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Final Report

on

ANALYTICAL STUDIES

of

TURBULENT FLOW FIELDS

AFOSR Grant No. 75-2756

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## STATEMENT OF WORK

Much of the work under this grant has culminated in journal articles which are listed chronologically in the next section of this report. References (2) and (6) describe our ongoing development of atmospheric boundary layer models; here the introduction of condensation physics consistent with our second moment turbulence model extends the model so as to include the prediction of clouds. Reference (3) was a fairly broad range paper (which is now being updated for submission to an archival journal) to provide an overview of our modeling work - both in geophysics and engineering - over the past half dozen years. Reference (7) is a theoretical and numerical analysis of a class of stratified boundary layer flows for which data have been published in the literature.

Reference (4) is a suggestion for a turbulence model for engineering boundary layers which should have the demonstrated predictive power and simplicity of our older eddy viscosity model but relates more rationally to higher order models.

Reference (5) is a separate study of the Kolmogoroff law for two point, turbulent, velocity correlations. An effort was made to relate the Kolmogoroff correlation law to the corresponding spectral law and to organize existing data on the empirical coefficients of " $r^{2/3}$ " and " $k^{-5/3}$ ".

Separated Flow Much of the effort under this grant has been (and continues to be) the development of numerical simulations of unsteady, separated flow using our version\* of a Rotta-Kolmogorov, second moment, turbulent closure model. This has been a somewhat risky undertaking

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\* Two other groups have developed models in the same category as ours. They are the ARAP group under Coleman Donaldson and the **Empirical College** group under Brian Launder. The latter group has relied on the use of a dissipation equation to supply a turbulent length scale, a strategy which we believe to be fundamentally incorrect.

with many problems to be solved between inception of the research and success. We can now anticipate success in that we believe we have a very good turbulent closure model and we have resolved important numerical problems.

Reference (1) reported on the early progress of this work and showed the numerically simulated development of the flow behind a step. After a long integrating time the flow became steady. This calculation used an upwind differencing scheme that, after diagnosis, contained "artificial viscosity" or artificial momentum transfer that was somewhat smaller but nevertheless significant relative to the turbulent momentum transfer that was modeled. We then initiated attempts to substitute a central difference algorithm which is known to introduce zero numerical viscosity although explicit viscous terms generally are required to maintain stability. The hope is, of course, that the required level of explicit viscosity is less than the level of artificial viscosity automatically introduced by the upwind scheme. A considerable effort was required before this method worked without numerical instability.

We now find that the turbulent Reynolds stress equations require explicit viscous terms where, indeed, the coefficient of viscosity may be set at a much lower level than the equivalent artificial viscosity introduced by the upwind scheme. Since the turbulent diffusion term that must be modeled in the Reynolds stress equations, the additional diffusion required by numerical stability seems quite tolerable.

On the other hand, we find that the vorticity transport equation requires no additional diffusion terms for numerical stability in which case the flow is unsteady, and we obtain results such as those depicted in Fig. 1. (If sufficient diffusion is added to the vorticity transport equation the flow becomes steady.)

The appearance of two-dimensional, unsteady structures (in what appears to be a stable algorithm) was a bit of a surprise. However, qualitatively these results appear to replicate observation. Our task now is to determine to what extent the calculated unsteady structures conform quantitatively to observation.

We also wish to compare calculations with experimental data for separated boundary layer flow on a flat surface. To do this properly and maintain sufficient resolution while the boundary layer thickness increases manyfold, the model equations and the code have been transformed so that an arbitrary orthogonal coordinate system may be specified. Not only will this accommodate the separating boundary layer problem but will eventually facilitate application of the code to flows with a wide variety of internal flow geometries (internal ducts, diffusers, cascades, etc.)

#### PUBLICATIONS

The following publications were prepared either totally or partially under the support of our AFOSR Grant 75-2756;

- (1) Briggs, M., G. Mellor, and T. Yamada, "A Second Moment Turbulence Model Applied to Fully Separated Flow," Proceedings of the SQUID Workshop on Turbulence in Internal Flows, June 1976. Hemisphere Publishing Co., Washington D.C.
- (2) Mellor, G.L., "The Gaussian Cloud Model Relations," J. Atmos. Sci., 34, 356-358, Feb. 1977.

