be said for skin friction. Not only are there gradients, but as one approaches the wall, the gradients become very steep. Consequently, the need to concentrate grid points near the walls or model the gradient at the wall will always be great.

Turbulence modeling is kind of a generic term applied to any kind of approximation used to deal with the turbulence changes in the flow. There is a tendency to think in terms of "the turbulence model", an elusive entity which, once found, will be used to solve all future turbulent flow and heat transfer problems. Not so, of course. There are many models for many uses. If one is not going to compute everything, then one must make approximations. That is what turbulence modeling is all about. If one accepts that there can be different approximations for different situations, one can put modeling on a more rational basis. Simply, use the least complex model that will do the job. The trick is to pick the right model or combination of models. In general, one can speak of two classes of modeling. One is an approximation to incorporate turbulence in the governing equations. The other is an analytic bypass. An end run on turbulence so to speak.

The main effort today is in attempting to approximate turbulence in the differential equations. For heat transfer, because gradients are involved, accurate modeling is important. On the other hand, this may not require a real complex model, since heat transfer requires knowledge of gradients only near the wall. It appears that models, which focus on the diffusion (i.e., normal gradient) term, such as mixing length models, are headed in the right direction. The surveys (55-58) suggest that for many classes of flows the two-equation k-e models should prove very useful. The k-equation is attractive because the important u'v' type terms are related to kinetic energy and the equation is rather rigorous. The e-equation allows one to deal with the scale of turbulence, which experiments suggest is important to heat transfer. This is by far the most vigorously pursued model at present. It seems to be weak in separated flows.

In the rush to be computationally sophisticated, analytic approximations or correlations, which by-pass turbulence modeling and attempt to find "universal" laws to account for turbulence, have received less attention recently. The reason is obvious. As the flows became more complex, the laws became less "universal". Nevertheless, correlations and wall functions are still a major piece of design practice. They are embedded in most codes in practical use today. They will not and should not be abandoned lightly. A recent report by Goldberg and Reshotko (59) suggests that it is possible to develop three-dimensional laws-of-the-walls, similar to the highly successful two-dimensional concepts.

It has been proposed that as computers grow so rapidly in size and speed, that one simply abandon turbulence modeling and compute the time dependent Navier-Stokes equations directly, Direct Numerical Simulation (DNS). This would be the ultimate by-pass on turbulence modeling. This, of course, would require a grid capable of resolving the fine scale of the turbulence. A close cousin Large Eddy Simulation (LES) would resolve the large scale and model the fine scale. From a heat transfer perspective, if one could achieve this level of resolution and include the energy equation, heat transfer could probably be calculated well. The computations are huge and, at present, reserved to pretty simple geometries and boundary conditions. This thrust, at present, is probably best reserved for performing numerical experiments on quantities that can't be measured well to assist in turbulence modeling.

The Turbine Blade As Heat Exchanger

In discussing figure 4, the author has described the turbine blade as a compact heat exchanger. In fact, almost all heat transfer in aeropropulsion systems is in the heat exchanger mode. That is, the cooling occurs by fluid on one side of a wall transferring heat through the wall to fluid on the another side of the wall. Unlike the heat exchanger, however the objective is not to

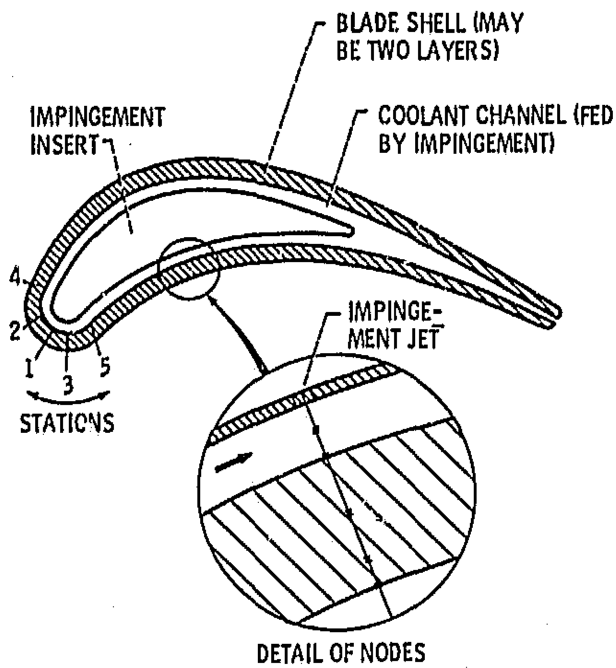


FIGURE 38. Typical blade model analyzed in the TACT 1 code.

