1989

NASA/ASEE SUMMER FACULTY FELLOWSHIP PROGRAM

MARSHALL SPACE FLIGHT CENTER
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

THE INFLUENCE OF A WALL FUNCTION ON TURBINE BLADE HEAT TRANSFER PREDICTION

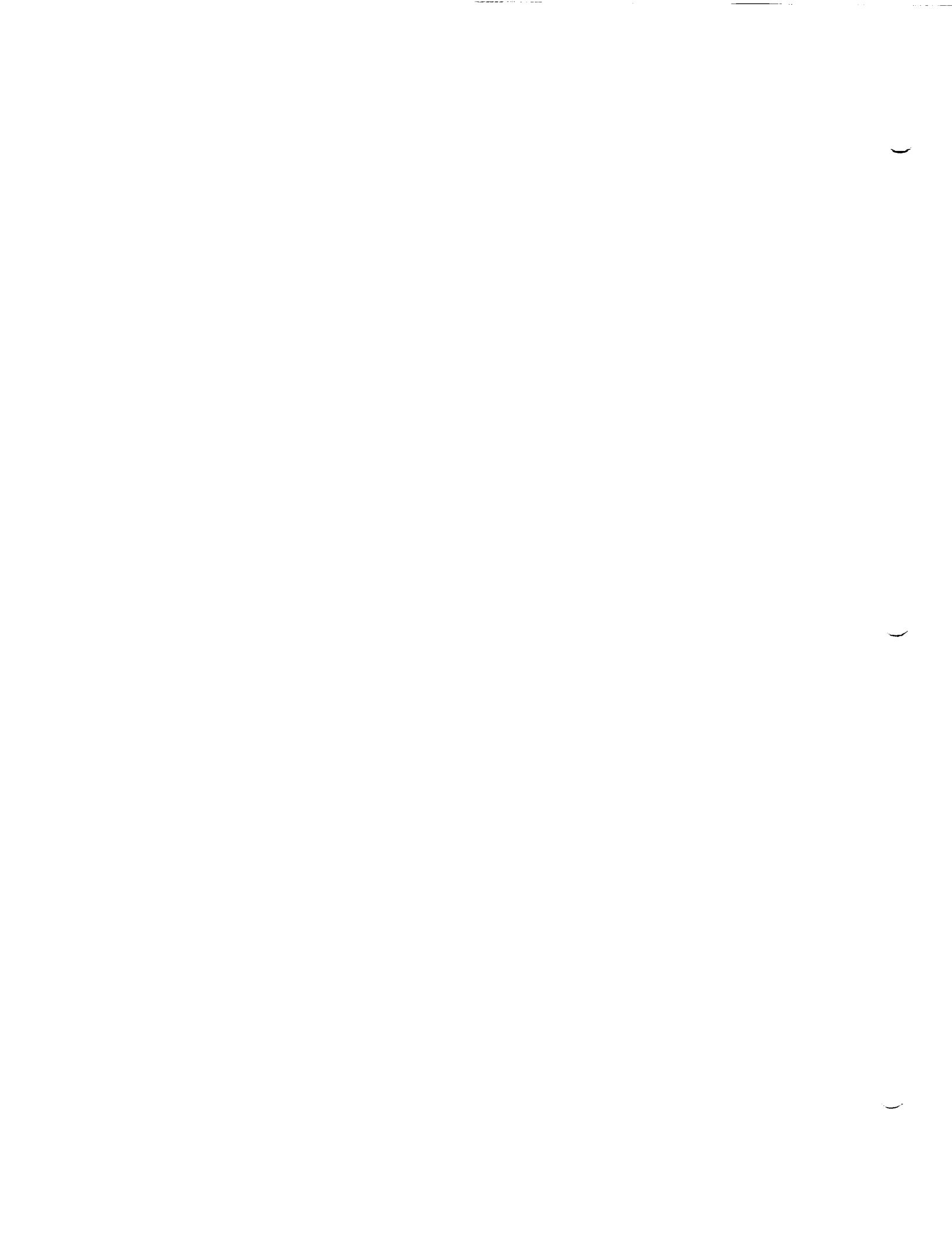Prepared by: Kevin W. Whitaker

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    Laboratory: Structures and Dynamics
    Division: Aerophysics
    Branch: Computational Fluid Dynamics

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Date: August 1, 1989

Contract No.:   NGT 01-008-021
                                       The University of Alabama
                                       in Huntsville

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ABSTRACT

The second phase of an continuing investigation to improve the prediction of turbine blade heat transfer coefficients has been completed. The present study specifically investigated how a numeric wall function in the turbulence model of a two-dimensional boundary layer code, STAN5, affected heat transfer prediction capabilities. Several sources of inaccuracy in the wall function were identified and then corrected or improved. Heat transfer coefficient predictions were then obtained using each one of the modifications to determine its effect. Results indicated that the modifications made to the wall function can significantly affect the prediction of heat transfer coefficients on turbine blades. The improvement in accuracy due the modifications is still inconclusive and is still being investigated.