- (3) Mellor, G.L. and T. Yamada, "A Turbulence Model Applied to Geophysical Fluid Problems," Proceedings of the Symposium on Turbulent Shear Flows, The Penn State University, April 1977.
- (4) Mellor, G.L. and H.J. Herring, "Simple Eddy Viscosity Relations for Three-Dimensional Turbulent Boundary Layers," A.I.A.A. Journal, 15, 886-887, June 1977.
- (5) Dickey T.D. and G.L. Mellor, "The Kolmogoroff  $r^{2/3}$  Law.," Physics of Fluids, Vol. 22, No. 6, June 1979.
- (6) Yamada, T. and G. Mellor, "A Numerical Simulation of the BOMEX Data Using a Turbulence Closure Model Coupled with Ensemble Cloud Relations," Quarterly Journal of the Royal Meteorological Society, 105, 915-944, October 1979.
- (7) Mellor G. and P.T. Strub, "Similarity Solutions for the Stratified Turbulent Rayleigh Problem," accepted for Publication in the Journal of Physical Oceanography.

#### PERSONNEL

In addition to the principal investigator, the following personnel have worked on the project:

Mr. Monina Briggs who obtained his Master's degree in September 1976.

Mr. Tetsuji Yamada, a postdoctoral scientist.

Mr. Cevdet Celenligil, a post graduate student who should complete his Ph.D. dissertation on the subject of separated flows in September 1980.

Mr. Fred Bartlett, an undergraduate who applied the model successfully to developing pipe flow.

#### IMPACT

Our turbulence closure model has been incorporated into the large, atmospheric general circulation models at the NOAA/Geophysical Fluid Dynamics Laboratory resulting in improved weather forecast and climatological simulations. In addition, there are now many scientists in the United States and elsewhere who have used our model for various

studies of geophysical significance. Dr. Yamada is himself heading up a major effort in developing a regional air pollution model at the Argonne National Laboratory.

Our older eddy viscosity models (or slightly modified versions thereof) are now in fairly standard use as design tools in the aircraft industry, and it can be anticipated that more recent turbulent moment closure models will be used in the future.