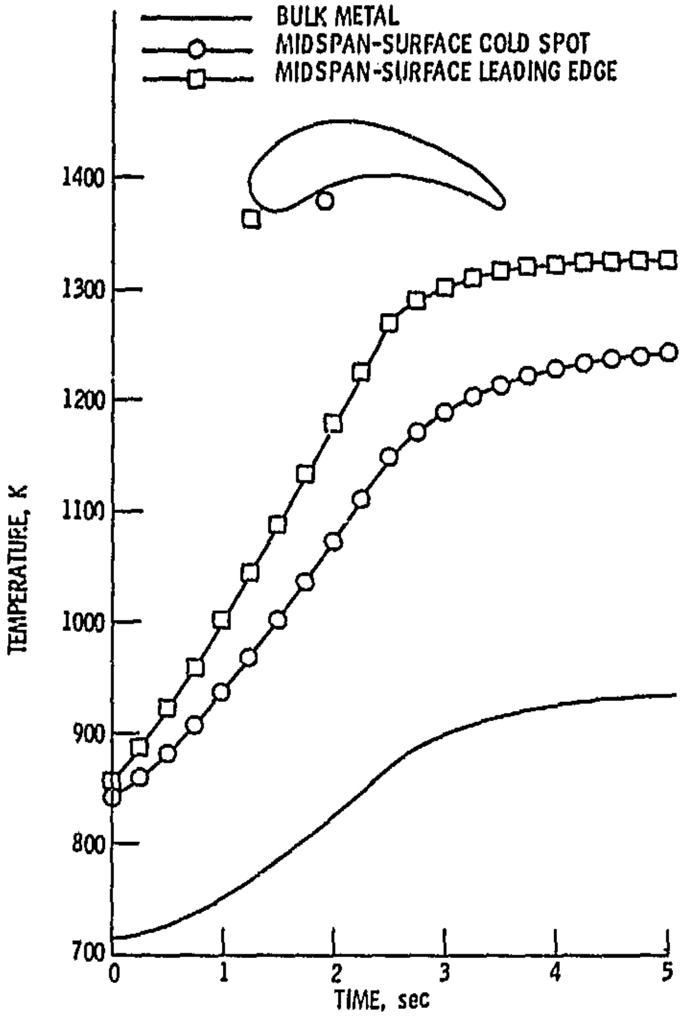


FIGURE 39. Typical output from the TACT 1 code.

transfer the heat from one fluid to the other. The objective is to control the wall temperature - which is harder. Nevertheless, the concepts which address heat exchangers also apply here. It is the heat transfer itself which determines the boundary conditions. It is a balance between the inner and outer flow fields. That balance, which yields the metal temperature, is what the heat transfer designer and thermal stress analyst want to know.

Even the best of today's analytic and experimental work limit the thermal boundary conditions to adiabatic walls, constant wall temperature, and/or constant heat flux. Every manufacturer, of course, has computational schemes to integrate these into a design analysis, but little is known of these. Some attempts to compute the whole blade have appeared in the literature. The TACT1 code by Gaugler (60) and the FCFC code by Meitner (61) are examples. Gaugler's code concentrates on the internal coolant flow and the metal temperature distribution and couples with an external flow code, such as STAN5 (11), to complete the heat exchanger description. Figure 38 is a cross section of the type of blade considered in TACT1 and figure 39 is a sample output. Since this is the ultimate goal in many cases, more attention is needed in this area.

Variable Property Heat Transfer

The gas path can usually be treated as an ideal gas or close to it. This is often not the case for the coolant passages. Most aircraft gas turbines are air cooled but other engines may use liquids. Water is common in intermittent combustion engines (5) and cryogenic cooling is often the case in space propulsion systems (6).