ACKNOWLEDGEMENTS

For the second straight year I would like to thank the National Aeronautics and Space Administration along with the American Society for Engineering Education for sponsoring this fabulous opportunity. I have found the Summer Faculty Fellowship Program to be extremely beneficial and enjoyable. Without question, the program has played an important role in my professional development.

Sincere appreciation is due Helen V. McConnaughey whose interest in the Summer Faculty Fellowship Program provided me with what turned out to be a very interesting and timely project. I also appreciate the valuable assistance provided by Gerald Karr and Frank Six throughout the course of the program.

INTRODUCTION

The thermal aspect of blade design is one of the more difficult engineering tasks facing a designer of any modern gas turbine engine. Thermal (and many times aerodynamic) analysis procedures currently available to designers have deficiencies that do not permit achievement of design goals without expensive experimental development programs. For example, the external (gas-to-blade) heat transfer coefficient still eludes satisfactory prediction using computational fluid dynamic codes. Even if consideration is restricted to the nominally two-dimensional midspan region of a turbine blade, prediction is still unsatisfactory. The reasons for the unsatisfactory prediction capability of the codes are complex but ultimately lie in the fundamental concepts and models used to define the fluid dynamic and heat transfer behavior. Without question, the complex gas turbine engine environment pushes current models to their limit. Thus, there exists a need for an improved design approach making use of codes with sufficiently improved turbulence modeling.

The work presented here is part of a continuing effort to improve the prediction of turbine blade heat transfer coefficients. Specifically, it investigates the influence a wall function has on the predictive capabilities of a typical design code. Although a wall function is only a small part of a total turbulence model, its influence was identified as being important during a previous study.

OBJECTIVE

The overall objective of this study was to improve the computational prediction of the external (gas-to-blade) heat transfer coefficient for gas turbine engine applications. Such an improvement would reduce and perhaps eliminate the expensive experimental iterations that current engine designers must endure. Accurate prediction of heat transfer within a gas turbine engine environment is necessary to assist designers in the selection of blade materials, blade cooling requirements, etc. The result is that improved prediction capabilities would impact engine design in a very positive way.

PROCEDURE

CODE SELECTION

Current gas turbine engine design practice is to use a two-dimensional boundary layer analysis to calculate the gas-to-blade heat transfer coefficients. Certainly any computational method which does not solve the full time-dependent Navier-Stokes and energy equations cannot be expected to be universally valid over the entire range of circumstances governed by these equations. However, there are solutions from reduced sets of these equations that are valid for a subset of problems. Such is the case here where it is implied that the flow field immediately adjacent to the surface of an airfoil in typical gas turbine geometries can be analytically modeled using boundary layer equations.

Perhaps the most familiar and widely used boundary layer method is a finite difference technique which relies on algebraic relations for defining turbulence quantities. A very common design tool of this type is STAN5, a code developed by Crawford and Kays [1] and later modified by NASA Lewis Research Center [2]. For boundary layer flow with heat transfer, STAN5 involves the solution of two governing partial differential equations using the numerical scheme of Patankar and Spalding [3]. Turbulence closure is obtained using eddy diffusivity concepts. The STAN5 code has received wide attention because of its careful development, flexibility, and adequate documentation. For those very reasons, STAN5 was selected to be used for this study.

The STAN5 code allows many parameters to be adjusted and it was felt that one set of parameters should be selected and held constant throughout the test so that the influence of the wall function could be determined. Of course it was desirable to have the parameters describe a true gas turbine engine flow field as closely as possible.

Reviewing published data for flow over turbine blades, it was decided that a fully turbulent boundary layer on both the suction and pressure surfaces of the blade would be assumed. This is perhaps a point of contention but it was adopted for a couple of reasons. First, many transition models have been tried in the past with limited success [4]. Second, a typical gas turbine engine

environment flow field has a high free stream turbulence level. Also, any boundary layer character change (such as relaminarization) that might occur would be modeled through the pressure gradient implicitly contained in the input data.

STAN5 has two eddy diffusivity models, the Prandtl mixing length hypothesis (MLH) and the higher order turbulent kinetic energy (TKE) concept. For this study, the MLH method was selected based on the past attention given to it - especially in gas turbine engine studies. Also the choice of the MLH model can be considered a practical selection. The detailed experimental data required to realistically tune higher order turbulence models for gas turbine engine applications are quite scarce. On the other hand, the global-type boundary layer data normally used to develop lower order turbulence models (such as the MLH) are more common.

Another consideration was whether to assume the blade surface was a flat plate or to include the blade curvature into the analysis. A curvature model was available in STAN5 but previous studies [4] have revealed that using the curvature model did not significantly affect the heat transfer results. Also, as pointed out earlier, current design practice is to assume the flat plate. Therefore a flat plate model of the blade was assumed in this study.

Finally, all specifiable constants in STAN5 were set equal to values suggested by Crawford and Kays.

EXPERIMENTAL DATA

In order to evaluate the predictive capabilities of any computational method, it needs to be compared to experimental data. Many well documented heat transfer studies have been performed and there is a fair amount of reliable data available. This study used the work performed at Detroit Diesel Allison by Hylton et al. [4]. The main reason for selecting this data was that in addition to presenting their experimental results, the authors also provided the necessary STAN5 input data for their experimental configuration. This eliminated the need to develop the required input data thus allowing more time to be devoted to the task at hand.

