D/13

Assessment of a 3-D Boundary Layer Code to Predict Heat Transfer and Flow Losses in a Turbine*

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The prediction of the complete flow field in a turbine passage is an extremely difficult task due to the complex three-dimensional pattern which contains separation and attachment lines, a saddle point and horseshoe vortex (Fig. 1). Whereas, in principle such a problem can be solved using full Navier-Stokes equations, in reality methods based on a Navier-Stokes solution procedure encounter difficulty in accurately predicting surface quantities (e.g. heat transfer) due to grid limitations imposed by the speed and size of the existing computers. On the other hand the overall problem is strongly three-dimensional and too complex to be analyzed by the current design methods based on inviscid and/or viscous strip theories. Thus there is a strong need for enhancing the current prediction techniques through inclusion of 3-D viscous effects. A potentially simple and cost effective way to achieve this is to use a prediction method based on three-dimensional boundary layer (3-DBL) theory. The major objective of this program is to assess the applicability of such a 3-DBL approach for the prediction of heat loads, boundary layer growth, pressure losses and streamline skewing in critical areas of a turbine passage. A brief discussion of the physical problem addressed here along with the overall approach is presented in the following paragraphs.

In the present investigation, zonal concepts are utilized to delineate regions of application of 3-DBL theory--these being the endwall, suction and pressure surfaces. Each of the regions selected for this investigation has some unique features. For example, the experimental data of Ref. 1 for the surface streamline pattern (Fig. 2a) and the corresponding Stanton (St) number distribution (Fig. 2b) for the endwall region of a planar cascade displays strong three-dimensional effects due to sweeping of the boundary layer across the passage from the pressure to the suction surface. A modified version of the 3-DBL code of Ref. 2, named "TABLET" (Three- Dimensional Algorithm for Boundary-Layer Equations in Turbulent Flows) will be used to analyze the viscous flow downstream of the attachment line between the pressure and suction surface junctures in the endwall region.

The second region of interest is the turbine blade suction surface. As shown in Fig. 3a, the growth of endwall boundary layers produces inward deflection of the streamlines along the suction surface. Thus strong crossflow velocities are induced from the endwall region towards midspan and the flow becomes progressively more three-dimensional as the trailing-edge is approached. The effect of cross flow induced three-dimensionality is also clear from the measured St number distributions (Ref. 1) shown in Fig. 3b. The "TABLET" code will be used to analyze the flow and predict the effect of streamline convergence on St number distributions in the region which lies downstream of the leading-edge and between the separation line and midspan.

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The final region of interest is the pressure side of the blade. Here, the three-dimensionality in the flow is induced by a different mechanism altogether--namely, that of blade rotation. A typical streamline pattern on the pressure surface of a rotating blade obtained from Ref. 3 is presented in Fig. 4, where a strong outward radial flow was encountered. Due to the lower flow velocities in the viscous-layer, the flow close to the wall is skewed outwards more than the inviscid flow. The flow downstream of the leading-edge and away from the hub will be analyzed to assess the "TABLET" code for predicting radial outflow of surface streamlines due to blade rotation effects.

The computer code "TABLET" being used in this investigation solves the finite-difference form of the compressible 3-DBL equations (including the energy equation) in a nonorthogonal surface coordinate system. An efficient, implicit, fully coupled finite-difference solution procedure is employed. Boundary conditions are obtained from experimental data to eliminate errors associated with inviscid approximations. Starting solutions along two inflow boundaries (selected from close examination of data) are obtained by solving the appropriate limiting form of the 3-DBL equations. Sample solutions obtained to date will be described in the next few paragraphs.

The first test case for this investigation was selected to establish the accuracy of the present 3-DBL code for analyzing passage flows. For this reason, the flow in a 60 deg curved duct, for which an extensive set of data is available in Ref. 4, was computed using the "TABLET" code. The schematic of the flow problem along with the nomenclature and locations of the measuring stations is shown in Fig. 5. The two inflow boundaries for this problem were selected to be along line A and along the radial line at Station 1. Streamwise velocity profiles along these inflow boundaries were generated from Whitfield's wall-wake correlation (Ref. 5) which uses experimentally measured values of the skin friction coefficient, momentum-thickness-Reynolds number and shape factor as input. Cross-flow velocity profiles along the inflow boundaries were generated from Mager's (Ref. 6) cross-flow representation using measured skewing of surface streamlines. The "TABLET" code has been used to compute the viscous flow on the upper wall of the curved duct from Station 1 to Station 15 in the streamwise direction and from the pressure side A to the suction side E in the spanwise direction. The predicted values for all the integral properties and the skin friction coefficient compare very well with the measured data. A typical comparison from this study is presented in Fig. 6 where the surface streamline skewing angle, β_W, is shown. This figure clearly indicates that relatively large skewing of surface streamlines, typically encountered in turbine passage flows, can be accurately predicted using the present 3-DBL analysis.