Liquid or cryogenic cooling is outside the zoom focus of this paper but it is important to say that the analyses of some aeropropulsion heat transfer systems will have to consider strongly varying thermophysical properties and possibly phase change. A couple examples from the work of Hendricks (62-64) will serve to illustrate the potential problem.

If a cryogen, such as hydrogen, is used to cool a space propulsion component, as in the SSME, it could start into a coolant passage at a very high pressure, several times the critical pressure. This highly compressible very dense fluid could drop dramatically in pressure, as it flows through the turns and constrictions, causing significant changes in pressure, even going locally two-phase. The resulting property variations are enormous. Such flow behavior is shown for nitrogen in figure 40.

This high degree of compressibility must be considered in the heat transfer. Hydrogen is an important coolant in rocket propulsion and thus has been studied extensively. Hendricks, et al., (63) have shown, that by modifying conventional correlations by a term which accounts for the fluid compressibility, a very wide range of heat transfer data can be correlated, figure 41.

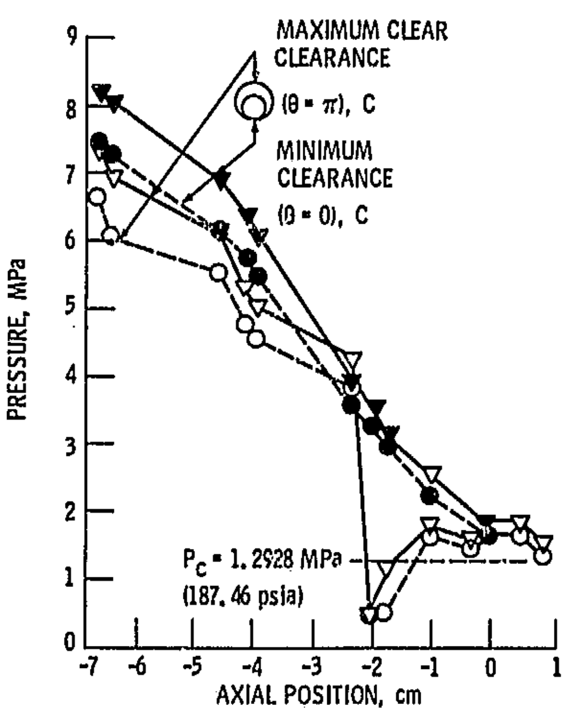


FIGURE 40. Pressure profile for fully eccentric non-rotating three-step SSME seal configuration.

