

## Conclusion

A new technique for computing viscous-incompressible flowfields is presented and validated for cascades. The present method permits computation on a regular grid instead of on a staggered grid and allows for the solution of the pressure and not the pressure correction. In most test cases, this procedure showed better convergence behavior than the original pressure correction method. The method closely couples the velocity and pressure field, and thus does not suffer from pressure oscillations.

For complex flow situations such as a separated compressor cascade, the code exhibits satisfactory convergence behavior.

The global parameters such as pressure distribution, lift coefficient, and losses are well predicted within engineering accuracy.

The agreement between the computed and measured boundary layer profiles for attached flows on both blade surfaces is very good.

Separated flow predictions need to be further investigated, most probably with higher order models that take into account the streamline curvature and anisotropy of the turbulence in the separated region.

Details of the leading edge flow and particularly the reattachment of the separated trailing edge flow on the suction surface have been resolved, which shed more light on these complex flow regions.

The code has predicted the cascade performance over a moderate incidence range; however, the minimum loss or high negative incidence test case still needs to be computed.

The effect of increasing the free-stream turbulence intensity has been investigated. At high positive incidence the flow separation was inhibited when the turbulence intensity was increased resulting in a decrease in the total pressure loss coefficient.

For flow over complex geometries with pressure gradients or separation, the minimum turbulence model that must be used is the low-Reynolds-number  $k-\epsilon$  model. Its ability to predict transition dependent on free-stream turbulence intensity is well known, and it was used in the present study to predict separated flow.

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## DISCUSSION

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The paper by Hobson and Lakshminarayana introduces a new technique for handling the computational difficulties associated with the assumption of incompressibility for the Navier-Stokes equations. From the point of view of the experimenter whose cascade data the authors attempt to match, however, the paper represents, first and foremost, an honest try at the calculation of this interesting and complex flowfield.

Although for the most part the flowfield is adequately captured, there are regions in which the computation could be improved. Transition is obviously one such region. We note here that the authors do not spend a great deal of space discussing their transition model, and we believe that this is symptomatic of the simplicity and empiricism of current transition models. Certainly, such models are not nearly so sophisticated as current turbulence models. The sensitivity of the transition model to the free-stream turbulence intensity is particularly distressing. From the point of view of an experimentalist, there is every reason to measure the turbulence intensity at an inlet plane a chord or so upstream of the blade row (which we measured as 0.18 percent) to provide an upstream boundary condition. There is no compelling reason to make the same measurement immediately upstream of the blade row. The authors used an inlet free-stream turbulence intensity of 2.0 percent, which seems to be based on the value of 1.5 percent that we measured with a hot wire just outside a leading-edge

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boundary layer. Evidently, their computations, especially their transition model, were quite sensitive to this value. Transition on the pressure surface is still not adequately predicted. From our experiment, we concluded that a very small separation "bubble" existed on this surface that causes at least a partial transition to turbulence. Clearly, research into the transition process and the subsequent development of transition models is very much needed.

A second region in which the calculation could be improved is in the region of separated flow on the suction surface. In particular, it is not all apparent to us why the flow would choose to reattach at 99 percent chord. It seems to us that this reattachment is the reason that the predicted near-wake profiles deviate so much from the measured profiles on the suction side. Perhaps the authors would care to comment on this.

The usefulness of the calculations is apparent both in the incidence angle parametric study and, most particularly, in the detail with which the incidence flow is captured. This improved resolution, above the experiment, makes it possible to determine the actual incidence angle and in this way helps to explain the measured pressure profile. We look forward to increasingly sophisticated attempts, by the authors and others, to calculate these flow fields.

### Authors' Closure

The authors would like to thank Drs. Zierke and Deutsch for their interesting comments. The low-Reynolds-number form of the two-equation turbulence model used accounts for the effect of free-stream turbulence intensity on transition. This model has been shown by Rodi and Scheuerer (1985) and Schmidt and Patankar (1988) to be sensitive to the level of inlet free-stream turbulence intensity. For boundary layer calculations they found that good predictions of transition could

be made by correctly specifying inlet turbulence levels. However, the dissipation levels had to be related to turbulent kinetic energy levels by a constant of proportionality, which in turn was dependent on the level of turbulence. The authors did not attempt to use this specification of the inlet turbulence, but rather used the turbulence model as given by Lam and Bremhorst (1981). For inlet free-stream turbulence intensities of 2 percent, transition, although not accurately, was predicted.

The reattachment of the suction side boundary layer at 99 percent chord was also a surprise to the authors. A possible explanation is that this is a steady-state solution of what is obviously an unsteady flow process. It would be interesting if this steady-state solution were now to be continued in an unsteady mode so that the stability of the flow at the trailing edge could be determined. The authors suspect that vortices are being shed from the trailing edge of the blade, which the present computations are not able to predict. The separation zone "washes out" anywhere from 10 to 30 percent chord length downstream of the trailing edge. The computation and measurements are consistent here. In a recent paper Schulz et al. (1990) observed, "The flow perceives the corner stall as a solid obstruction, which ends abruptly downstream of the blade trailing edge. Here the flows from both sides of the separated zone merge again." The authors believe that the same mechanisms are applicable in this two-dimensional cascade flow.

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