The experimental program of Hylton et al. studied flow through a turbine cascade. The cascade contained three blades that were characteristic of a first-stage turbine. The blades were designated as "C3X" airfoils and the

profile of one is shown in Figure 1. The center blade in the cascade was instrumented and provided the aerodynamic and heat transfer data. The operating conditions for the data set used for comparison in this study are given below.

Inlet Total Temperature:	1460°F
Inlet Mach Number:	0.16
Inlet Reynolds Number:	640,000
Free-stream Turbulence Level:	6.55%
Blade Surface Temperature:	1182°F

THE WALL FUNCTION

A recent study [5] investigated the role turbulent Prandtl number models played in the prediction of heat transfer coefficients. It was found was that the turbulent Prandtl number models did not appear to significantly improve the prediction of heat transfer coefficient. However, it was observed that the viscous sublayer model was _very_ significant.

Within STAN5, the viscous sublayer is modeled via a wall function - a very common technique in computational fluid dynamics. Wall functions exist because boundary layers are regions of high gradients and, perhaps more important, very high gradients exist near a wall. Thus, a large number of grid points are needed to fully resolve the boundary layer region. Wall functions provide analytical expressions which can be used to "solve" the flow field in the near wall region. This solution can then be "patched" into the finite difference solution at some distance away from the wall.

Typically what is desired of the wall function is a distribution of nondimensional velocity (U⁺) and enthalpy (I⁺) with respect to a normalized distance from the wall (Y⁺). The wall function in STAN5 assumes that the flow near a wall can be approximated by a Couette flow analysis. Thus the near-wall flow field is solved in STAN5 by using the following equations:

$$\frac{dU^+}{dY^+} = \frac{2\tau^+}{1 + [1 + 4\ell^{+2}\tau^+]^{\frac{1}{2}}} \tag{1}$$

$$\frac{dI^+}{dY^+} = \frac{Pr_{eff}}{\mu^+} + (Pr_{eff} - 1)W\frac{d}{dY^+}(U^{+2}/2) \tag{2}$$
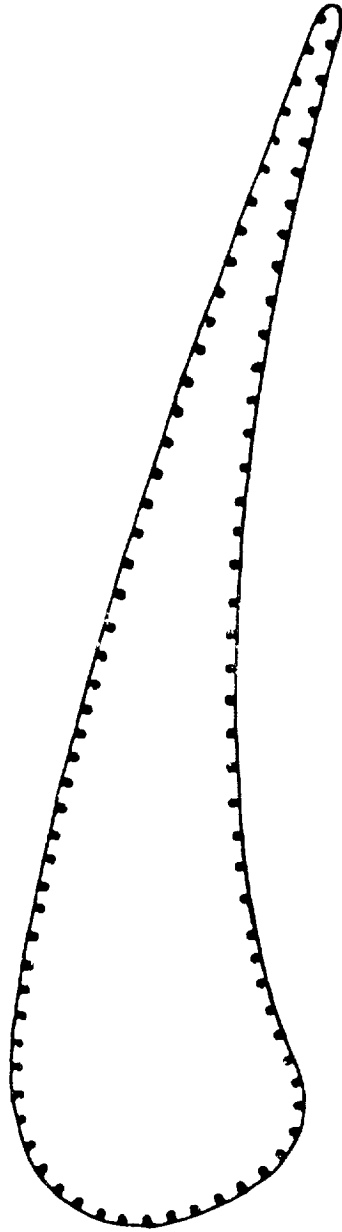
Figure 1. Profile of C3X Turbine Blade

Solution of these equations is very easy if shear stress (τ^+) and Prandtl mixing length (ℓ^+) are known as functions of Y^+. The distributions of U^+ and I^+ can be determined by simply integrating the Couette flow equations from the wall out to some user defined distance (Y^+_{max}) into the flow field.

An expression for τ^+ as a function of Y^+ can be obtained by normalizing and rearranging the momentum equation:

$$\tau^+ = 1 + P^+Y^+ + [\text{acceleration terms}] \qquad (3)$$

P^+ is a normalized pressure gradient term and the term designated "acceleration terms" represents the convective terms in the momentum equation.

An expression for ℓ^+ as a function of Y^+ can be found in Prandtl's mixing length theory:

$$\ell^+ = KY^+D \quad \text{where } D = 1 - \exp(Y^+/A^+) \qquad (4)$$

The parameter "D" is the Van Driest damping function which essentially suppresses the linear dependence of ℓ^+ near the wall. The effective thickness of the viscous sublayer is represented by A^+. The Von Karman constant is represented by K.

Equations (1)-(4) thus constitute the wall function utilized by STAN5. With a turbine blade flow field in mind, looking closely at how these equations are implemented in STAN5 reveals sources of inaccuracy. Five possible sources of error were identified. They are described below along with a brief explanation of how modifications were implemented to correct the deficiency.