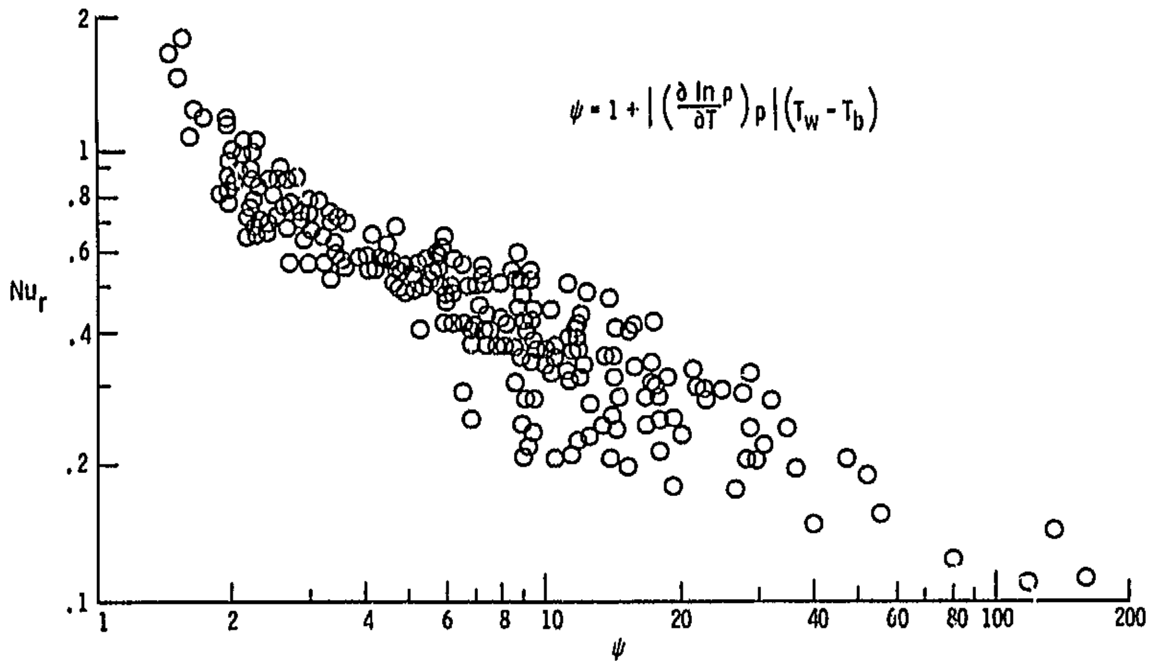


FIGURE 41. Correlation of hydrogen heat transfer data in the near-critical region by accounting for strong density variations.

THE FUTURE

As suggested in the INTRODUCTION, it is the author's position that we are already in the future, albeit just barely, with regard to aeropropulsion heat transfer. The juxtaposition of computational and experimental capability created by modern electronics has placed us on a path I expect to see for years.

The future has two drivers. First, comes increased technical capability. Very simply, we can do things we could never do before. Second, is new or increased propulsion needs. We wish to go higher, faster, longer, carry more load and pay less to do it. It is the first which really drives the research. It is the second which fuels it.

The Technology Drivers

The real drivers for research are the ability to do something and knowledge that there is something new out there. If it can be done, it will be done. The only question is who will do it.

In aeropropulsion heat transfer I see the following:

(1) There will be continued dramatic growth in our ability to compute, measure and analyze information. This in turn will make us more bold in attempting complex flows and geometries.

(2) Three-dimensional flow fields are our next great horizon. These are already well underway in fluid mechanics and significantly underway in heat transfer.

(3) Unsteady flow field heat transfer research is just beginning, but making a rapid start. This may be an area where heat transfer leads fluid mechanics, at least experimentally. This is because heat transfer is one of the better ways to measure unsteady effects. Some people are beginning to ask whether any flows are steady. In doing this there will be a greater distinction drawn between forced and random unsteadiness.

(4) To a large degree we will be doing old problems over again - this time with greater understanding - moving steadily from a correlation based approach to an analytic based approach.

(5) There will be an increased emphasis on heat transfer in supersonic and hypersonic flows.

(6) The return of cryogenic cooling needs will see an increase and renewal in variable property research.

(7) The technical problems of the future will amost surely involve higher energy concentrations and steeper gradients. This is always the way to get better performance out of a propulsion system. In some cases we will push the limits of the basic assumptions in the Navier-Stokes equations and we will be back full circle to basic physics.

Of course, significant technical challenges or hurdles exist. I will mention just two. One is turbulence modeling - or better said - level of approximation. How sophisticated do we have to be in turbulence modeling for heat transfer work? Is modeling just a fancy correlation? Is there some universality? With bigger and faster computers should we just forget correlation and/or modeling and calculate everything? Can we ever calculate enough for heat transfer?

A second challenge or problem is a measurement one. We have still been largely unsuccessful in measuring heat flux with anywhere near the accuracy or resolution comparable to flow field measurements, especially in strong gradients.

The Propulsion-Needs Drivers

In aeronautical propulsion heat transfer we can look to two documents for needs drivers, a policy statement by G. A. Keyworth, II, the Science Advisor to the President (65) and a conference known as Aero-2000 (66). Keyworth (65) stated that the national aeronautics R & D goals are: (1) to build trans-century renewal in subsonic aircraft technology; (2) to attain long-distance efficiency in supersonic flight; and (3) to secure future options for trans-atmospheric flight. The last goal to fly into and out of the atmosphere is particularly challenging to NASA, since it holds out the hope for finally marrying the nation's aeronautic and space technology. The Aero-2000 conference (66) covered a wide range of topics. The propulsion panel identified heat transfer and internal computational fluid mechanics as particularly critical areas which hold exceptional promise for improving propulsion system performance.