The next test case chosen for this study is the flow in the endwall region of a turbine passage. The surface streamline pattern and St number distribution for this case have already been shown in Figs. 2(a) and (b). Figure 7a shows the schematic diagram of the computational mesh which consists of boundary fitted lines at constant percentage pitch locations and vertical lines at constant percentage axial locations. The upstream inflow boundry is selected to be the line at 10 percent chord distance downstream of the leading edge and the pressure side inflow boundary is taken to be along the intersection of endwall and pressure surfaces (Fig. 7a). Locally similar solutions are used along these inflow boundaries to generate the starting profiles. Since the location and extent of the transition zone is not known for this problem, a preliminary case has been run by assuming that the flow is fully laminar in the leading-edge region and it transits to turbulent flow instantaneously at the second streamwise mesh point (x/Bx = 0.105). The computed Stanton

(St) number distribution at x/Bx = 0.2, 0.4, 0.6 and 0.8 is shown in Fig. 7b along with the measured data. The predicted values of St number display the correct qualitative variation when traversing from pressure side to suction side over the region considered here. Keeping in mind the fact that no attempt has been made to modify the turbulence model, the present results are very encouraging. A sensitivity study will be conducted to determine the effect of changes in transition location and turbulence model on the St number distribution in the near future.

It is planned to use the "TABLET" code for predicting the viscous flow on the suction surface of the blade to study the effect of streamline convergence on heat transfer. Finally, this code will be used to predict the skewing of surface streamlines on the pressure surface of the rotating turbine blade of Ref. 3, to complete the assessment of the applicability of the 3-DBL theory for analyzing viscous flow in a turbine passage.

References

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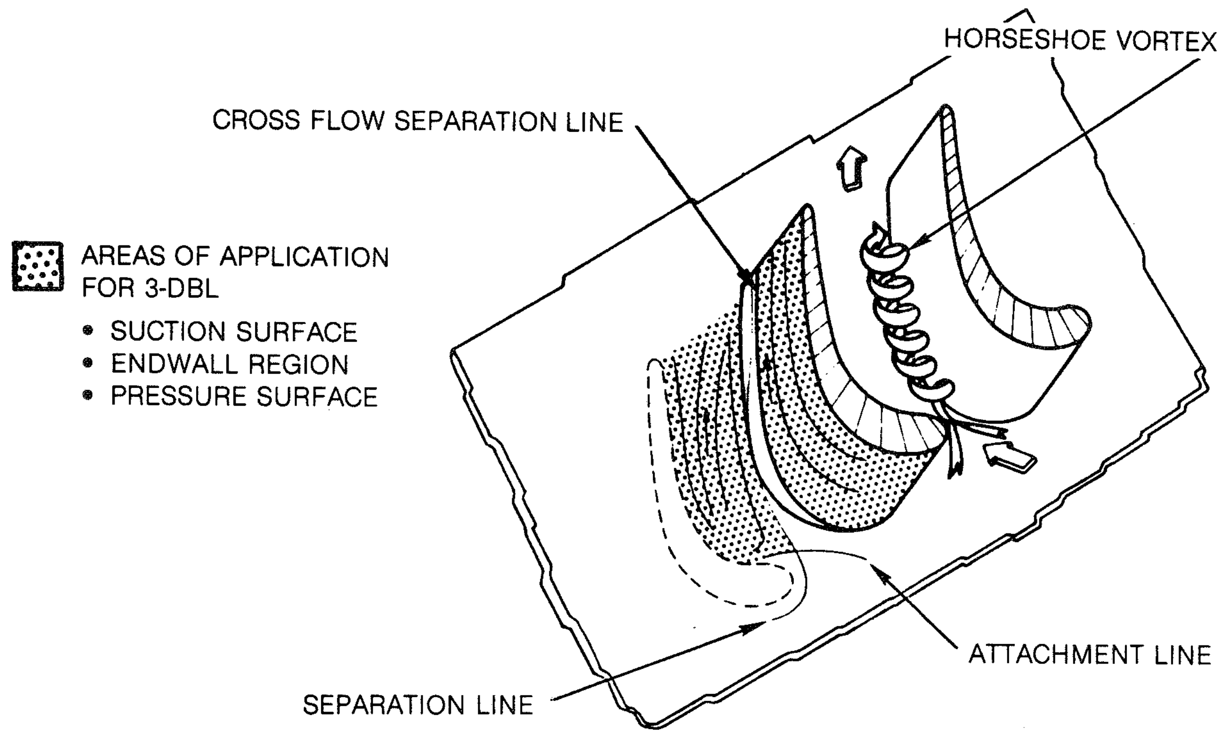

