

# STUDY OF BOUNDARY LAYER DEVELOPMENT IN A TWO-STAGE LOW-PRESSURE TURBINE

Daniel J. Dorney \*  
Virginia Commonwealth University  
Richmond, VA

David E. Ashpis<sup>a</sup>  
NASA Lewis Research Center  
Cleveland, OH

David E. Halstead<sup>b</sup>  
GE Aircraft Engines  
Cincinnati, OH

David C. Wisler<sup>c</sup>  
GE Aircraft Engines  
Cincinnati, OH

## NOMENCLATURE

### ROMAN SYMBOLS

$H$  Shape factor,  $\delta^*/\theta$   
 $S$  Arc length  
 $Tu$  Free stream turbulence level  
 $u$  Local velocity  
 $U_\infty$  Free stream velocity

### GREEK SYMBOL

$\delta^*$  Displacement thickness

### SUBSCRIPTS

$ex$  Exit value  
 $wet$  Wetted distance  
 $\infty$  Free stream value

## INTRODUCTION

Experimental data from jet-engine tests have indicated that unsteady blade row (wake) interactions and separation can have a significant impact on the efficiency of turbine stages. The effects of these interactions can be intensified in low-pressure turbine stages because of the low Reynolds number operating environment. Measured turbine efficiencies at takeoff can be as much as two points higher than those at cruise conditions [1]. Thus, during the last decade a significant amount of effort has been put into determining the effects of transition and turbulence on the performance of low pressure turbine stages. Experimental investigations have been performed, for example, by Hodson *et al.* [2] and Halstead *et al.* [3]. These investigations have helped identify/clarify the roles that factors such as the Reynolds number, free stream turbulence intensity, pressure gradient and curvature have in the generation of losses. In parallel to the experimental investigations,

\* Associate Professor, Senior Member AIAA.

<sup>a</sup> Aerospace Engineer, Senior Member AIAA.

<sup>b</sup> Engineering Manager, Senior Member AIAA.

<sup>c</sup> Mgr of Univ. Strategic Alliances and Aero Tech Labs.

there have been significant analytical efforts to improve the modeling of transition. Examples of such efforts include the works of Mayle [4] and Gostelow *et al.* [5]. These newer models show promise of providing accurate transition predictions over a wide range of flow conditions [6], although they have yet to be implemented into the numerical flow analyses used by the turbine design community. Some recent computational investigations of interest include the works of Chernobrovkin and Lakshminarayana [7] and Eulitz and Engel [8].

The focus of the current effort has been to use a viscous, unsteady quasi-three-dimensional Navier-Stokes analysis to study boundary layer development in a two-stage low-pressure turbine. A two-layer algebraic turbulence model, along with a natural transition model and a bubble transition model, have been used. The geometry used in the simulations has been the subject of extensive experiments [3]. The predicted results have been compared with experimental data, including airfoil loadings and time-averaged/unsteady integral boundary layer quantities.

## ALGORITHM

In the numerical analysis the flow field is divided into two types of zones. O-type grids are used to resolve the flow field near the airfoils. The O-grids are overlaid on H-grids which are used to resolve the flow field in the passages between airfoils. The H-grids are allowed to slip relative to one another to simulate the relative motion between rotors and stators. The thin-layer or full Navier-Stokes equations are solved on both the O- and H-grids. The governing equations are cast in the strong conservation form. A fully implicit, finite-difference method is used to advance the solution of the governing equations in time. A Newton-Raphson subiteration scheme is used to reduce the linearization and factorization errors at each time step. The convective terms are evaluated using a third-order-accurate upwind-biased Roe scheme. The viscous terms are evaluated using second-order accurate central differences and the scheme is second-order accurate in time. Details of the solution procedure and boundary conditions are discussed in Ref. [9]

## TURBULENCE AND TRANSITION MODELS

The two-layer algebraic model based on the work of Baldwin and Lomax (BL) was used to model turbulence [10]. Several modifications were made to the original BL model based on previous experiences with compressor and turbine geometries:

- The switchover location between the inner and outer models cannot move more than a specified number of grid points between adjacent streamwise locations. This eliminates non-physical gradients in the turbulent viscosity near separation points.
- A second derivative smoothing function is used on the turbulent viscosity field in separated flow regions. This also helps remove non-physical gradients in the turbulent viscosity in separation regions.
- A cutoff value is imposed on the turbulent viscosity (nominally 1200 times the free stream laminar viscosity).