The author is unaware of similar formal documents on the space program; however, agency reports, such as by Sadin (67), offer guidance. Basically, NASA has an agency goal to build a space station, service it routinely from the ground, and move from it to other orbits. This is going to require significant advances in power and propulsion. Heat transfer will be on the rise, particularly in cryogenics and two-phase flow. Turbines of even greater performance than the existing SSME will demand the same technical detail that the aircraft gas turbine community is currently seeking.

Although in my opinion the technology drivers are primary, the propulsion-needs drivers are very important. Very simply, if there is no fuel, there is no fire. A good example is high speed flow. Heat transfer in highly supersonic and hypersonic flow fields has not received as much attention as other flow regimes. The driving interest to fund the research has not been there. This will change, as a result of the new R & D goals.

CONCLUDING REMARKS

Since this paper is an overview and perspective on aeropropulsion heat transfer, the text contains many opinions and observations on the state of the research. In summary it is only necessary to say that aeronautical and space propulsion systems offer and will continue to offer many challenging heat transfer opportunities. Although there is an active research effort on adiabatic surfaces, in general, one simply cannot operate a propulsion system without transferring heat. Frequently, heat transfer is a limiting factor in the performance and durability of an engine.

Heat transfer as a limiting factor will undoubtedly continue as we go to higher and higher speeds. This will be especially true for hypersonic vehicles, where the overall thermal management of the vehicle and the propulsion system could become one integrated interactive entity.

We have at our disposal tremendous technological tools with which one can attack these very complex problems. The horizon appears bright.

REFERENCES

1. Rohlik, H.E., Current and Future Technology in Radial and Axial Gas Turbines, NASA TM-83414, 1983.

2. Rudey, R.A. and Graham, R.W., A Review of NASA Combustor and Turbine Heat Transfer Research, NASA TM-83541, 1984.

3. Metzger, D.E. and Mayle, R.E., Heat Transfer: Gas Turbine Engines, Mechanical Engineering, vol. 105, no. 6, pp. 44-52, 1983.

4. Suo, M., Turbine Cooling, in The Aerothermodynamics of Aircraft Gas Turbine Engines, ed. G.C. Oates, Chapter 19, AFAPL-TR-78-52, July 1978.

5. Willis, E.A. and Wintucky, W.T., An Overview of NASA Intermittent Combustion Engine Research, AIAA Paper 84-1393, June 1984.

6. Dankoff, W., Herr, P. and McIlwain, M.C., Space Shuttle Main Engine (SSME) - The "Maturing" Process, Astronautics and Aeronautics, vol. 21, no. 1, pp. 26-32, 1983.

7. Stepka, F.S., Analysis of Uncertainties in Turbine Metal Temperature Predictions, NASA TP-1593, 1980.

8. Sokolowski, D.E., and Ensign, C.R., Improved Durability in Advanced Combustors and Turbines Through Enhanced Analytical Design Capabilities, AIAA/SAE/ASME Joint Propulsion Conf., Monterey, CA, July 1985.

9. Marsik, S.J. (ed), Structural Integrity and Durability of Reusable Space Propulsion Systems, NASA CP-2381, 1985.

10. Gaugler, R.E., A Review and Analysis of Boundary Layer Transition Data for Turbine Application, ASME Paper 85-GT-83, Mar. 1985.

11. Crawford, M.E. and Kays, W.M., STAN5: A Program for Numerical Computation of Two-Dimensional Internal and External Boundary Layer Flows, NASA CR-2742, 1976.

12. Blair, M.F., Influence of Free-Stream Turbulence on Turbulent Boundary Layer Heat Transfer and Mean Profile Development, Part I - Experimental Data, Journal of Heat Transfer, vol. 105, no. 1, pp. 33-40, 1983.

13. Lander, R.D., Evaluation of the Effect of Free Stream Turbulence on the Heat Transfer to Turbine Airfoils, AFAPL-TR-69-70, Sept. 1969.