Fig. 1. Schematic of Flow in a Turbine Passage

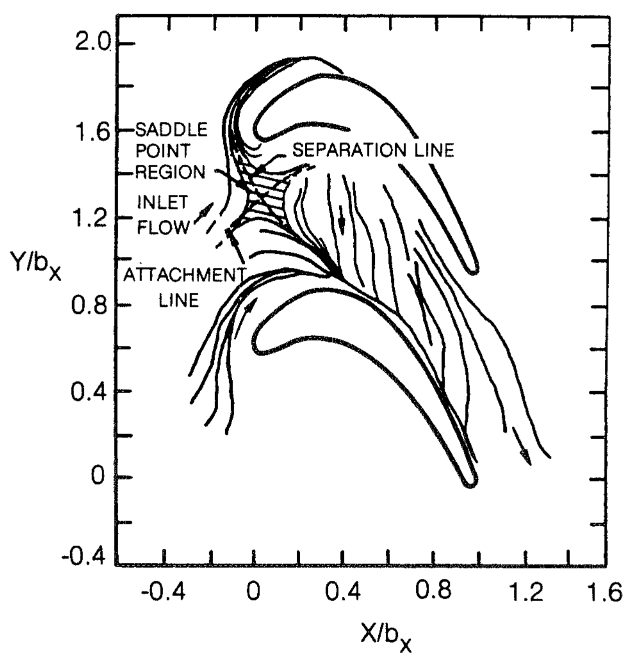

Fig. 2a. Endwall Surface Limiting Streamlines

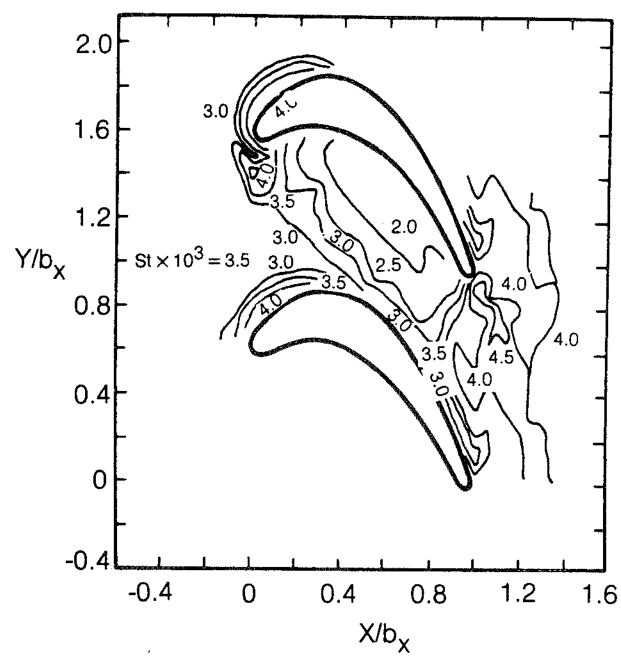

Fig. 2b. Endwall Stanton Number Contours

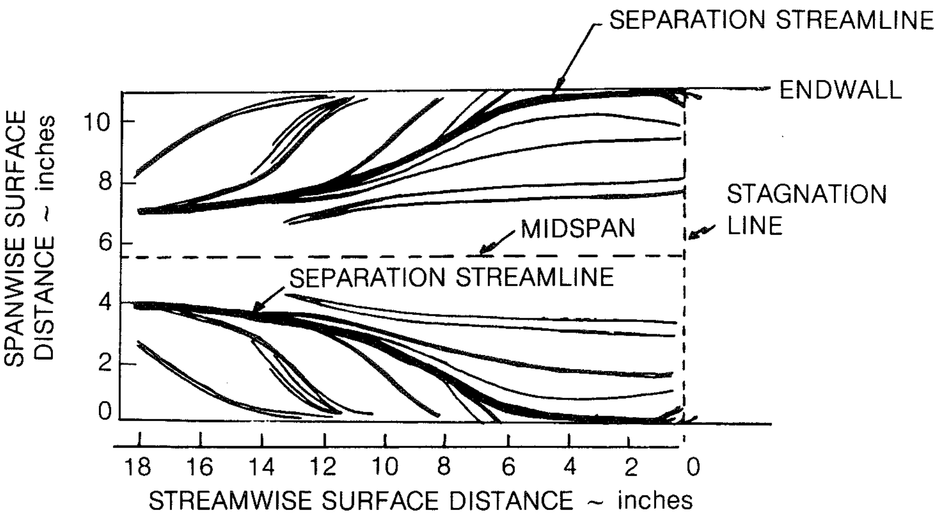

Fig. 3a. Blade Suction Surface Limiting Streamlines

