Chen, Y. S., 1989, "Compressible and Incompressible Flow Computations With a Pressure Based Method," AIAA Paper No. 89-0286.

Chien, K. Y., 1982, "Predictions of Channel and Boundary-Layer Flows With a Low-Reynolds-Number Turbulence Model," *AIAA Journal*, Vol. 20, No. 1, pp. 33–38.

Copenhaver, W. W., Hah, C., and Puterbauch, S. L., 1992, "Three-Dimensional Flow Phenomena in a Transonic, High-Through-Flow Compressor Stage," ASME JOURNAL OF TURBOMACHINERY, Vol. 115, pp. 240–248.

Dawes, W. N., 1988, "Development of a 3D Navier–Stokes Solver for Application to all Types of Turbomachinery," ASME Paper No. 88-GT-70.

Deng, G. B., Queutey, P., and Visonneau, M., 1993, "Navier–Stokes Computations of Ship Stern Flows: A Detailed Comparative Study of Turbulence Models and Discretization Schemes," presented at the 6th International Conference on Numerical Ship Hydrodynamics, Iowa City, IA.

Dring, R. P., and Spear, D. A., 1991, "The Effects of Wake Mixing on Compressor Aerodynamics," ASME JOURNAL OF TURBOMACHINERY, Vol. 113, pp. 600–607.

Farrell, K. J., McBride, M. W., and Billet, M. L., 1987, "High Reynolds Number Pump Facility for Cavitation Research," The Pennsylvania State University/ARL Technical Report No. TR 87-011.

Garcia, R., Jacson, E. D., and Schutzenhofer, L. A., 1992a, "A Summary of the Activities of the NASA/MSFC Pump Stage Technology Team," *Proceedings of the Fourth International Symposium on Transport Phenomena and Dynamics of Rotating Machinery*, Honolulu, HI.

Garcia, R., McConnaughey, P., and Eastland, A., 1992b, "Activities of MSFC Pump Stage Technology Team," AIAA Paper No. 92-3232.

Giles, M. B., 1988, "Stator/Rotor Interaction in a Transonic Turbine," AIAA Paper No. 88-3093.

Hah, C., 1985, "Modeling of Turbulent Flow Fields Through Cascade of Airfoils at Stall Condition," *AIAA Journal*, Vol. 23, pp. 1411–1417.

Hah, C., 1987, "Calculation of Three-Dimensional Viscous Flows in Turbomachinery With an Implicit Relaxation Method," *AIAA Journal of Propulsion and Power*, Vol. 3, No. 5, pp. 415–422.

Hah, C., and Leylek, J. H., 1987, "Numerical Solution of Three-Dimensional Turbulent Flows for Modern Gas Turbine Components," ASME Paper No. 87-GT-84.

Hah, C., Brayns, A. C., Moussa, Z., and Tomsho, M. E., 1988, "Application of Viscous Flow Computations for Aerodynamic Performance of a Backswept Impeller at Viscous Operating Conditions," ASME JOURNAL OF TURBOMACHINERY, Vol. 110, pp. 303–311.

Jorgenson, P. C. E., and Chima, R. V., 1988, "An Explicit Runge–Kutta Method for Unsteady Rotor/Stator Interaction," AIAA Paper No. 88-0049.

Kiris, C., Chang, L., Kwak, D., and Rogers, S., 1993, "Incompressible Navier–Stokes Computations of Rotating Flows," AIAA Paper No. 93-0678.

Leylek, J. H., and Wisler, D. C., 1991, "Mixing in Axial-Flow Compressors: Conclusions Drawn From Three-Dimensional Navier–Stokes Analysis and Experiment," ASME JOURNAL OF TURBOMACHINERY, Vol. 113, pp. 139–160.

Rai, M. M., 1985, "Navier–Stokes Simulations of Rotor–Stator Interaction Using Patched and Overlaid Grids," AIAA Paper No. 85-1519.

Rao, K., and Delaney, R., 1990, "Investigation of Unsteady Flow Through Transonic Turbine Stage," AIAA Paper No. 90-2408.

Stanier, M. J., 1992, "Design and Devaluation of New Propeller Blade Section," presented at the Int. Sym. on Propulsors and Cavitation, Hamburg, June 22–25.