14. Simon, T.W. and Moffat, R.J., Turbulent Boundary Layer Heat Transfer Experiments: A Separate Effects Study on a Convexly Curved Wall, Journal of Heat Transfer, vol. 105, no. 4, pp. 835-840, 1983.

15. Furuhama, K. and Moffat, R.J., Turbulent Boundary-Layer Heat-Transfer on a Convex Wall with Discrete Hole Injection, ASME/JSME Thermal Engineering Joint Conference, vol. 3, pp. 71-77, 1983.

16. Weinberg, B.C., Yang, R.J., McDonald, H., and Shamroth, S.J., Calculations of Two- and Three-Dimensional Transonic Cascade Flow Fields Using the Navier-Stokes Equations, ASME Paper 85-GT-66, Mar. 1985.

17. Hylton, L.D., Mihelc, M.S., Turner, E.R., and York, R.E., Experimental Investigation of Turbine Endwall Heat Transfer, AFWAL-TR-81-2077, 3 volumes, Sept. 1981.

18. Gaugler, R.E. and Russell, L.M., Comparison on Visualized Turbine Endwall Secondary Flows and Measured Heat Transfer Patterns, Journal of Engineering For Gas Turbines and Power, vol. 106, no. 1, pp. 168-172, 1984.

19. VanFossen, G.J., Jr., and Simoneau, R.J., Preliminary Results of a Study of the Relationship Between Free Stream Turbulence and Stagnation Region Heat Transfer, ASME Paper 85-GT-84, Mar. 1985.

20. Claus, R.W., Calculation of a Single Jet in Crossflow and Comparison with Experiment, AIAA Paper 83-0238, Jan. 1983.

21. Patankar, S.V., and Shih, T.M., Numerical Heat Transfer and Fluid Flow, McGraw Hill, New York, 1980.

22. Goldstein, R.J., Film Cooling in Advances in Heat Transfer, eds. T.F. Irvine Jr. and J.P. Hartnett, vol. 7, pp. 321-379, Academic Press, New York, 1971.

23. Papell, S.S., Vortex-Generating Coolant-Flow-Passage Design for Increased Film-Cooling Effectiveness and Surface Coverage, NASA TP-2388, 1984.

24. Simon, F.F. and Ciacone, M.L., Flow Visualization Study of the Effect of Injection Hole Geometry on an Inclined Jet in Crossflow, in Symposium on Transport Phenomena in Rotating Machinery, Honolulu, Hawaii, pp. 144-166, 1985.

25. Gladden, H.J., Yeh, F.C., and Fronek, D.L., Heat Transfer Results and Operational Characteristics of the NASA Lewis Research Center Hot Section Cascade Test Facility, ASME Paper 85-GT-82, Mar. 1985.

26. Gladden, H.J. and Proctor, M.P., Transient Technique for Measuring Heat Transfer Coefficients on Stator Airfoils in a Jet Engine Environment, AIAA Paper 85-1471, July 1985.

27. McNally, W.D. and Sockol, P.M., Computational Methods for Internal Flows with Emphasis on Turbomachinery, in Computers in Flow Predictions and Fluid Dynamics Experiments, eds. K.N. Ghia, T.J. Mueller, and B.R. Patel, pp. 101-102, ASME, New York, 1981.

28. Povinelli, L.A., Assessment of Three-Dimensional Inviscid Codes and Loss Calculations for Turbine Aerodynamic Computations, Journal of Engineering for Gas Turbines and Power, vol. 107, no. 2, pp. 265-275, 1985.

29. Anderson, B.H., Three-Dimensional Viscous Design Methodology for Advanced Technology Aircraft Supersonic Inlet Systems, AIAA Paper 84-0194, Jan. 1984.

30. Anderson, B.H., Muramoto, K., and Levy, R., A Study of the Three-Dimensional Viscous Flow within High Aspect Ratio Transition Ducts, AIAA Paper 85-0085, Jan. 1985.

31. Levy, R., McDonald, H., Briley, W.R., and Kreskovsky, J.P., A Three-Dimensional Turbulent Compressible Subsonic Duct Flow Analysis for Use with Constructed Coordinate Systems, NASA CR-3389, 1981.