- The acceleration terms in the definition of τ^+ (Eqn (3)) are neglected. A correction factor is applied in STAN5 to account for these missing terms but, for the most part, the correction is only for very mild accelerations. Flow around a turbine blade experiences very high accelerations and thus is not modeled correctly in STAN5. The code was modified by including the acceleration terms in their entirety when calculating τ^+.

- The Van Driest damping function is normalized using the value of shear stress at the wall (τ_{wall}). This could cause problems in regions where the flow is very close to separating from the wall. Near separation the value of τ_{wall} is very small and can

cause divergence of the numerical scheme or an arithmetic overflow. To avoid this, the Van Driest damping function was redefined using the local value of shear stress (τ_{local}) to normalize.

- The Von Karman constant used in the definition of the mixing length is assumed to be a constant in STAN5 - a very common practice. However, recent studies of flows with strong accelerations suggest that the Von Karman constant is not constant and in fact varies with streamwise pressure gradient. An expression amenable to numerical implementation was suggested by Glowacki and Chi [6] and was included added to STAN5.

- A user defined value of Y^{+}_{max} dictates where the wall function is "patched" into the finite difference solution. Suggested values of Y^{+}_{max} range from 1 to 500 but all of these suggestions are based on flat plate studies. To determine the influence of Y^{+}_{max} on heat transfer coefficient predictions for a turbine blade flow field, a set of test cases having different values of Y^{+}_{max} was run.

- The thickness of the viscous sublayer depends on the stability of the boundary layer. Streamwise pressure gradients directly influence the stability of the boundary layer - favorable pressure gradients tend to stabilize and adverse pressure tend to destabilize. Therefore there is a direct relationship between streamwise pressure gradient and viscous sublayer thickness. An empirical correlation is included in STAN5 to correct the viscous sublayer thickness (represented by A^{+}) for the streamwise pressure gradient experienced by the flow. The correlation was based on numerous flat plate studies [1]. It was felt that the correlation should be modified to account for the actual relationship between sublayer thickness and pressure gradient on a turbine blade.

RESULTS

The heat transfer coefficient predictions produced by STAN5 with each one of the wall function modifications can be seen in Figures 2 through 6. For presentation, the heat transfer coefficient (H) has been normalized by a reference value (HO) of 200 BTU/Hr/ft^2/°F and the distance along the blade surface (S) is normalized by the total surface arc length (ARC). Also shown with the predictions is the experimental data of Hylton et al. Only distributions on the suction surface were investigated. The reason for this is that very good predictions on the pressure surface of the C3X blade were obtained in a previous study [5] by simply eliminating the viscous sublayer correction and using the wall function with no further modifications.

Figure 2 shows the heat transfer coefficient distributions using a shear stress definition with and without the acceleration terms. It can be seen that by including the acceleration terms in the wall function, the laminar-to-turbulent transition at 20% of the blade surface is no longer predicted. The coefficients are predicted reasonably well in the region from 25% to about 70% but are then over-predicted beyond that.

The effects of changing the normalized definition of the Van Driest damping function are shown in Figure 3. By using the local value of shear stress (τ_{local}) the previous over-prediction at the laminar-to-turbulent transition area is reduced. Beyond about the first 25% of the blade surface, the two curves exhibit similar trends. However, both of the predicted distributions are different from the distribution suggested by the experimental data.

Figure 4 shows predictions obtained by letting the Von Karman "constant" vary with streamwise pressure gradient. The distribution of heat transfer coefficients is predicted very well up to about 40% of the blade surface and then the coefficients are severely under predicted. It is perhaps important to note that although the predicted values are low beyond 40%, the shape of the distribution is generally correct.