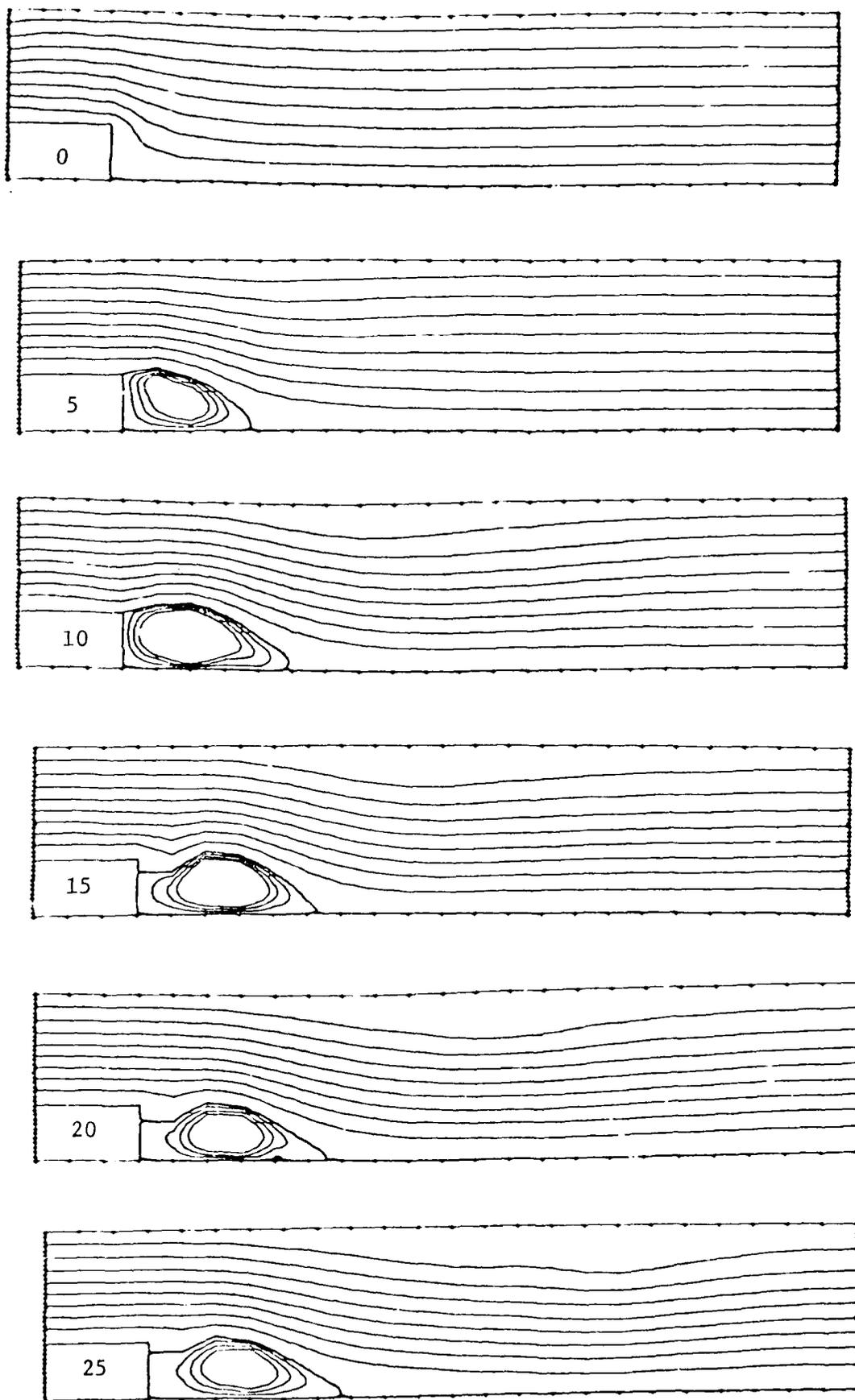


Fig. 1: Computed flow streamlines behind a sudden expansion or step. The flow is bounded by solid walls from above as well as below. The number labels are non-dimensional time,  $U_0 t/h$ , where  $U_0$  is the entrance mean flow velocity and  $h$  is the step height.

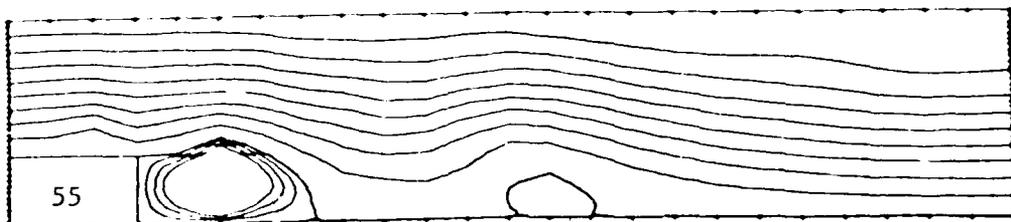
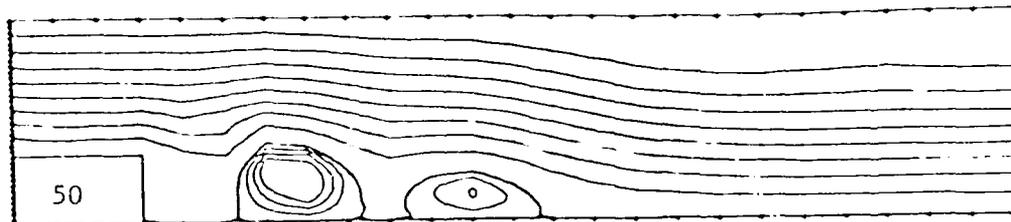
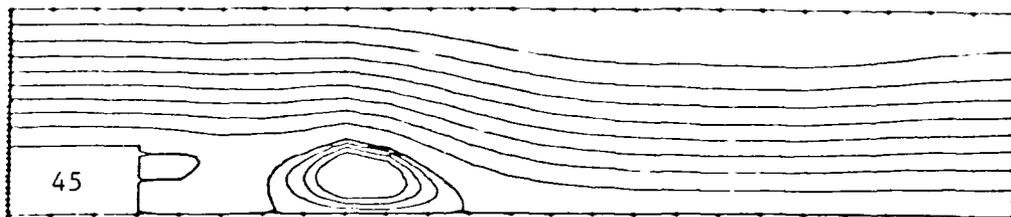
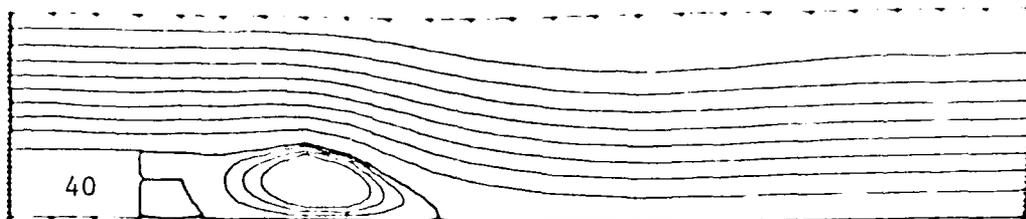
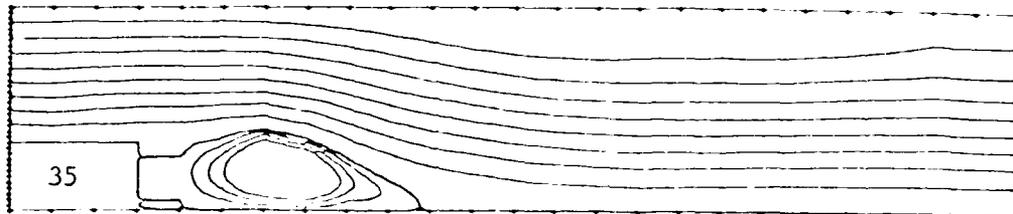
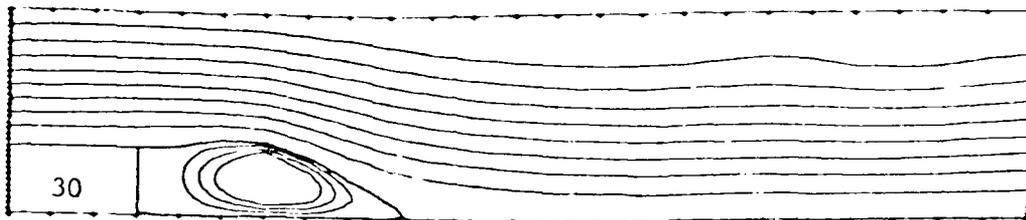