32. Yeh, F.C. and Stepka, F.S., Review and Status of Heat-Transfer Technology for Internal Passages of Air-Cooled Turbine Blades, NASA TP-2232, 1984.

33. Patankar, S.V. and Spaulding, D.B., A Calculation Procedure for Heat, Mass and Momentum Transfer in Three-Dimensional Parabolic Flows, International Journal of Heat and Mass Transfer, vol. 15, no. 10, pp. 1787-1806, 1972.

34. VanFossen, G.J., Heat-Transfer Coefficients for Staggered Arrays of Short Pin Fins, Journal of Engineering for Power, vol. 104, no. 2, pp 268-274, 1982.

35. Kercher, D.M. and Tabakoff, W., Heat Transfer by a Square Array of Round Air Jets Impinging Perpendicular to a Flat Surface Including the Effect of Spent Air, Journal of Engineering for Power, vol. 92, no. 1, pp. 73-82, 1970.

36. Florschuetz, L.W., Berry, R.A., and Metzger, D.E., Periodic Streamwise Variations of Heat Transfer Coefficients for Inline and Staggered Arrays of Circular Jets with Crossflow of Spent Air, Journal of Heat Transfer, vol. 102, no. 1, pp. 132-137, 1980.

37. Hippensteele, S.A., Russell, L.M., and Stepka, F.S., Evaluation of a Method for Heat Transfer Measurements and Thermal Visualization Using a Composite of a Heater Element and Liquid Crystals, Journal of Heat Transfer, vol. 105, no. 1, pp. 184-189, 1983.

38. Boyle, R.J., Heat Transfer in Serpentine Passages with Turbulence Promoters, ASME Paper 84-HT-24, Aug. 1984.

39. Johnson, B., Wagner, J., Kopper, F., and Higgins, W., unpublished research.

40. Epstein, A.H., Kerrebrock, J.L., Koo, J.J., Cheng, W.K., and Preiser, U.H., Rotational Effects on Impingement Cooling, in Symposium on Transport Phenomena in Rotating Machinery, Honolulu, Hawaii, pp. 84-100, 1985.

41. Hodson, H.P., Measurements of Wake-Generated Unsteadiness in the Rotor Passages of Axial Flow Turbines, Journal of Engineering for Gas Turbines and Power, vol. 7, no. 2, pp. 467-476, 1985.

42. Binder, A., Forster, W., Kruse, H., and Rogge, H., An Experimental Investigation into the Effect of Wakes on the Unsteady Turbine Rotor Flow, Journal of Engineering for Gas Turbines and Power, vol. 7, no. 2, pp. 458-466, 1985.

43. Hathaway, M.D., Measurements of the Rotor Wake Generated Unsteady Flowfield Within the Stator of an Axial Fan Stage, to be presented at the 1986 International Gas Turbine Engine Conference, Dusseldorf, Germany.

44. Oring, R.P., Joslyn, H.D., Hardin, L.W. and Wagner, J.H., Turbine Rotor-Stator Interaction, Journal of Engineering for Power, vol. 104, no. 4, pp. 729-742, 1982.

45. Simoneau, R.J., Morehouse, K.A., and VanFossen, G.J., Effect of a Rotor Wake on Heat Transfer from a Circular Cylinder, ASME paper 84-HT-25, Aug. 1984.

47. Dunn, M.G., Lukis, G., Urso, M., Hiemenz, R.J., Orszulak, R.L., and Kay, N.J., Instrumentation for Gas Turbine Research in Short-Duration Facilities, SAE Paper 841504, Oct. 1984.

48. Doorly, D.J. and Oldfield, M.L.G., Simulation of the Effects of Shock Wave Passing on a Turbine Rotor Blade, ASME Paper 85-GT-112, Mar. 1985.

49. Ashworth, D.A., LaGraff, J.E., Schultz, D.L., and Grindrod, K.J., Unsteady Aerodynamic and Heat Transfer Processes in a Transonic Turbine Stage, ASME Paper 85-GT-128, Mar. 1985.

50. Epstein, A.H., Guenette, G.R., and Norton, R.J.G., The MIT Blowdown Turbine Facility, ASME Paper 84-GT-116, June 1984.