The effect of where the wall function is patched into the finite difference grid is seen in Figure 5. Cases were run varying Y^+_{max} from 200 down to 5. Out to a surface distance of 20% the predictions were identical for all values of Y^+_{max}. After that the larger values of Y^+_{max}
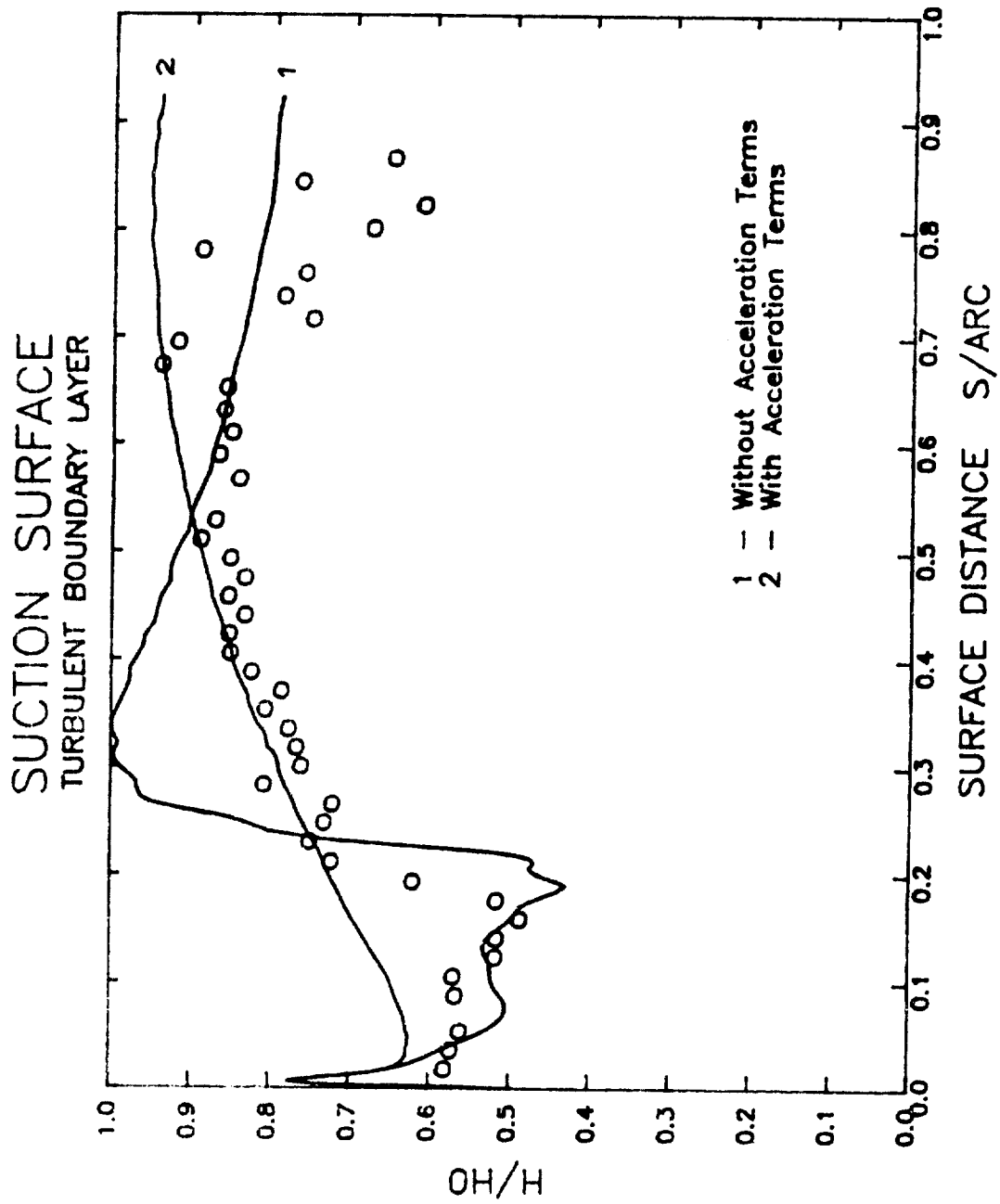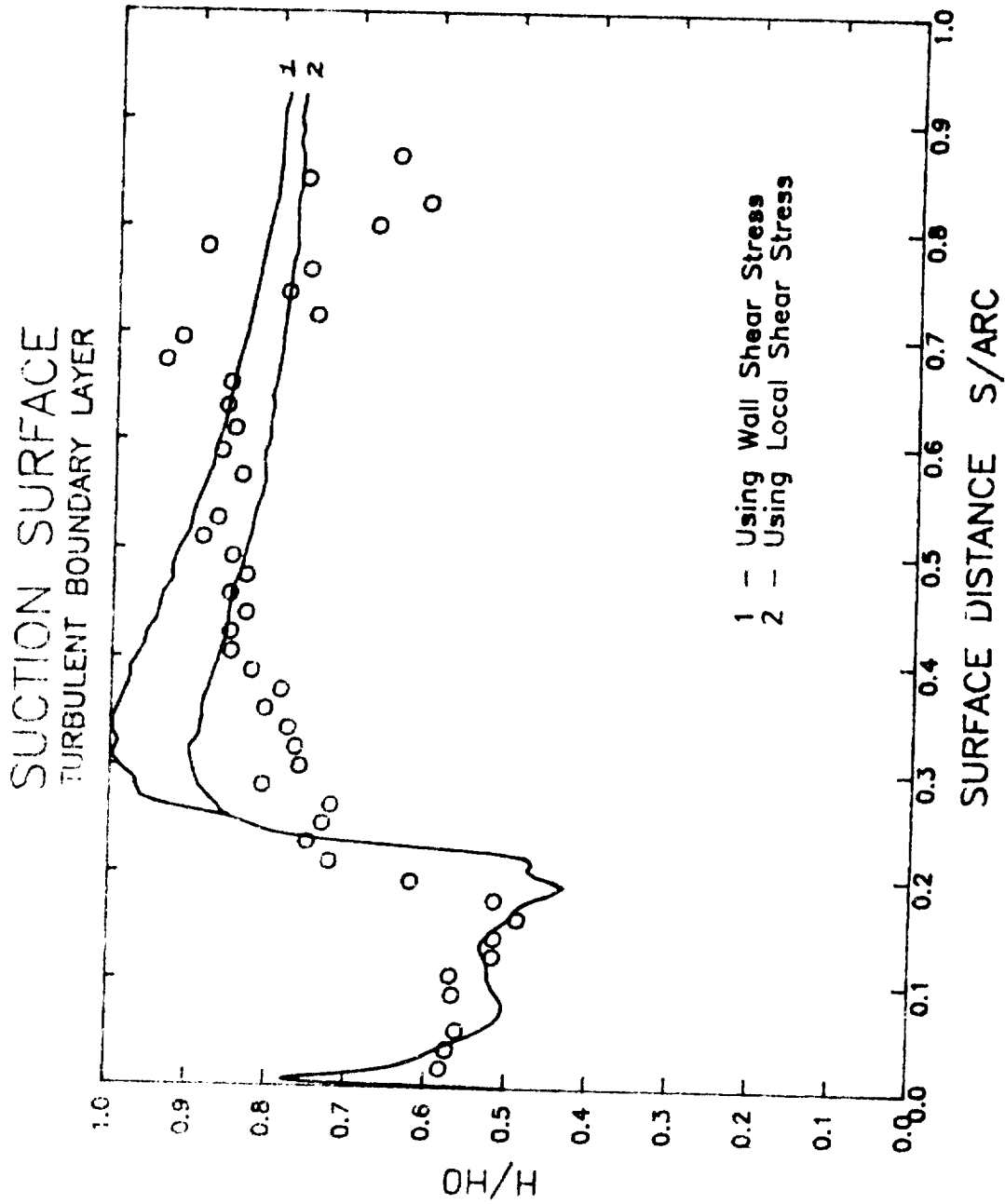
Figure 2. Effect of Acceleration Terms