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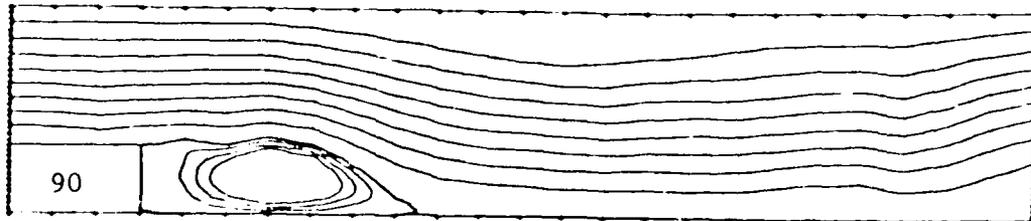
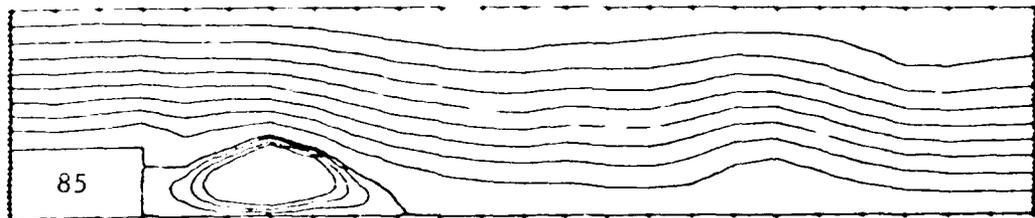
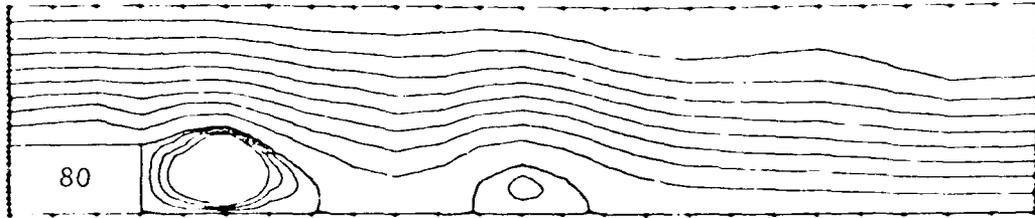
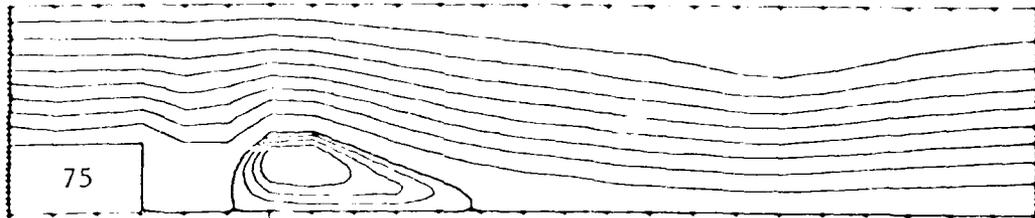
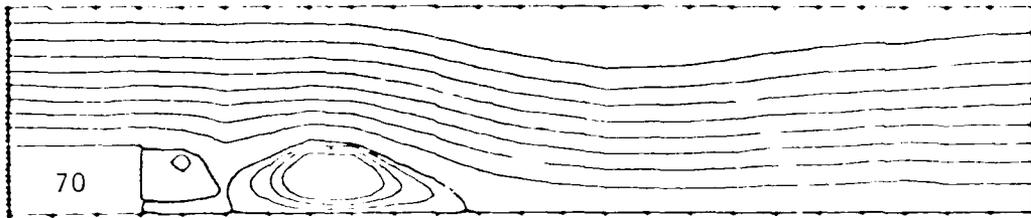
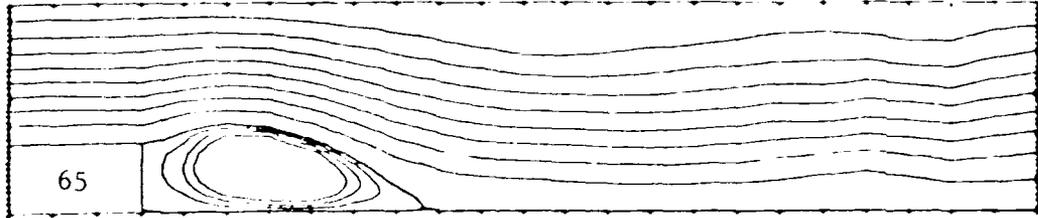
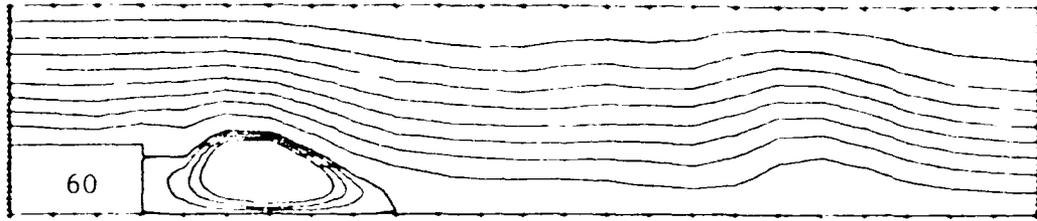


Fig. 1 - continued