The comparison of predicted and experimental integral boundary layer quantities warrants discussion of the technique used to determine the location of the boundary layer edge in the simulations. The following steps, based on the work of Davis *et al.* [11], were used to determine the edge of the boundary layer:

1. determine the minimum value of  $|U_\infty - u|$ , where  $U_\infty$  is the free stream velocity based on isentropic conditions and  $u$  is the local velocity
2. correct the location based on where the local vorticity exceeds a specified limiting value
3. within the new range, determine where  $u$  is greater than  $U_\infty$
4. determine where the local velocity is 99% of the free stream value

The low Reynolds number environment in low-pressure turbines suggests that the flow may be transitional. The natural transition model of Abu-Ghannam and Shaw has been utilized in the current study [12]. In the region between the start and end of transition, the intermittency function is determined using the model developed by Dhawan and Narasimha [13]. For cases involving separation bubbles the model developed by Roberts [14], and modified by Davis *et al.* [15], is used. Instantaneous transition is assumed using the bubble model.

## GEOMETRY AND GRID

The test article used in this study has been studied extensively by Halstead *et al.* [3]. The turbine is typical of the those found in modern aircraft engines. The experimental turbine contains 82 first-stage nozzles, 72 first-stage rotors, 108 second-stage nozzles and 72 second-stage stators (*i.e.*, a 82-72-108-72 blade count ratio). For modeling purposes a blade count ratio of 78-78-104-78 was assumed, thus requiring the use of 3 first-stage nozzles, 3 first-stage rotors, 4 second-stage nozzles and 3 second-stage rotors in the simulations. The complete grid topology contained 329,997 grid points. The average value of  $y^+$ , the non-dimensional distance of the first grid point above the surface, was approximately 1.0 for all four blade rows. The boundary layers for all four blade rows were discretized with approximately 20-30 grid points.

The simulations were run on Silicon Graphics Inc. (SGI) Origin 200 workstations with 195-MHz processors. The average computation time was  $4 \times 10^{-5}$  sec/grid point/iteration. The simulation was run for 20 global periods, at 18,000 time steps per global period. A global period is defined as the second rotor moving through a distance equal to 4 second nozzle pitches or, similarly, the first rotor moving through a distance equal to 3 first nozzle pitches. The 20 global periods allowed the efficiency, losses and integral boundary layer quantities to become time periodic.

## RESULTS

The operating point studied corresponds to takeoff conditions. In accordance with the experiments, the free stream turbulence level (used in the transition models) was set at  $Tu = 3\%$ .

Numerical and experimental time-averaged loadings on the second nozzle and second rotor are shown in Figs. 1 and 2, respectively. The predicted results exhibit good agreement with the experimental data, except in the suction surface leading edge region of the second nozzle. The differences in this region suggest the flow entering the second nozzle in the simulations has somewhat greater positive incidence. On the second rotor, both the numerical results and experimental data show an acceleration region near the suction surface leading edge followed by a zone of constant velocity, a second acceleration region and finally a deceleration zone as the flow moves downstream of the throat into the uncovered portion of the passage.

Figure 3 contains the time history of the unsteady displacement thickness at 82% of the suction surface length on the second nozzle. Included in these figures are the predicted results using the Abu-Ghannam and Shaw transition model, as well as the experimental data. There is generally good agreement between the predicted results and the experimental data.

Minimum, maximum and time-averaged distributions of the displacement thickness on the suction surface of the second nozzle are shown in Fig. 4, while the corresponding time-averaged shape factor distributions are shown in Fig. 5. The time-averaged values obtained with the ABS model show excellent agreement with the experimental data.