Figure 3. Effect of Van Driest Damping Function
Normalization Technique

SUCTION SURFACE
TURBULENT BOUNDARY LAYER

$1 - K = 0.41$
$2 - K = f(\Delta P)$
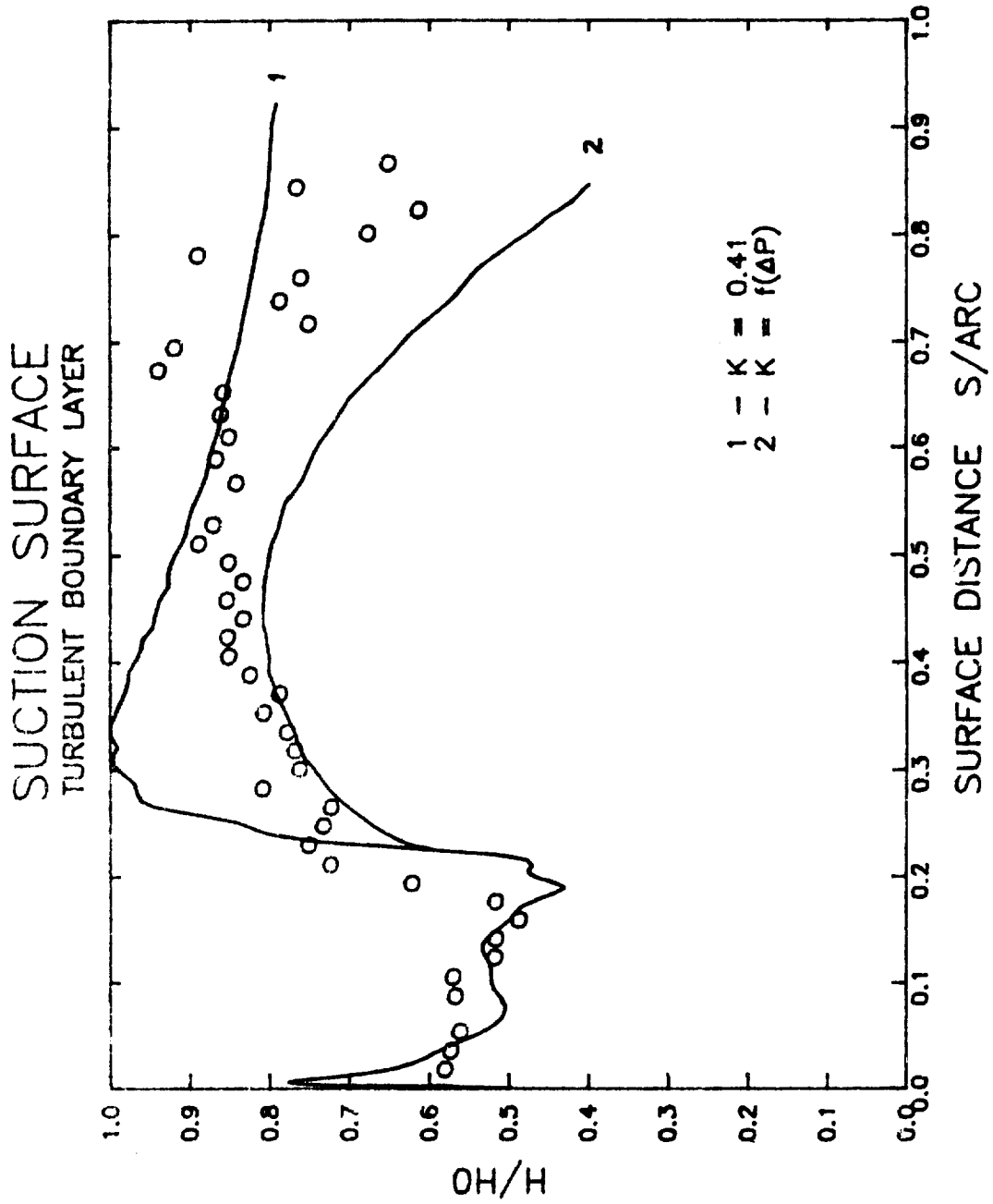
SURFACE DISTANCE S/ARC