51. Cebeci, T., Carr, L.W., Khattab, A.A., and Schimke, S.M., Computational Aspects of Unsteady Flows, AGARD, France, May 1985.

52. Jayaramon, R., Parikh, P., and Reynolds, W.C., An Experimental Study of the Dynamics of an Unsteady Turbulent Boundary Layer, Stanford Technical Report TF-18, Dec. 1982.

53. Adamczyk, J.J., A Model Equation for Simulating Flows in Multi-Stage Turbomachinery, ASME Paper 85-GT-226, Mar. 1985.

54. Rai, M.M., Navier-Stokes Simulations of Rotor-Stator Interaction Using Patched and Overlaid Grids, AIAA Paper 85-1519-CP, July 1985.

55. Hirata, M., Tanaka, H., Kawamura, H., and Kasagi, N., Heat Transfer in Turbulent Flows, in Heat Transfer 1982, vol. 1, pp. 31-57, Hemisphere Publishing Co., Washington, D.C., 1982.

56. Rodi, W., Examples of Turbulence Models for Incompressible Flows, AIAA Journal, vol. 20, no. 7, pp. 872-879, 1982.

57. Spalding, D.B., Turbulence Models for Heat Transfer, in Heat Transfer 1978, vol. 6, pp. 33-43, Hemisphere Publishing Co., Washington, D.C., 1978.

58. Nallasamy, M., A Critical Evaluation of Various Turbulence Models as Applied to Internal Fluid Flows, NASA TP-2474, 1985.

59. Goldberg, U.C. and Reshotko, E., Scaling and Modeling of Three-Dimensional, End-Wall, Turbulent Boundary Layers, NASA CR-3792, 1984.

60. Gaugler, R.E., TACT1, A Computer Program for the Transient Thermal Analysis of a Cooled Turbine Blade or Vane Equipped with a Coolant Insert, I - Users Manual, NASA TP-1271, 1978.

61. Meitner, P.L., FORTRAN Program for Calculating Coolant Flow and Metal Temperatures of a Full-Coverage-Film-Cooled Vane or Blade, NASA TP-1259, 1978.

62. Hendricks, R.C., Braun, M.J., Wheeler, R.L. III, and Mullen, R.L., Nested Subcritical Flows Within Supercritical Systems, NASA TM-86980, 1985.

63. Hendricks, R.C., Yeroshenko, V.M., Yaskin, L.A., and Starostin, A.D., Bulk Expansion Factors and Density Fluctuations in Heat and Mass Transfer, Paper B1-119, XV International Congress of Refrigeration, Venice, Italy, Sept. 1979.

64. Hendricks, R.C., Niino, M., Kumakawa, A., Yeroshenko, V.M., Yaskin, L.A., Majumdar, A.K., and Mukerjee, T., Friction Factors and Heat Transfer Coefficients for Hydrogen Systems Operating at Supercritical Pressures, Presented at the Beijing International Symposium on Hydrogen Systems, Beijing, China, May 1985.

65. Keyworth, G.A., II, National Aeronautics R&D Goals, Technology for America's Future, Executive Office of the President, Office of Sciences and Technology Policy, Washington, D.C., Mar. 1985.

66. Aeronautics Technology Possibilities for 2000: Report of a Workshop, NASA CR-174018, 1984.

67. Sadin, S.R., ed, NASA Space Systems Technology Model, Vol IIA - Space Technology Trends and Forecasts, NASA Office of Aeronautics and Space Technology, Washington, D.C., 1984.

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16. Abstract

An overview and perspective on aeropropulsion heat transfer is presented. A research methodology based on a growing synergism between computations and experiments is examined. The aeropropulsion heat transfer arena is identified as high Reynolds number forced convection in a highly disturbed environment subject to strong gradients, body forces, abrupt geometry changes and high three-dimensionality - all in an unsteady flow field. Numerous examples based on heat transfer to the aircraft gas turbine blade are presented to illustrate the types of heat transfer problems which are generic to aeropropulsion systems. Projections are made for the research focus of the near future in aeropropulsion heat transfer.

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