## CONCLUSIONS

Quasi-three-dimensional numerical simulations have been performed for flow through a two-stage low-pressure turbine. The simulations were performed for takeoff operating conditions, and employed natural and bubble transition models. The results of this study have shown that the Abu-Ghannam and Shaw transition model yields accurate results for the transient and time-averaged integral boundary layer quantities.

## ACKNOWLEDGEMENT

The work of the first author was supported by NASA Lewis Research Center under Grant NCC3-645.

## References

- [1] Simon, F. F. and Ashpis, D. E., "Progress in Modeling of Laminar to Turbulent Transition on Turbine Vanes and Blades," International Conference on Turbulent Heat Transfer, 1996, also NASA TM 107180.
- [2] Hodson, H. P., Huntsman, I. and Steele, A. B., "An Investigation of Boundary Layer Development in a Multistage LP Turbine," *Journal of Turbomachinery*, Vol. 116, 1994, pp. 375-383.

- [3] Halstead, D. E., Wisler, D. C., Okiishi, T. H., Walker, G. J., Hodson, H. P. and Shin, H.-W., "Boundary Layer Development in Axial Compressors and Turbines - Part 3 of 4: LP Turbines," *ASME Journal of Turbomachinery*, Vol. 119, April, 1997, pp. 225-237.
- [4] Mayle, R. E., "The Role of Laminar-Turbulent Transition in Gas Turbine Engines," ASME Paper 91-GT-261, Orlando, FL, 1991.
- [5] Gostelow, J. P., Blunden, A. R. and Walker, G. J., "Effects of Free-Stream Turbulence and Adverse Pressure Gradients on Boundary Layer Transition," *ASME Journal of Turbomachinery*, Vol. 116, 1994, pp. 392-404.
- [6] Boyle, R. J. and Simon, F. F., "Mach Number Effects on Turbine Blade Transition Length Prediction," ASME Paper 98-GT-367, International Gas Turbine and Aeroengine Congress and Exhibition, Stockholm, Sweden, June 2-5, 1998, also accepted for publication in the *ASME Journal of Turbomachinery*.
- [7] Chernobrovkin, A. and Lakshminarayana, B., "Development and Validation of Navier-Stokes Procedure for Turbomachinery Unsteady Flow," AIAA Paper 97-3281, Seattle, WA, 1997.
- [8] Eulitz, F. and Engel, K., "Numerical Investigation of Wake Interaction in a Low Pressure Turbine," ASME Paper 98-GT-563, International Gas Turbine and Aeroengine Congress and Exhibition, Stockholm, Sweden, June 2-5, 1998.
- [9] Dorney, D. J., and Verdon, J. M., "Numerical Simulations of Unsteady Cascade Flow," *ASME Journal of Turbomachinery*, Vol. 116, No. 4, October, 1994, pp. 665-675.
- [10] Baldwin, B. S., and Lomax, H., "Thin Layer Approximation and Algebraic Model for Separated Turbulent Flow", AIAA Paper 78-257, Huntsville, AL, January, 1978.
- [11] Davis, R. L., Hobbs, D. E., and Weingold, H. D., "Prediction of Compressor Cascade Performance Using a Navier-Stokes Technique," *ASME Journal of Turbomachinery*, Vol. 110, No. 4, October, 1988, pp. 520-531.
- [12] Abu-Ghannam, B. J., and Shaw, R., "Natural Transition of Boundary Layers - The Effects of Turbulence, Pressure Gradient, and Flow History," *IMEchE Journal of Mechanical Engineering Science*, Vol. 22, No. 5, 1980, pp. 213-228.
- [13] Dhawan, S., and Narasimha, R., "Some Properties of Boundary Layer Flow During Transition from Laminar to Turbulent Motion," *Journal of Fluid Mechanics*, Vol. 3., 1958.
- [14] Roberts, W. B., "Calculation of Laminar Separation Bubbles and Their Effect on Airfoil Performance," AIAA Paper 79-0285, New Orleans, LA, January, 1979.
- [15] Davis, R. L., Carter, J. E., and Reshotko, E., "Analysis of Transitional Separation Bubbles on Infinite Swept Wings," *AIAA Journal*, Vol. 25, No. 3, March, 1987, pp. 421-428.