H/HO

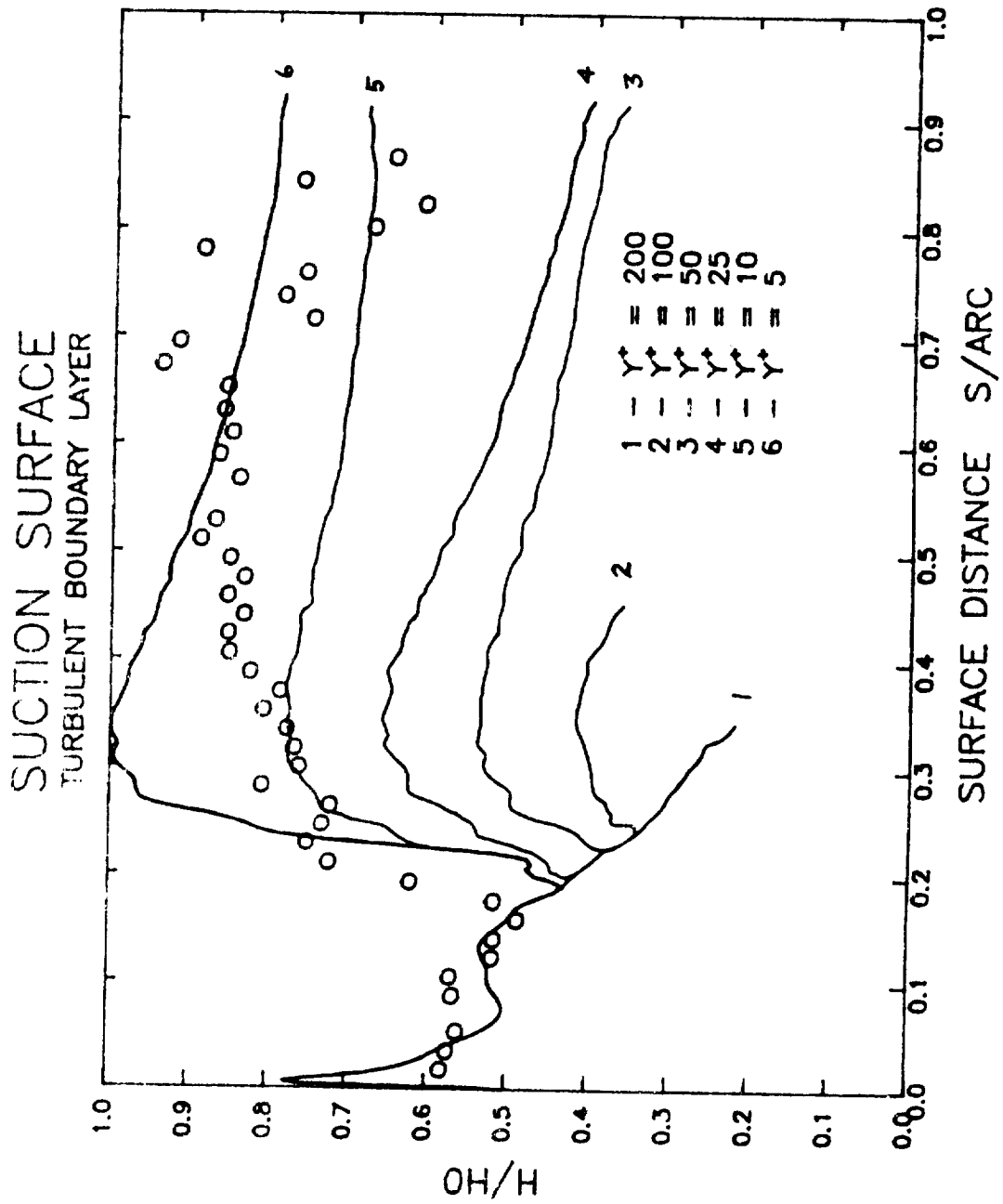Figure 4. Effect of Von Karman "Constant" Definition

Figure 5. Effect of Wall Function "Thickness"

produced very erroneous results. As would be expected
however, as the finite difference grid is brought closer to
the wall (i.e. lower Y^+_{max} values) the predictions are
improved. It appears that the best prediction for a
turbine blade suction surface occurs with $Y^+_{max}=10$. This is
questionable since $Y^+_{max}=5$ should be more accurate.
Although the better agreement with $Y^+_{max}=10$ is most likely a
coincidence, this observation merits further investigation.