Walker, P. J., and Dawes, W. N., 1990, "The Extension and Application of Three-Dimensional Time-Marching Analysis to Incompressible Turbomachinery Flows," ASME JOURNAL OF TURBOMACHINERY, Vol. 112, pp. 385–390.

Zierke, W. C., Straka, W. A., and Taylor, P. D., 1993, "The High Reynolds Number Flow Through an Axial-Flow Pump," The Pennsylvania State University/ARL Technical Report No. TR93-12, Nov.

DISCUSSION

W. C. Zierke[1]

As an experimentalist, I am pleased to see engineers compare my data with their numerical computations. This particular data set offers measurements of a very complex flow field to those attempting to compute the incompressible flow through a turbomachine. The authors should be commended for attempting to use their code in such a severe test case.

First, I would like to clear up a few discrepancies between the authors' paper and the experimental report of Zierke et al. (1993). The authors' description of the rotor blade thickness and camber distributions is incorrect, although I am sure that they did in fact use the correct blade coordinates for their computations. Also, the experimental data used in the inlet axial-velocity profile of Fig. 2(*a*) must have been some preliminary data, since these data do not correspond to data from the experimental report. Finally, the computations in Fig. 5(*b*) were performed with lifting surface theory, not lifting line theory.

Next, I would like to address some of the comparisons between the experimental and computational results. First, the authors stated that the secondary velocity vectors predicted in Figs. 5(*c*) and 6(*a*) came from single blade passages; and yet, the radial components do not seem to show periodicity. Is the entire passage shown in each of these figures? Then, for the predicted axial-velocity contours of Fig. 6(*b*), the authors predict a "separation induced vortex" not shown in the measurements. Lee et al. feel that this vortex is damped out quicker in the measurements than in the prediction. And yet, Zierke et al. (1993) report additional data measured much closer to the trailing edge near the rotor blade root and these data also show no sign of this vortex. Therefore, our laser-Doppler velocimeter measurements do not detect a significant vortex in this region—in contrast to the computations. Finally, the velocities predicted downstream of each blade row are fair, although the tangential velocities predicted downstream of the inlet guide vanes are poor and this leads to a poorly predicted harmonic content. Downstream of the rotor blades, the mismatch in the comparisons does not necessarily mean that the measured and computed strengths of the tip leakage vortex are different. The plots in Fig. 8 are simply two-dimensional cuts through a complex, three-dimensional flow field. The computed vortex strength could be very good—but simply computed to be in the wrong location.

Finally, I would like to comment on statements made by the Lee et al.—in particular, those concerning the flow patterns near the rotor blade suction surface. Contrary to their statement, the flow reversal in the corner separation does not produce the strong radial flow in the experimental flow visualization. Centrifugal effects cause this radial migration. By altering characteristics of the rotor blade design (such as the blade lean), one could design a blade with a flow reversal in the corner separation without having a strong radial migration. Later, in their alternate computation with a variation in their turbulence model, Lee et al. stated that our water tunnel experiment could produce a characteristic length scale of the incoming turbulence that might be much larger than the length scale based on the IGV dimension. Using this reasoning, they increased the inlet length scale to 100 times their original length scale. I have a very difficult time following this argument. As stated by Zierke et al. (1993), the water tunnel turbulence is controlled using a honeycomb. This honeycomb will establish an inlet turbulent length scale that is much smaller than the IGV dimensions. Even without a honeycomb, the inlet turbulent length scale cannot be larger than the IGV dimensions. If the authors need to change their length scale so dramatically—and change it in the wrong direction—one should question both the sensitivity and the utility of using their turbulence model for this type of flow field.

In summary, I feel that the comparison of these computations with our experimental data show just how difficult it is to compute the flow through a turbomachine. This type of complex, unsteady, three-dimensional flow field places a large burden on the numerical analyst. Issues with the numerical algorithms, the turbulence models, and the computational grids must all be addressed in order to improve the predictions of this and similar turbomachinery flow fields. Again, the authors should be commended for testing their code by performing these computations.

Authors' Closure

As the computational analysts, we are delighted to see the experimentalist providing his view about our computational results.

First of all, these computational results were obtained almost two and half years ago. We were the first group attempting to

[1] Applied Research Laboratory, The Pennsylvania State University, State College, PA 16804.