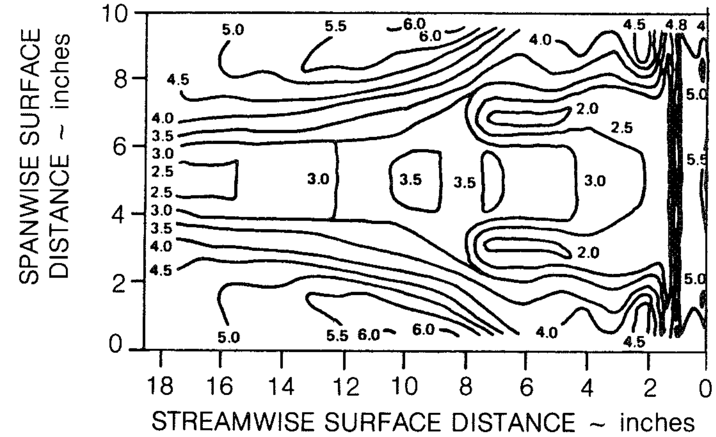

Fig. 3b. Blade Suction Surface Stanton Number Contours

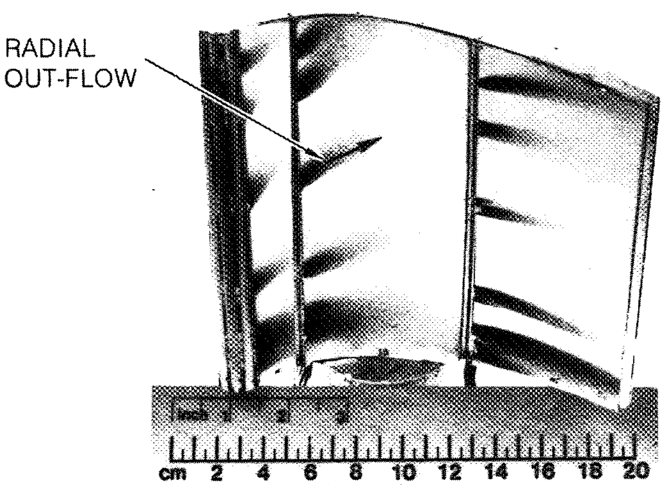

Fig. 4. Pressure Surface Limiting Streamlines

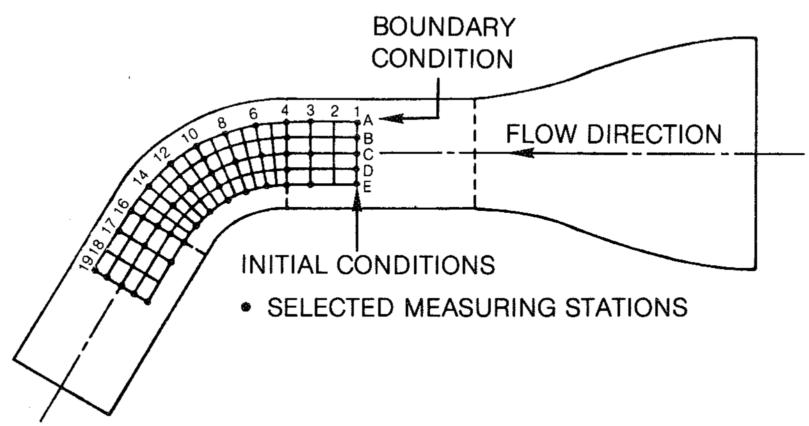

Fig. 5. Schematic of Experimental Setup for Flow in a Curved Duct

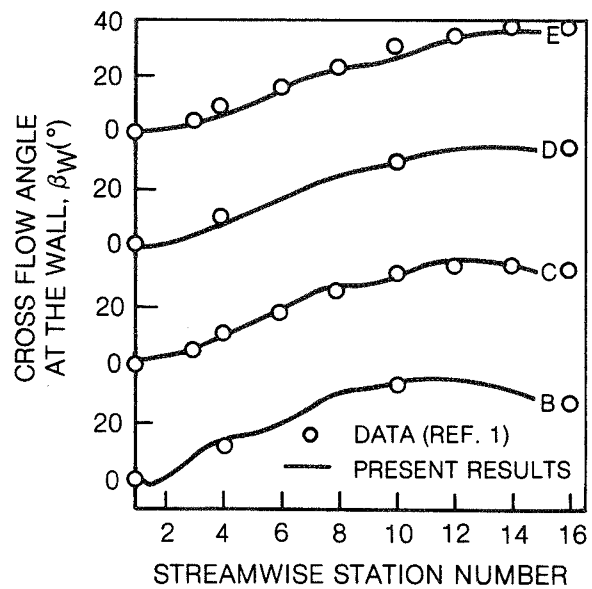

Fig. 6. Wall Cross Flow Angle Distribution for Flow in a Curved Duct

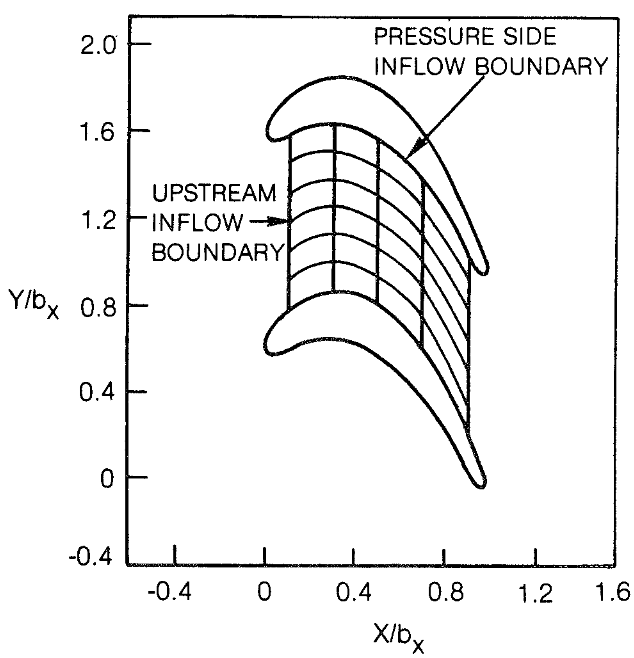

Fig. 7a. Schematic Diagram of Endwall Computational Region

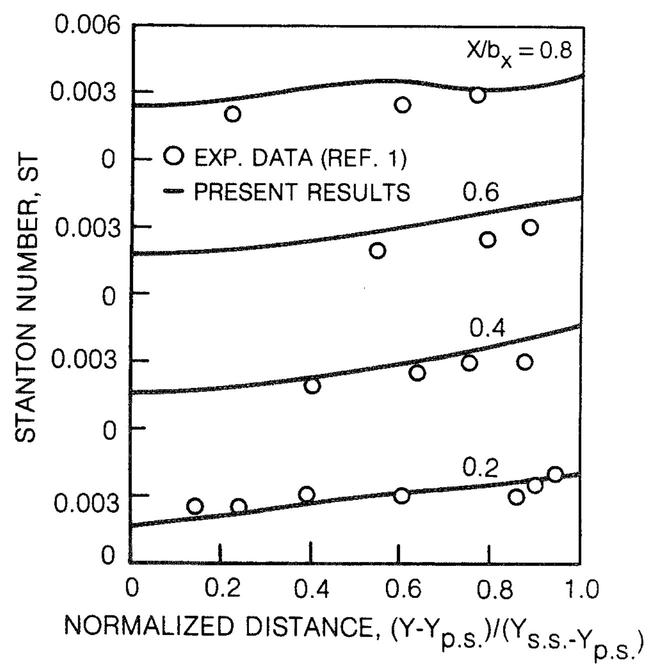

Fig. 7b. Comparison of Endwall Stanton Number Distributions