Shown in Figure 6 is the correlation contained in STAN5
to correct the viscous sublayer thickness (A+) for a
streamwise pressure gradient. As discussed above, it was
felt that this correlation needed to be modified for a
turbine blade flow field. Qualitatively however, the curve
is correct. Favorable pressure gradients stabilize the
boundary layer promoting relaminarization and hence a thick
viscous sublayer. Adverse pressure gradients destabilize
the boundary layer thus reducing the thickness of the
viscous sublayer. The curve as shown was generated from
experiments on a flat plate [1]. It is highly probable
that this curve does not represent a turbine blade but an
experimental data base is necessary before any
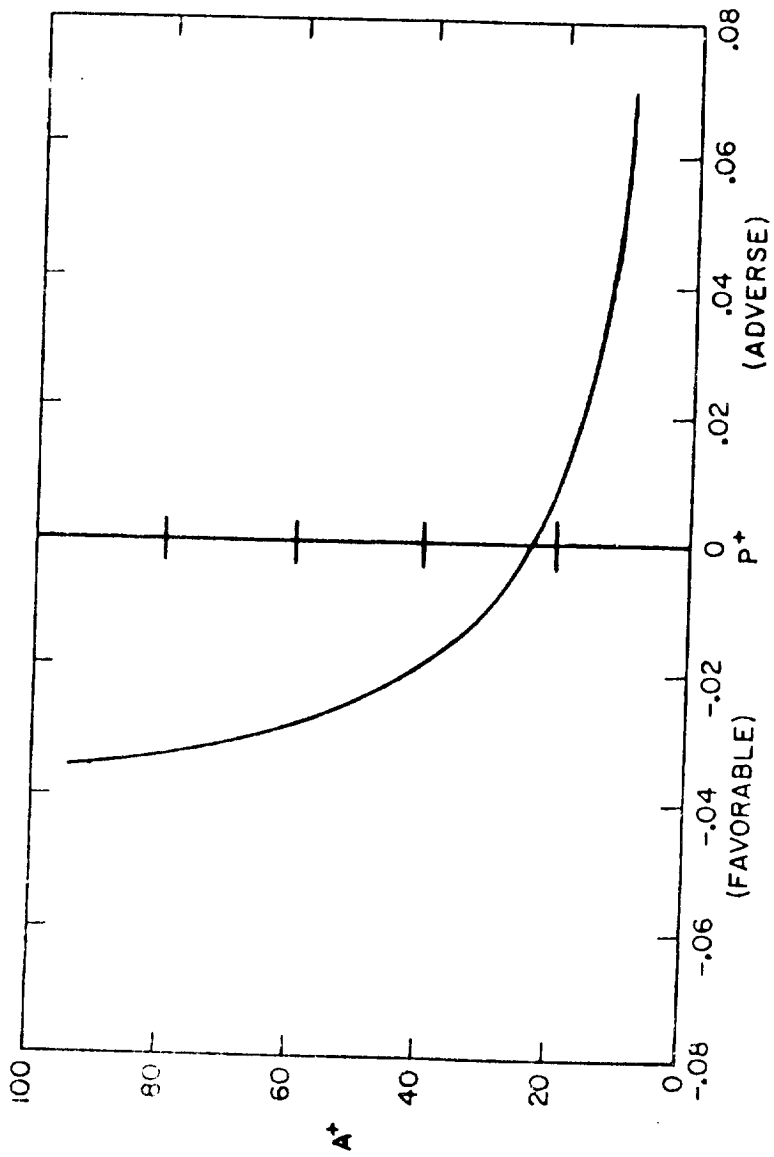modifications can be made.

Figure 6. Correlation for Viscous Sublayer Correction

CONCLUSIONS AND RECOMMENDATIONS

Based on this investigation it was concluded that the wall function in STAN5 can be altered to improve the prediction of heat transfer coefficients. It should be realized that these statements are based on the code's performance compared with one data set. Further comparison is necessary to increase the confidence in the conclusions made. With that in mind the following statements summarize the findings of the study.

- With a favorable streamwise pressure gradient Y^+_{max} should be kept a small as possible. Suggested values are Y^+_{max}=5 or 10.

- Using the local value of shear stress (τ_{local}) to normalize the Van Driest damping function improves the heat transfer coefficient predictions.

- Use of the acceleration terms in the Couette flow equations did not accurately predict the transition region. However it is felt that use of the modification is still important and perhaps significant effects will be observed when this modification is coupled with a transition model.

- The use of a Von Karman "constant" which varies with streamwise pressure gradient gave good results on the first 40% of the blade surface. Beyond that the predictions are under-predicted. However, the trend of the curve was correct and thus further investigation is warranted.

- The viscous sublayer thickness correction in STAN5 is suspect. Qualitative enhancements were not possible due to the lack of experimental data on turbine blade boundary layers.

The following recommendations are also suggested by this study:

- The wall function enhancements need to be incorporated with other improvements like turbulent Prandtl number models, transition models, etc. It is very likely that each modification made does not improve the prediction capabilities significantly but modifications used in unison will produce improvement.

- The useful range of the wall function still needs to be identified for turbine blades. Comparisons with many sets of experimental data will be necessary to identify when the wall function must be patched into the finite difference grid.

- A correlation for correcting the viscous sublayer thickness must be developed for turbine blades. Development of such a correlation dictates a need for detailed boundary layer measurements on various turbine blades.

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