Figure 1. Normalized loading on nozzle-2.

Figure 2. Normalized loading on rotor-2.

Figure 3. Unsteady displacement thickness, nozzle-2, 82% SSL.

Figure 4. Displacement thickness envelope, nozzle-2.

Figure 5. Time-averaged shape factor, nozzle-2.

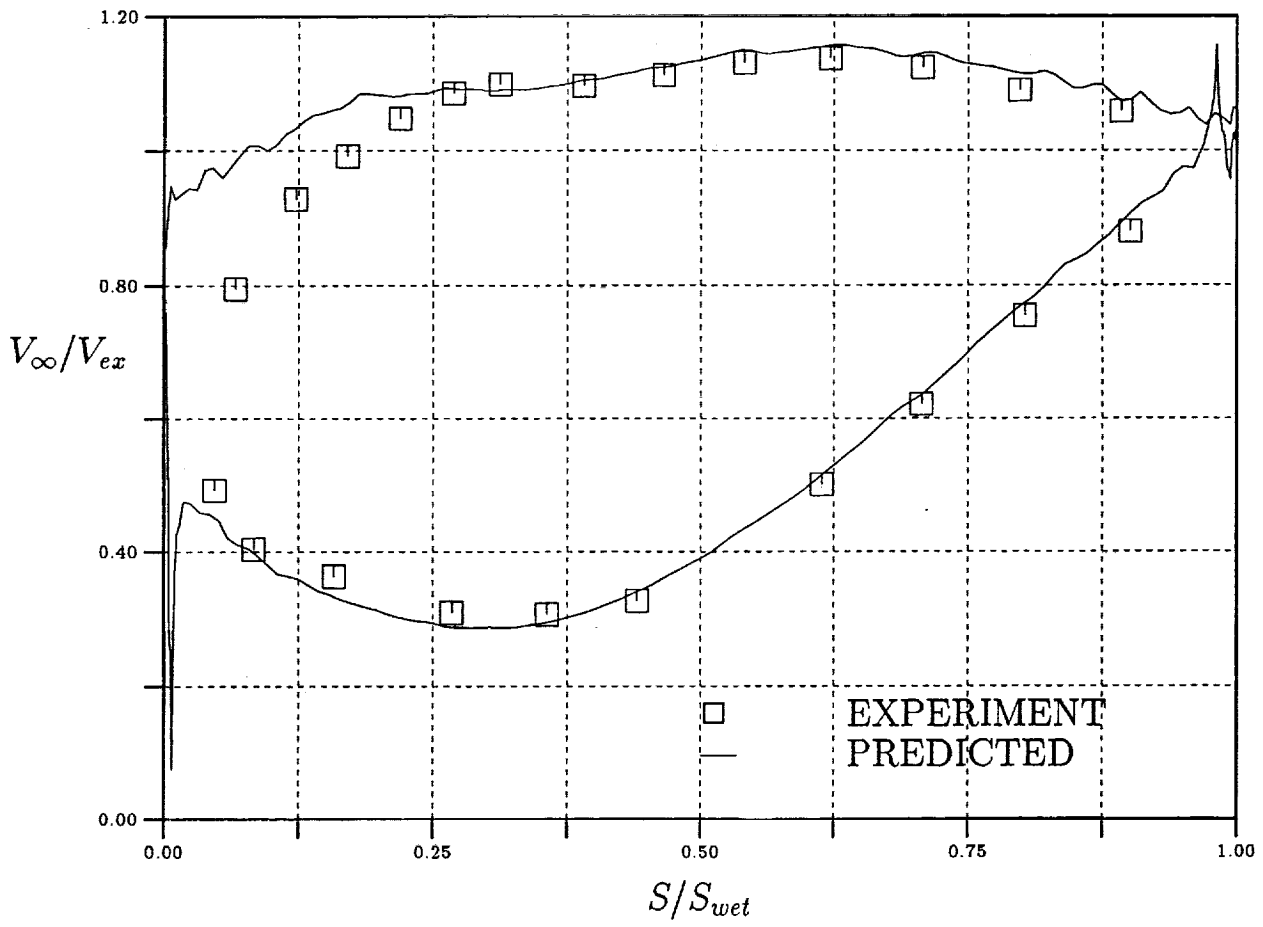


Figure 1:

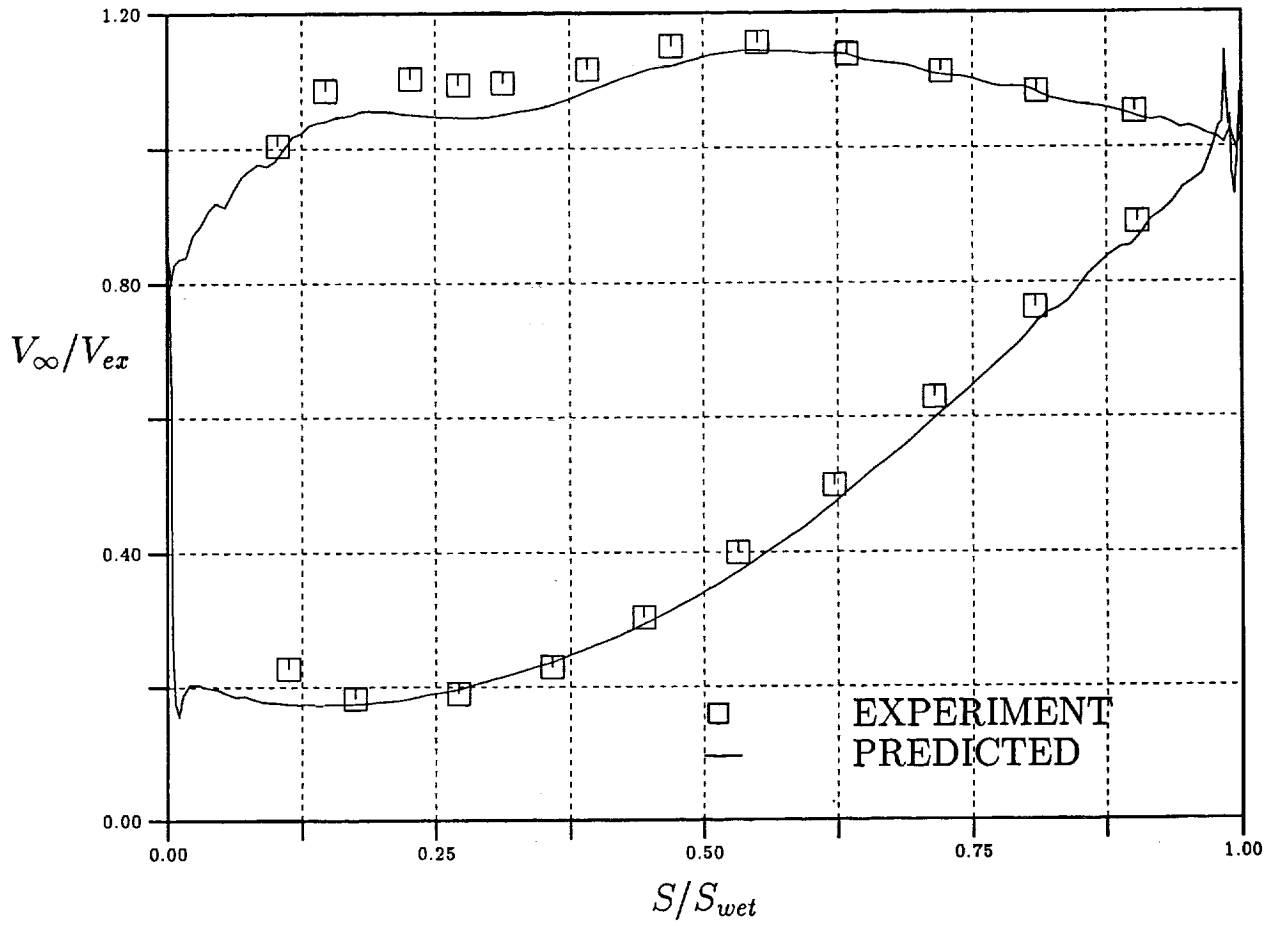


Figure 2:

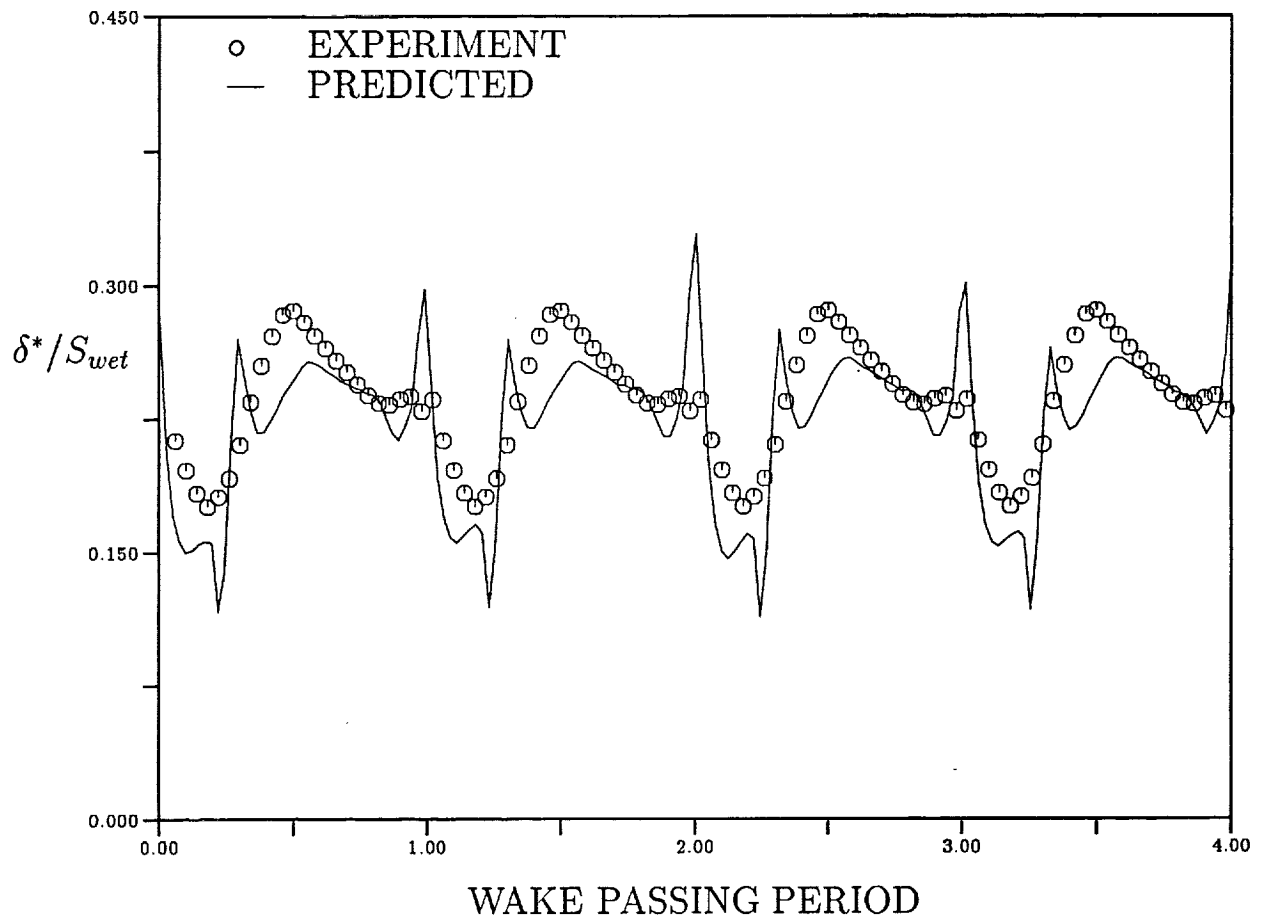


Figure 3:



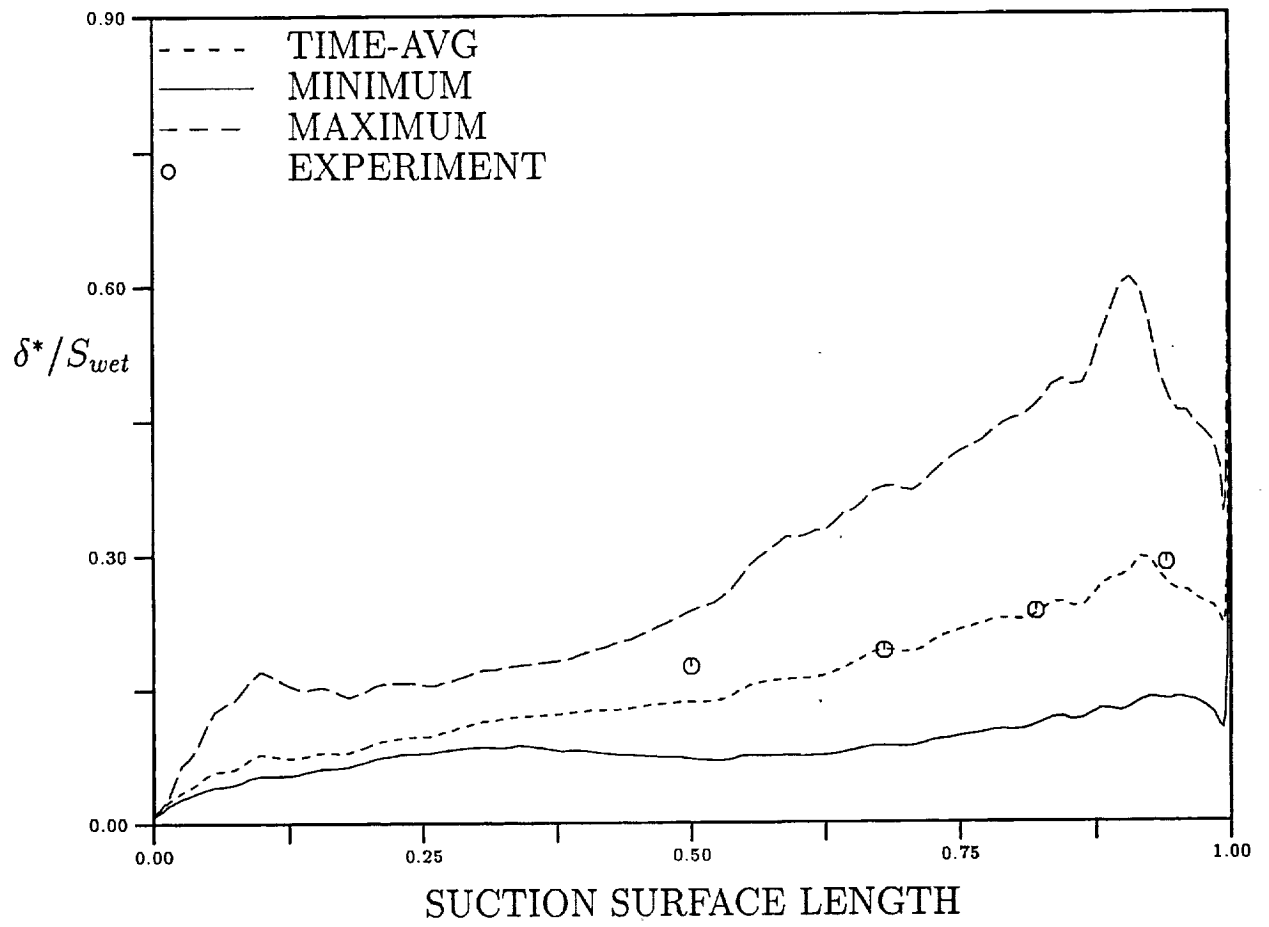


Figure 4:

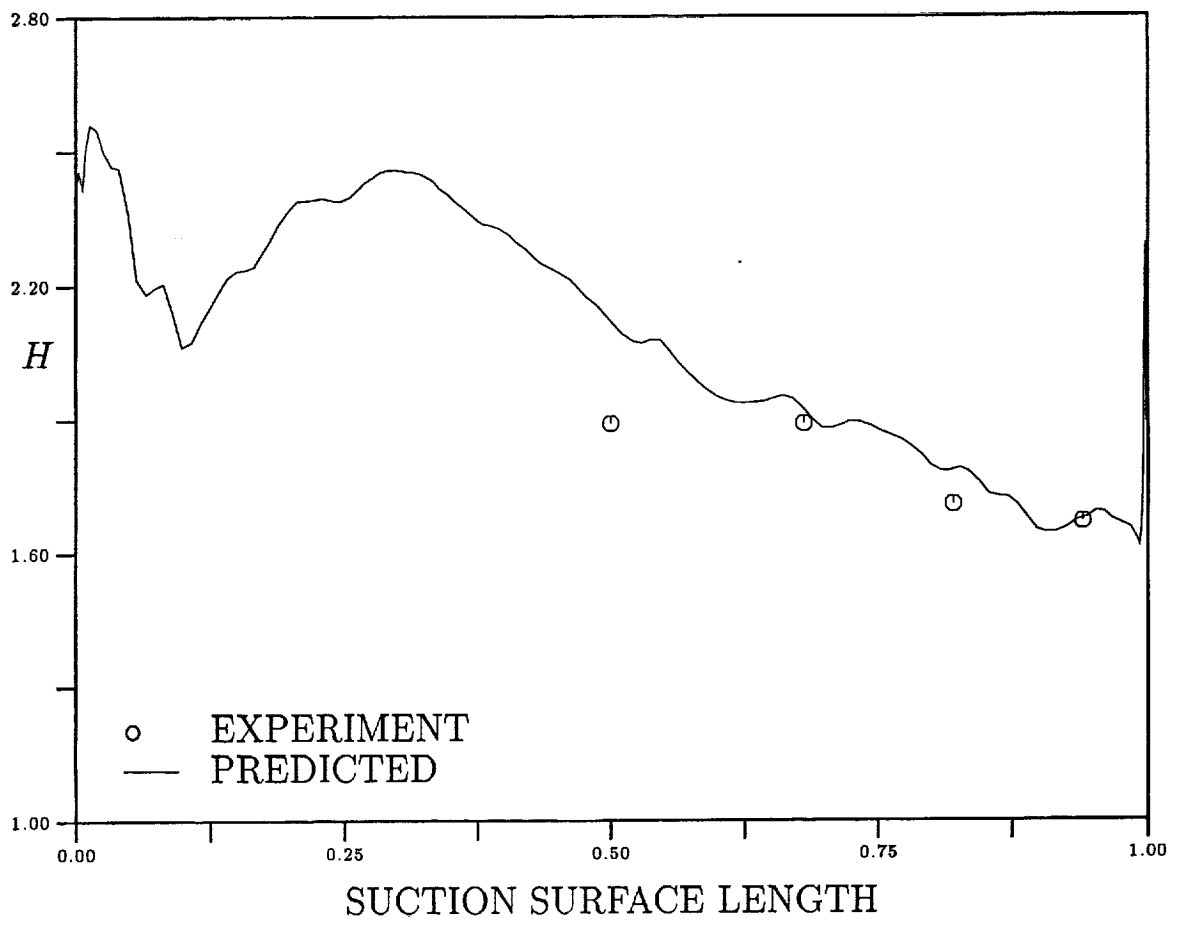


Figure 5: