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Annual Scientific Report

on the

THEORETICAL & EXPERIMENTAL INVESTIGATION OF COHERENT STRUCTURE IN THE TURBULENT BOUNDARY LAYER

AFOSR Contract No. F49620-78-C-0071

Reporting Period 1 May 1981 to 30 April 1982

by

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This project combines both experimental video flow visualization studies and theoretical investigations of a series of phenomenological and theoretical models based upon the three-dimensional details of convected, coherent structural elements of a turbulent flow as it interacts with a solid surface. The experimental program considers a range of sub-problems including the effect of surface modification on low speed streak formation and drag as well as the effect of vortex loop interactions with the boundary layers on a solid boundary. To augment the visual studies, a computerized interface with the video system

20. (cont.)

has been developed which allows quantitative data to be obtained from the flow visualization pictures. The specific thrust of the theoretical studies has been focussed on three areas. The two relatively minor areas are (1) the development of prediction methods for two-dimensional turbulent boundary layer flows which are based in whole or in part on the observed coherent behavior; (2) the development of improved numerical methods for the solution of boundary layer problems. The major effort in the program is directed toward the development of an understanding of how two and three dimensional vortex structures interact with themselves and with wall boundary layers.

I. RESEARCH OBJECTIVES AND APPROACH

The basic objective of this research program is to obtain a clear physical and theoretical understanding of the dynamics of the turbulent boundary layer which will ultimately provide improved models for the turbulence quantities in the time-mean boundary-layer equations. The long range goals of the program continue to be both the improvement of the turbulent boundary-layer prediction methods and development of rational methods for control and/or modification of turbulent boundary layer behavior.

This project combines both experimental video flow visualization studies and theoretical investigations of a series of phenomenological and theoretical models based upon the three-dimensional details of convected, coherent structural elements of a turbulent flow as it interacts with a solid surface. The experimental program is considering a range of sub-problems including the effect of surface modification on low speed streak formation and drag, and the effect of vortex loop interaction with a solid boundary. To augment visual studies, a computerized interface with the video system has been developed which allows quantitative data to be obtained from flow visualization pictures. The specific thrust of the theoretical studies has been focussed on three areas: 1) how two- and three-dimensional vortex structures interact with wall boundary layers, 2) the development of a new type of prediction method for two-dimensional turbulent boundary-layer flows, and 3) improvement in numerical techniques for solving parabolic, boundary-layer equations.

II. STATUS OF RESEARCH

Experimental Program

During the past year, the Lehigh experimental program on Coherent Structure of Turbulent Boundary Layers has pursued investigations in four complementary areas: 1) Identification and quantification of turbulence structure characteristics, 2) Control of turbulence structure, 3) Simulation of hypothesized turbulence flow structures, and 4) Recreation of 3-D motion in a turbulent boundary layer using computer augmented display of video information. These studies have made heavy use of high-speed flow visualization to identify, characterize, and quantify the characteristics of the flows in question. In addition, a substantial amount of parallel hot-film anemometry data have been taken for quantification of flow structure effects and to assure comparison with accepted turbulence characteristics.

Turbulent Structure Characteristics

Our studies of fully turbulent flows have centered on establishing the characteristics of the near-wall region of a turbulent boundary layer where the most organized behavior, low-speed streaks, occurs. As pointed out last year, the non-dimensional spacing of the low-speed streaks have been shown to be universally present and to maintain a constant spanwise spacing of $\lambda^+ \simeq 100$ over a wide range of Reynolds number (Figure 1). In addition, we have established that the distribution of this spanwise spacing also appears to be universal, closely approximating a log normal distribution (Figure 2). This latter piece of information is of particular importance to new prediction and turbulence simulation efforts which require statistical flow structure models as input.

An additional discovery, which has substantial implications with regard to the flow structure governing near-wall behavior, is the observation of the "persistence" of low-speed streaks, i.e. the tendency of streaks to perpetuate themselves. This self perpetuation, despite continual disruption by the quasi-periodic bursting behavior, implies that the flow structure which forms the streak must also be dependent upon the presence of the streaks for its origin. Detailed visual studies indicate that this structure is a series of nested loop-like vortices (Figure 3) generated as a consequence of the "bursting" of a streak. A continuing study attempting to validate this hypothesis is described below under simulation studies.

Turbulence Control

As a result of our observations of low-speed streak "persistence", we have been conducting a study to examine if artificial modifications of the flow surface in the streamwise direction can act as "sites" for streaks and thus "lock" them in place. Using very fine fishing line as our artificial streaks, we have established that streak formation can be stabilized by the fish line "sites". Hot-film studies just completed indicate that the boundary layer appears normal by all comparisons, except in the near-wall region. Spectral analyses to determine modification of bursting behavior and calculation of induced changes in skin friction characteristics are still in progress.

This study of streamwise surface modification is very significant since it indicates that near-wall turbulent structure can be controlled by passive means. Thus, we should potentially be able to determine surface geometries employing streamwise modifications which can reduce surface drag by modification of the mechanism of momentum exchange at a surface. Work is continuing on this study, expanding our investigations to riblet surface geometries which NASA-Langley has shown to reduce surface drag by 10%.

Turbulence Simulation

The premise upon which the Lehigh turbulence program and a number of other programs across the country are based is that complex turbulent flows are "built" of different "flow structures." However, determining the basic flow structures and extracting their role in the complex entanglement of fluid motion which is turbulence is an extremely difficult task, complicated by the fact that we do not understand the behavior of some of the simpler flow structures turbulence has been speculated to be comprised of. Therefore, we have undertaken investigations of the behavior of two simple flow structures which appear to have the potential for modeling some of the key characteristics of turbulence.

The most mature of these studies is of the interaction of a ring vortex as it impacts a solid surface. As pointed out last year, a complex inviscid-viscous interaction takes place which generates secondary and tertiary vortices. The resulting group of vortices then interact in a very three-dimensional, but symmetric fashion to rapidly disperse the vorticity of the initial vortex. During the past year, over 90 different initial conditions have been examined, indicating the complexities which can arise from such interactions. Figure 4 shows a top view of a vortex impact with a surface covered with dye which illustrates the extreme three dimensionality of the interaction process. Figure 5 shows one of our dramatic discoveries, i.e. that an impacting vortex can create a secondary vortex ring which "rebounds" back in opposition to the direction of travel of the original vortex ring. It is felt that this effect may have implications, although indirectly, to the bursting and ejection behavior observed in a turbulent boundary layer.

As mentioned above, our turbulence studies have suggested that nested loop-vortices appear to be generated by the bursting process and to result in the formation of low-speed streaks. To examine this hypothesis, we have developed a technique for generating very consistent loop vortices similar in appearance to the schematic shown in Figure 3. It was found that under the proper conditions, loop vortices will be shed in a very periodic fashion from a hemisphere placed on a surface beneath a laminar boundary layer. Very extensive visualization and hot-film probe studies have been done of these loops, and the results have proven extremely encouraging. Thus far it has been determined that many of the visual patterns observed in the near-wall region of a turbulent boundary layer can be observed in the wake of the hemisphere.

This study of loop vortices is continuing in order to better establish the parallel between these systematically generated structures in a laminar boundary layer and the less well defined structures arising from the near-wall of a fully turbulent boundary layer.

Recreation of 3-D Motion

In our previous work, the dual-camera video system was used in conjunction with a fiber-optic lens to obtain combined top-end views of single realization hydrogen bubble-lines in the near-wall region of a turbulent boundary layer. From these combined views, we were able to establish a number of characteristics regarding behavior in the near-wall region, particularly the characteristics and potential formation mechanism for low-speed streaks. However, the presentation of the two-view, time-sequence behavior was awkward (requiring numerous pictures). Additionally, the two-views could not be taken in true orthogonal perspective, which provoked some confusion for the unfamiliar observer.

To rectify these shortcomings, and to provide the potential for reduction of these two-view sequences to quantitative velocity field information, a system for digitizing the bubble-line sequences into a computer-aided display system has been developed. Using this system, the Lagrangian motion of a single bubble-line in time and space can be displayed in proper orthographic perspective (computer corrected for viewing orientation) as shown in Figure 6. Since the digitized bubble-line information is stored as a three-dimensional matrix, any view of the recreated bubble-line motion and deformation can also be displayed, as shown by the oblique view in Figure 6. In addition, by computer manipulation, orthogonal splines can be matched to the original bubble-lines to create a grid-like "surface" of the bubble-line motion. Such a surface, created from the bubble-line data of Figure 6, is shown in Figure 7.

Presently this computer display process is being used to examine a number of near-wall sequences. In addition, modifications to both the display program and to the visualization system are being done which will allow velocity field information to be derived from the same input as was used to create Figures 6 and 7.

ANALYTICAL PROGRAM

The objective of this report is to review the progress made over the past year as well as to delineate the current direction of the program and the expected results that will be obtained by the end of the current contract year (April, 1983). The analytical program is directed in three separate but related phases. The first of these areas is development of improved numerical methods for parabolic partial differential equations. This area is an outgrowth of previous work in the development of turbulent boundary layer prediction methods where the need to improve the efficiency of the calculation procedures became apparent. The overall goal of this portion of the program is to develop a numerical procedure for nonlinear parabolic equations which is both fourth accurate and allows an arbitrary non-uniform mesh spacing. This latter requirement is particularly important in the calculation of turbulent boundary layer flows where packing of the mesh near the wall is necessary to achieve good accuracy. A fourth order method is important to substantially reduce computer storage requirements as well as computation times. At this stage, it appears the goal will be realized by April, 1983.

During the past year, Mr. W.-C. Lee completed work on his Master's degree program and his thesis work concerned the development of a new second order accurate parabolic equation method. The thesis is currently in preparation as an AFOSR technical report. Some typical results are illustrated in Figure 8 where the root-mean-square error for two new calculation methods is compared with that associated with two existing second order methods (the Keller Box method and the Crank-Nicolson method). The example problem for which the error is illustrated in Figure 1 is the Howarth laminar boundary layer problem; this flow is a boundary layer developing in an adverse pressure gradient, similar to a diffuser-type flow. The boundary layer originates at $\xi=0$ and a separation point is predicted at $\xi \approx 0.90$; the RMS error plotted in Figure 8 is the average error incurred by each method at each ξ station in a boundary layer integration initiated at $\xi = 0$. It may be observed that the new methods offer a good increase in accuracy. The study of Mr. Lee is also important because it illustrated that spatial differencing techniques developed for ordinary differential equations may be carried over with some additional ingenuity to parabolic partial differential equations. During the past year a fourth order scheme for both linear and nonlinear equations has been developed; this method is restricted to uniform mesh spacings. The results of this study are part of the Ph.D. thesis work of Mr. E.A. Bogucz and have been submitted for publication. The results of this study are very encouraging and illustrate how the number of mesh points may be reduced by two orders of magnitude. At present, there are three remaining tasks to complete this portion of the study; these are development of:

(a) a fourth order method for parabolic partial differential equations using a uniform spatial mesh;

(b) a fourth order method for ordinary differential equations with an arbitrary non-uniform mesh;

(c) a fourth order method for partial differential equations with an arbitrary non-uniform mesh.

Currently the feasibility of tasks (a) and (b) has been demonstrated and the methods under development are being tested. It is evident that the methods being produced here will have wide applicability in other areas of engineering and the physical sciences.

The second area of present effort is concerned with the development of improved turbulence models. In previous years of this contract, a model for the inner layer of the turbulent boundary layer was developed which was based on the observed coherent nature of the wall layer flow. Current interest surrounds development of a model for the outer layer and in this portion of the contract work, consideration is given to obtaining a simple eddy viscosity model. During the past year, Mr. L.J. Yuhas completed a Master's thesis (which has been submitted as an AFOSR technical report); in this study, a procedure is described wherein the basic parameters in the eddy viscosity model may be correlated to account for various physical effects; the correlations are obtained by comparing a turbulent velocity profile directly with measured experimental profile data. An optimization computer code has been developed to carry this procedure out and the method has been applied to flows with pressure gradient and flows with mainstream turbulence. As an illustration of how well the velocity profiles match, some data (taken under an AFOSR program at United Technologies Research Center, East Hartford, Conn.) for mainstream turbulence levels ranging from 3.5% to 6.5% is illustrated in Figure 9 for a zero pressure gradient flow. Such mainstream turbulence levels are typical of boundary layer flows in the gas turbine environment. It may be observed in Figure 9 that the profiles calculated in the optimization procedure represent the measured data very well. From these optimizations it proved possible to correlate a single parameter K in the simple eddy viscosity formula. The quadratic correlation is illustrated in Figure 10 and may now be used in the eddy viscosity formula in a prediction method.

A second approach to the problem of model development of the outer layer of the turbulent boundary layer constitutes the third and a major phase of the research. In this portion of the contract, physical mechanisms and the underlying causes of the observed structure and bursting event in turbulent boundary layers are under investigation. During the past year, a study has been completed on the viscous effects that are due to be expected due to a pair of counter-rotating vortices above a plane wall. Such vortices are observed in the wall region of a turbulent boundary layer and are believed by some authors to play an important role in the dynamics of the production of turbulence. Moreover the longitudinal† vortices in a turbulent boundary layer are observed to persist for long periods of time and apparently do not migrate outwards as a purely inviscid theory would suggest they should. Consequently it was decided to undertake a study to elucidate the viscous effects induced near a wall by a pair of counter-rotating vortices. The study that was completed this year was for a pair of two-dimensional vortices which initially are at the same height above a plane wall; inviscid theory predicts that both vortices will move on the

† In fact, the observed vortices cannot be entirely longitudinal and must be portions of an elongated three dimensional loop.

hyperbolic illustrated in Figure 11. The vortices will either move away from the wall or toward it depending on the sense of rotation of the vortices. The flow is symmetric about a line bisecting the vortex paths. In all cases considered, a boundary layer separation occurs leading to the creation of a counter-rotating pair of secondary vortices. In the case of an upward moving pair of vortices, separation occurs on the wall inboard of the rising vortices. A typical case is illustrated in Figure 12 where a developing separation occurs on the symmetry plane; note that the illustrations in Figure 12 are for one half of a symmetric boundary layer flow and that there is a mirror-image boundary layer flow for $x<0$. If the vortices are started further apart, a separation occurs which again is inboard of the rising vortices but which is not connected with the mirror image on the symmetry plane. Such a case is illustrated in Figure 13. Note that in Figures 5 and 6 the bold arrows at the top of the figures denote the current streamwise location of the parent vortex in the inviscid flow; the smaller arrow indicates the initial starting location of the vortex. In the case of the upward moving pair, the eruption of the secondary vortices from the boundary layer will arrest the upward and inward movement of the parent vortices. For a downward moving pair, it was determined that the creation of secondary vortices in the boundary layer also occurs but now outboard of the parent vortices. Consequently in this case as well, the eruption of the secondary vortices will act to arrest the motion of the parents. This study is part of the Ph.D. program of Mr. S. Ersoy and a paper describing the complete results is currently in preparation.

At present, the vortex interaction part of the program is directed towards carrying out the following major tasks:

(a) the calculation of the boundary layer induced by a pair of vortices moving toward a wall at an angle

(b) the calculation of the inviscid flow due to a three dimensional loop vortex and the boundary layer flow induced by the motion of the loop.

At this time, work is well along the way for task (a). In Figure 14, a typical trajectory for a vortex pair approaching a wall obliquely is given. The boundary layer flow induced by an asymmetric pair of vortex disturbances is much more complex than the previous problems considered in this contract. For this reason, it has required a considerable effort to deduce the appropriate analytic transformations and numerical methods required to handle the problem. Some initial results have been produced and in Figure 15 the boundary layer flow due to the pair in Figure 14 is plotted at a certain stage in the boundary layer development. Note that a secondary eddy has been created in the region near $x=-3$ by the lower of the parent vortices (in Figure 14). There is a tendancy for a weaker secondary separation near $x=2.5$ but at the stage of development in Figure 15, the second secondary separation has not yet occurred. Over the next year a number of such cases will be considered.

Work has started on task (b) and at this stage is focused primarily on the calculation of the inviscid three dimensional loop motion. The boundary layer flow in this case is somewhat more complex than case (a); however, many of the techniques of solution developed for task (a) can and will be adapted to the vortex loop problem in the next contract year.

III. ASSOCIATED PUBLICATIONS, PRESENTATIONS AND THESES

A. PUBLICATIONS

[1] Walker, J.D.A., "The Boundary Layer Due to Rectilinear Vortex" Proc. R. Soc. Lond. A., Vol. 359, 1978, pp. 167-188.

[2] Doligalski, T.L. and Walker, J.D.A., "Shear Layer Breakdown Due to Vortex Motion," Proceedings of the AFOSR Workshop on Coherent Structure of Turbulent Boundary Layers, C. Smith and D. Abbott, eds., Lehigh University, November, 1978, pp. 288-339.

[3] Smith, C.R., Brown, J.J. and Crosen, D.A., "Hydrogen Bubble-Wire Simulation of a Transverse Vortex in a Turbulent Boundary Layer," Technical Report CFMTR-78-2, School of Mechanical Engineering, Purdue University, April 1978.

[4] Smith, C.R., "Visualization of Turbulent Boundary-Layer Structure Using a Moving Hydrogen Bubble-Wire Probe," Proceedings of the Workshop on Coherent Structure of Turbulent Boundary Layers, Lehigh University, May, 1978.

[5] Smith, C.R. and Abbott, D.E., Proceedings of Workshop on Coherent Structure of Turbulent Boundary Layers, Lehigh University, November 1978.

[6] Doligalski, T.L., Smith, C.R. and Walker, J.D.A., "A Production Mechanism for Turbulent Boundary Layer Flows", presented at the "Symposium on Viscous Drag Reduction", Progress in Astronautics and Aeronautics, Vol. 72, G.R. Hough, ed., 1980., pp. 47-71.

[7] Smith, C.R., Schwartz, S.P. Metzler, S.P., and Cerra, A.W., "Video Flow Visualization of Turbulent Boundary Layer Streak Structure," in Flow Visualization II, W. Merzkirch, ed., Hemisphere Pub. Co., Washington, D.C., 1981.

[8] Smith, C.R., "Flow Visualization Using High-Speed Videography," Photomethods, Vol. 24, No. 11, November, 1981, pp. 49-54.

[9] Smith, C.R. and Metzler, S.P., "A Visual Study of the Characteristics, Formation, and Regeneration of Turbulent Boundary Layer Streaks," Developments in Theoretical and Applied Mechanics, Vol. XI, Chung, T.J. and Karr, G.R., eds., University of Alabama in Huntsville, April 1982, pp. 533-544.

[10] Smith, C.R., "Application of High-Speed Videography for Study of Complex, Three-Dimensional Water Flows," Proceedings of the 15th International Congress on High-Speed Photography and Photonics, International Society for Optical Engineering, August 1982 (in press).

[11] Smith, C.R. and Schwartz, S.P., "Observation of Streamwise Vortices in the Near-Wall Region of a Turbulent Boundary Layer," Accepted for publication in Physics of Fluids.

[12] Smith, C.R. and Metzler, S.P., "The Characteristics of Low-Speed Streaks in the Near-Wall Region of a Turbulent Boundary Layer," Under review, conditionally accepted for publication in Journal of Fluid Mechanics.

[13] Bogucz, E.A. and Walker, J.D.A., "Fourth Order Methods for Two Point Boundary Value Problems", submitted for publication to Institute of Math Applics, J. Numerical Analysis, in review.

[14] Yuhas, L.J. and Walker, J.D.A., "An Optimization Technique for the Development of Two-Dimensional Steady Turbulent Boundary Layer Models," Technical Report FM-82-1, Dept. of Mechanical Engineering and Mechanics, Lehigh University, March 1982; to appear as an AFOSR technical report.

[15] Lee, W.V. and Walker, J.D.A., "Two Improved Methods for Parabolic Partial Differential Equations", Technical Report FM-82-2, Department of Mechanical Engineering and Mechanics, Lehigh University, April, 1982; to appear as an AFOSR technical report.

[16] Ersoy, S. and Walker, J.D.A., "The Boundary Layer Due to a Vortex Pair", to appear in proceedings of BAIL II Conference (Boundary and Interior Layers - Computational and Asymptotic Methods), held at Trinity College, Dublin, Ireland, June 16-18, 1982.

[17] Ersoy, S. and Walker, J.D.A., "The Boundary Layer Induced by a Pair of Counter-Rotating Vortices", journal article in preparation.

[18] Doligalski, T.L. and Walker, J.D.A., "The Boundary Layer Induced by a Convected Two-Dimensional Vortex", submitted to Journal of Fluid Mechanics, in review.

[19] Cerra, T., Doligalski, T.L., Smith, C.R. and Walker, J.D.A., "The Boundary Layer due to an Impacting Vortex Ring", journal article in preparation.

B. PRESENTATIONS

J.D.A. WALKER

1. "Shear Layer Breakdown Due to Vortex Motion", AFOSR Workshop on Coherent Structure of Turbulent Boundary Layers, Bethlehem, PA. May, 1978.

2. "Survey of Analytical and Experimental Investigation of the Coherent Structure of Turbulent Boundary Layers", invited seminar, United Technologies Research Center, East Hartford, Connecticut, June, 1978.

3. "The Effect of Vortex Motion on Wall Boundary Layers", First Annual Specialists Workshop on Coherent Structure of Turbulent Boundary Layers, Stanford, California, July 24, 1978.

4. "Some Aspects of Turbulent Boundary Layer Separation", SQUID Colloquium on Turbulent Flow Separation, Southern Methodist University, July 19, 1979.

5. "Boundary Layer Eruptions Induced by Vortex Motion", Second Annual Specialists Workshop on Coherent Structure of Turbulent Boundary Layers, East Lansing, Michigan, July 29, 1979.

6. "A Production Mechanism for Turbulent Boundary Layer Flows", Symposium on Viscous Drag Reduction, Dallas, Texas, November 7, 1979.

7. "The Boundary Layer Due to a Vortex Convected in a Shear Flow", 32nd Annual Meeting, Division of Fluid Dynamics, American Physical Society, Notre Dame, Indiana, November 18, 1979.

8. "Vortex Wall Interactions", invited seminar, The Ohio State University, Columbus, Ohio, May 30, 1980.

9. "Boundary Layer Due to an Impacting Vortex Ring", 33rd Annual Meeting, Division of Fluid Dynamics, American Physical Society, Cornell U., Ithaca, N.Y., 23 November 1980.

10. "Boundary Layer Flow Due to a Pair of Counter-Rotating Vortices", 34th Annual Meeting, Division of Fluid Dynamics, American Physical Society, Naval Postgraduate School, Monterey, CA, Nov. 1981.

11. "The Boundary Layer Due to a Vortex Pair", BAIL II Conference (Boundary and Interior Layers - Computational and Asymptotic Methods), Trinity College, Dublin, Ireland, June 1982.

C.R. SMITH

1. "Visualization of Turbulent Boundary-Layer Structure Using a Moving Hydrogen Bubble-Wire Probe", Workshop on Coherent Structure of Turbulent Boundary Layers, Bethlehem, Pennsylvania, May 1978.

2. "Visualization of Coherent Turbulence Structure Using Conventional Video Technique", First Annual Specialists Workshop on Coherent Structure of Turbulent Boundary Layers, Stanford, California, July 24, 1978.

3. "High-Speed Video Analysis of Flow Visualized Turbulence Structure", Second Annual Specialists Workshop on Coherent Structure of Turbulent Boundary Layers, East Lansing, Michigan, July 28, 1979.

4. "The Visualization of Localized, Convected Fluid Pockets in the Wall Region of a Turbulent Boundary Layer", 31st Annual Meeting, Division of Fluid Dynamics, American Physical Society, Los Angeles, California, November, 1978.

5. "Visualization of Turbulent Boundary-Layer Structure Using a Moving Hydrogen Bubble-Wire Probe and a T.V. Viewing System", invited seminar, Penn State Department of Mechanical Engineering, May 3, 1979.

6. "A Production Mechanism for Turbulent Boundary Layer Flows", Symposium on Viscous Drag Reduction, Dallas, Texas, November 7, 1979.

7. "Streak Formation in Turbulent Boundary Layers: Recent Observations", 32nd Annual Meeting, Division of Fluid Dynamics, American Physical Society, Notre Dame, Indiana, November 1979.

8. "Experimental Observation of Vortex Loop-Boundary Layer Interactions", 32nd Annual Meeting, Division of Fluid Dynamics, American Physical Society, Notre Dame, Indiana, November 1979.

9. "Video Flow Visualization of Coherent Structures in a Turbulent Boundary Layer", invited seminar, University of Maryland Fluid Mechanics Seminar Series, 7 March 1980.

10. "The Presence of Axial Vortices in Turbulent Boundary Layers: A Visual Study", invited talk, Ohio State University Colloquium on Turbulent Boundary Layer Structure, 21-23 March, 1980.

11. "Flow Visualization Results in the Near-Wall Region of a Turbulent Boundary Layer", Applied Mechanics Seminar, University of Southern California, Los Angeles, CA., July 17, 1980.

12. "Video Flow Visualization of Turbulent Boundary Layer Flows", International Symposium on Flow Visualization, Bochum, W. Germany, September 11, 1980.

13. & 14. "Flow Visualization Using High Speed Video Techniques", Invited seminars at Max-Planck Institute, Gottingen, W. Germany, September 15, 1980 and at University of Lercester, England, September 18, 1980.

15. "Effects of Reynolds Number and Surface Modifications on Streak Spacing in Turbulent Boundary Layers", 33rd Annual Meeting, Division of Fluid Dynamics, APS, Ithaca, N.Y., 23 November 1980.

16. "Experimental Observation of the Interaction of a Vortex Ring With a Flat Plate", 33rd Annual Meeting, Division of Fluid Dynamics, APS, Ithaca, N.Y., 23 November 1980.

17. "The Appearance of Axial Vortices in Vortex Shedding From a Cylinder", 33rd Annual Meeting, Division of Fluid Dynamics, APS, Ithaca, N.Y., 23 November 1980.

18. "Effects of Surface Modifications on Turbulent Boundary Layer Structure", Invited seminar NASA Langley Research Center, Virginia, 18 December 1980.

19. "The Characteristics of Low-Speed Streaks in the Near-Wall Region of a Turbulent Boundary Layer", 34th Annual Meeting, Division of Fluid Dynamics, APS, Monterey, Calif., 22 November 1981.

20. "A Visual Study of the Characteristics, Formation, and Regeneration of Turbulent Boundary Layer Streaks", Invited Paper, Eleventh Southeastern Conference on Theoretical and Applied Mechanics, Huntsville, Alabama, April 1982.

D.E. ABBOTT

1. "Theoretical and Experimental Investigation of Turbulent Boundary-Layer Structure-An Integrated Research Program," Thermal-Science Colloquium, Rutgers University, October, 1978.

2. "Investigation of the Fundamental Structure of Turbulent Boundary Layers," Ingersoll-Rand Corp., Phillipsburg, N.J., December, 1978.

3. "Specialists Workshop on Coherent Structure in Turbulent Boundary Layers", panalist, East Lansing, Michigan, July, 1979.

4. "Review of the A.F.O.S.R.-Lehigh University Program on Turbulent Boundary Layers," Lehigh University Research Center's Review, September, 1979.

5. "Boundary Layers," Technical Session Chairman, 32nd Annual Meeting, Division of Fluid Dynamics, American Physical Society, Notre Dame, Indiana, November, 1979. (Also elected Fellow, American Physical Society.)

C. THESES

Completed Theses

1. Scharnhorst, R.K., "An Analysis and Prediction of Nominally Steady, Two-Dimensional, Constant Property Turbulent Boundary Layer", Ph.D. thesis, Purdue University, Aug. 1978.

2. Doligalski, T.L., "The Influence of Vortex Motion on Wall Boundary Layers", Ph.D. Thesis, Lehigh University, October 1980.

3. Metzler, S.P., "Processes in the Wall Region of a Turbulent Boundary Layer", MSME thesis, Lehigh University, December 1980.

4. Schwartz, S.P., "The Detection and Quantification of Axial Vortices in the Wall-Region of a Turbulent Boundary Layer", MSME thesis, Lehigh University, June 1981.

5. Lee, W.C., "Two Improved Methods for Parabolic Equations", MSME thesis, Lehigh University, June 1981.

6. Yuhas, L.J., "An Optimization Technique for the Development of a Two-Dimensional Turbulent Boundary Layer Model", MSME, Lehigh University, October, 1981.

7. Wei, T., "The Presence of Secondary Vortices in the Wake of Circular Cylinders", MSME Thesis, Lehigh University, June 1982.

Theses in Progress (expected completion date in parentheses)

1. Bogucz, E.A., "Numerical Methods for Turbulent Boundary Layers", Ph.D. thesis, (Aug. 1983).

2. Johansen, J.J., "The Effect of Longitudinal Surface Modifications on Streak Formation and Bursting in Turbulent Boundary Layers", MSME thesis (Aug. 1982).

3. Acarlar, M.S., "Creation of Synthesized Turbulent Structure Using Surface Modifications", Ph.D. thesis (Dec. 1983).

4. S. Ersoy, "The Motion and Effects of Multiple Vortex Boundary Layers", Ph.D. Thesis, (Dec. 1983).

5. Cerra, A.W. (M.S.), "Vortex Loop-Boundary Layer Interaction," (August 1982).

6. Hon, G.T., "The Boundary Layers Induced by Loop Vortex Filaments", Ph.D. thesis, (Dec. 1984).

IV. PERSONNEL

A. Co-Principal Investigators

D.E. Abbott, Professor and Chairman of Mechanical Engineering
C.R. Smith, Associate Professor of Mechanical Engineering
J.D.A. Walker, Associate Professor of Mechanical Engineering

B. Student Research Assistants

		(Comp. date)
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M.S. Acarlar	Ph.D. Candidate	(Dec. 1983)
E.A. Bogucz	Ph.D. Candidate	(Aug. 1983)
G.T. Hon	Ph.D. Candidate	(Dec. 1984)
T. Wei	MSME Candidate	(June 1982)
J.J. Johansen	MSME Candidate	(Aug. 1982)

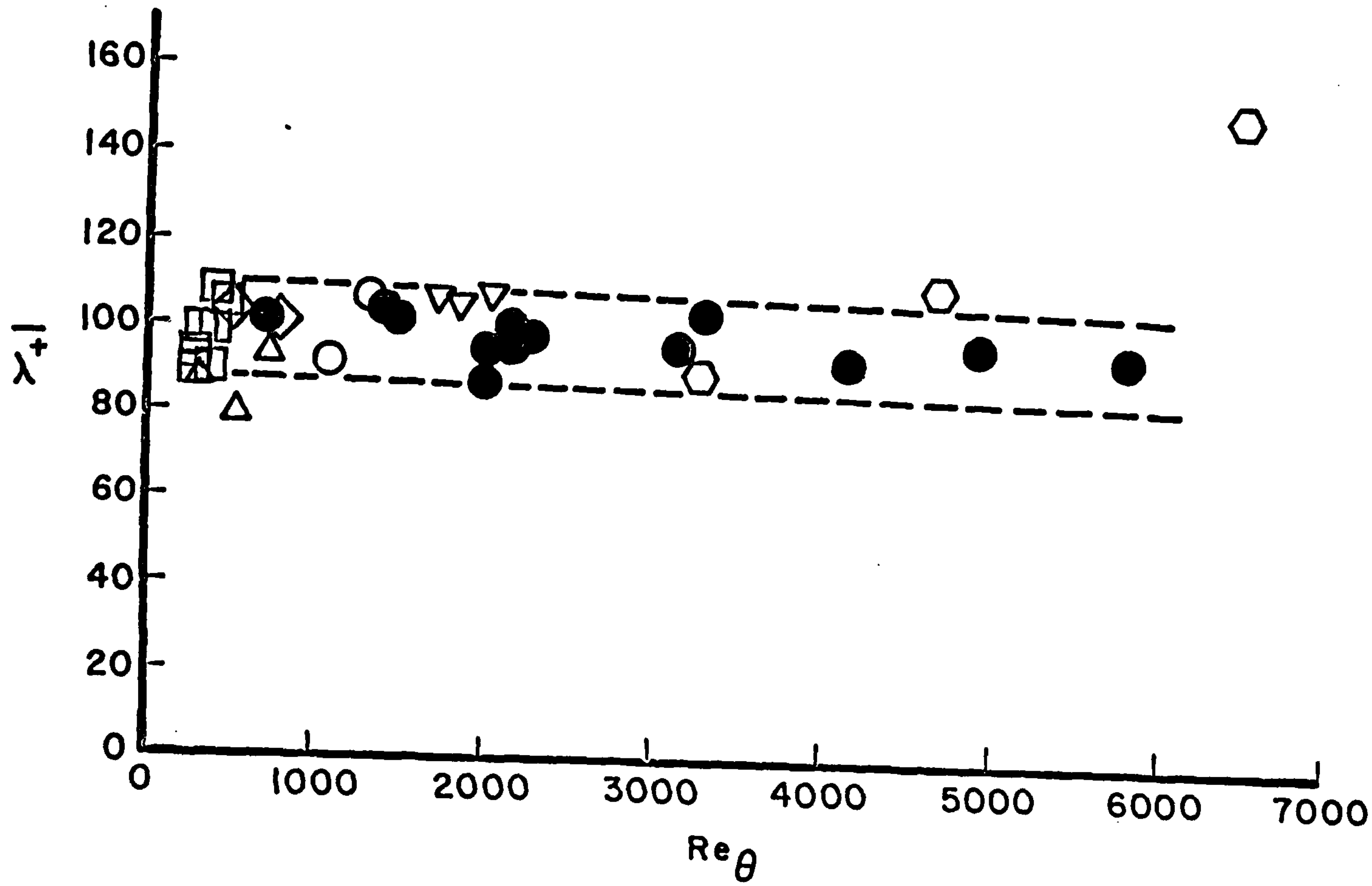


Figure 1. Mean nondimensional streak spacing as a function of Reynolds number. ●, present study; ○, Schraub & Kline (1965); □, Oldaker & Tiederman (1977); ⬡, Gupta et al (1971); △, Achia & Thompson (1976); ▽, Lee et al (1974); ◇, Nakagawa & Nezu (1981). ---, $\pm 2\sigma$ interval about linear regression fit to data of present study.

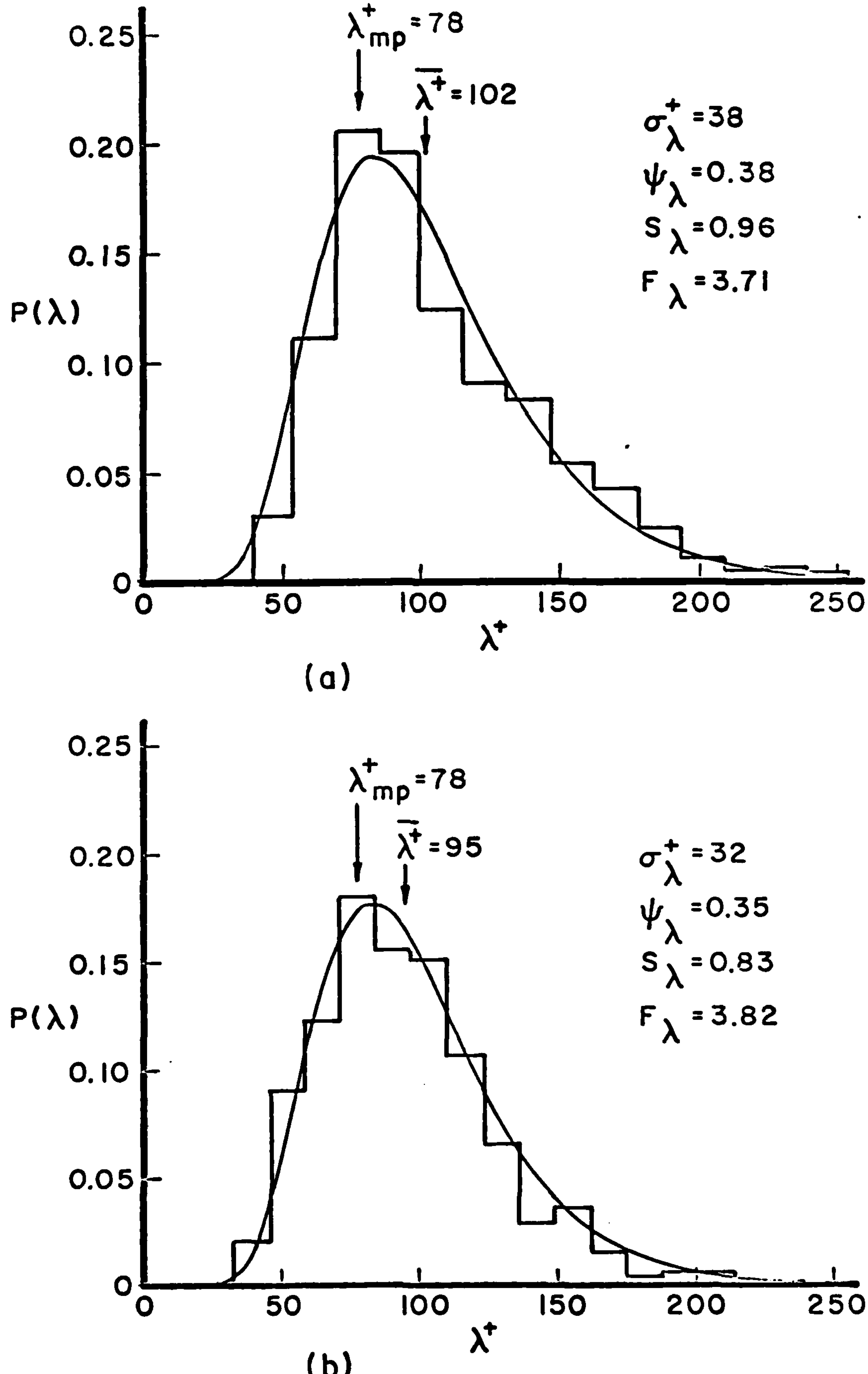


Figure 2. Probability density histograms of spanwise streak spacing at $y^+ = 5$. a) $Re_\theta = 1490$, n = 437; b) $Re_\theta = 5830$, n = 411. ——, lognormal probability density distribution for corresponding λ^+ and ψ_λ.

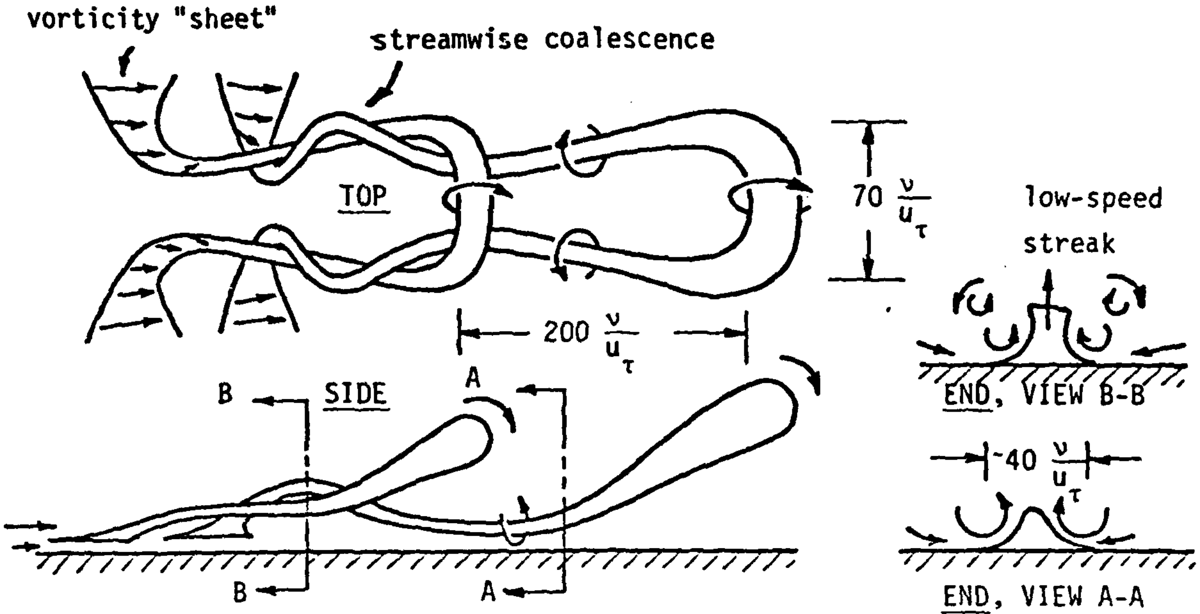


Figure 3 Orthographic Projection of Hypothesized Model of Vortex-Loop Flow Structure causing Low-Speed Streak Formation. A Two-loop array (not to scale) is shown.

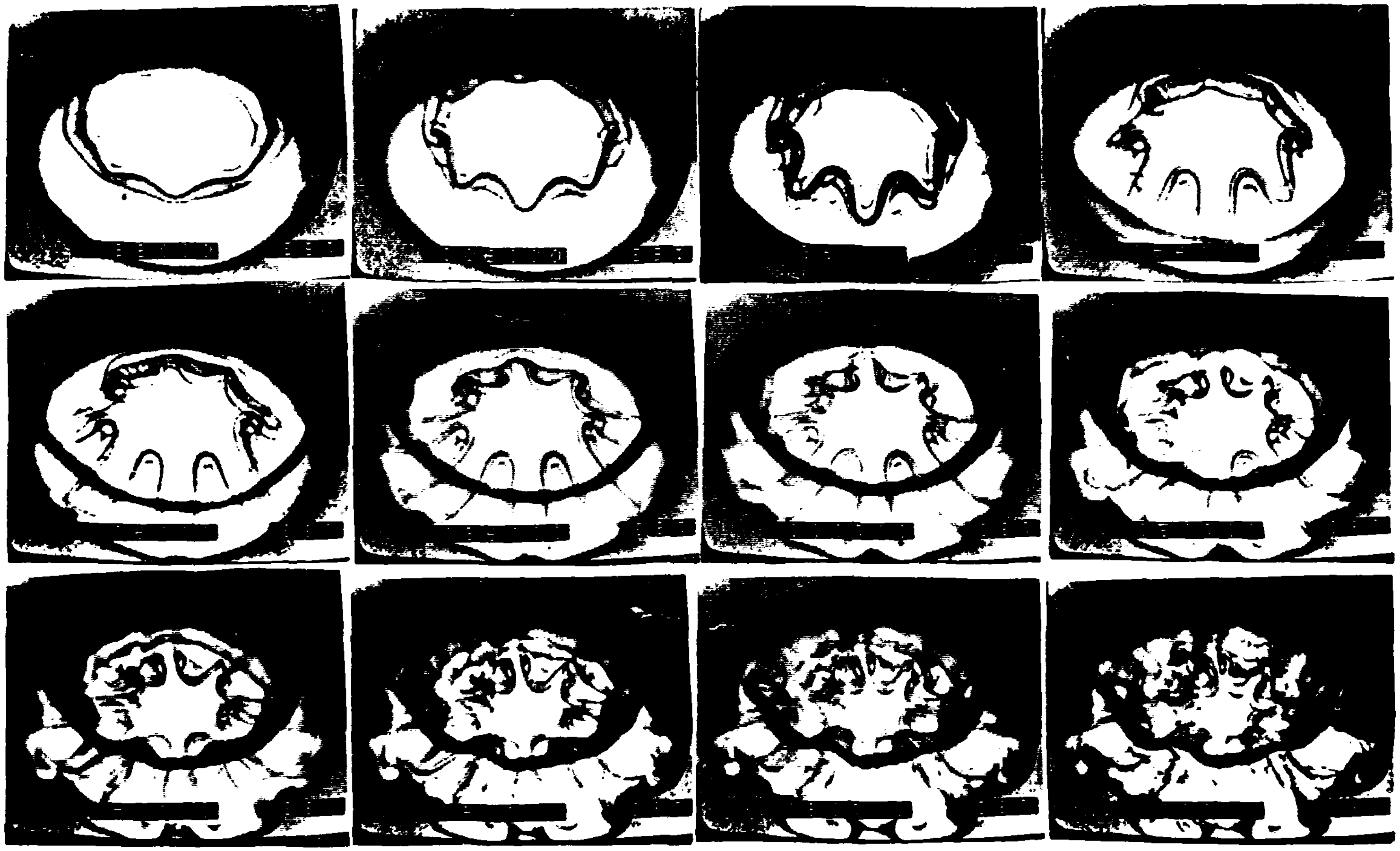
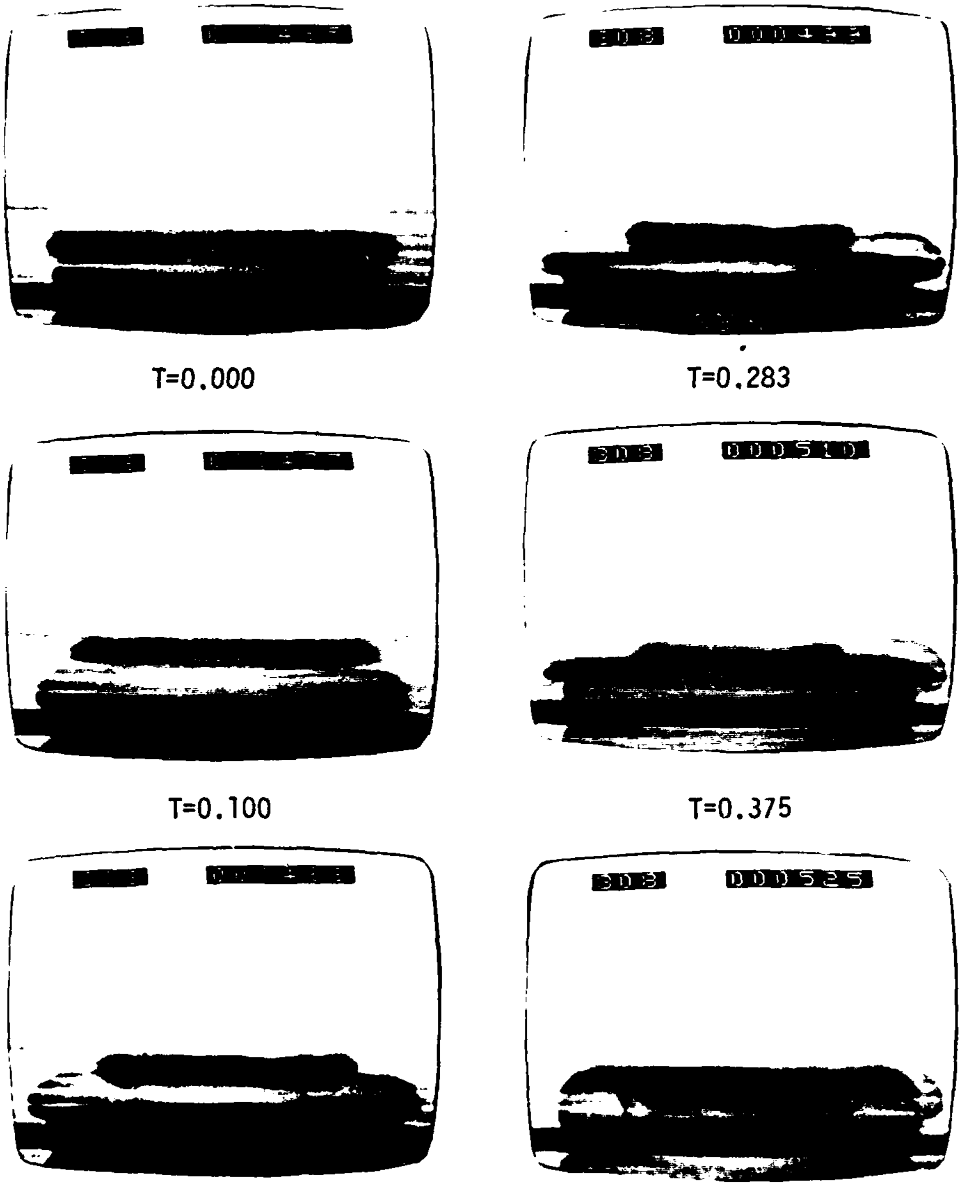


Figure 4 — Development of loop structured secondary vortex (oblique plan view, dye placed on surface). Vortex ID.#51.130, Re_0=811. Pictures are 0.167 seconds apart.



T=0.000

T=0.283

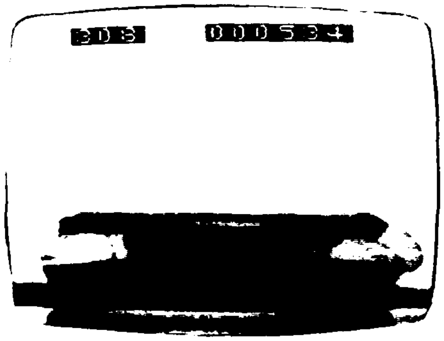
T=0.100

T=0.375

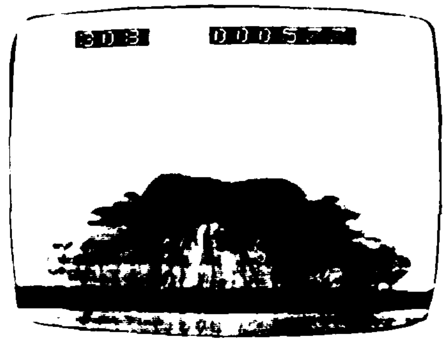
T=0.192

T=0.492

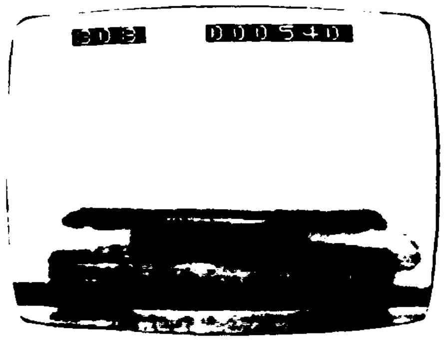
Figure 5 Secondary vortex ejection (side view, dye placed on surface). Vortex ID. #52.265, Re_o=3000. Sequence continued on next page.



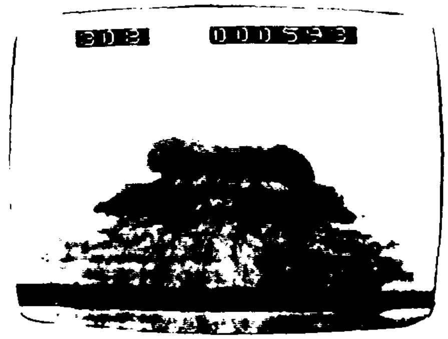
T=0.575



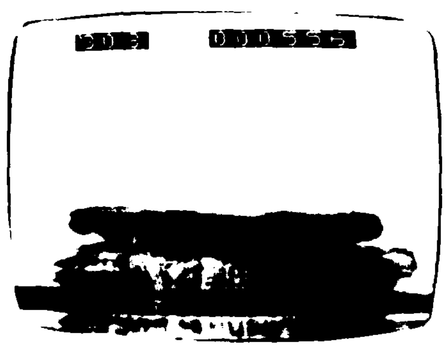
T=0.933



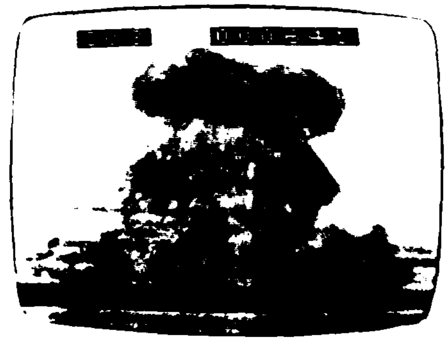
T=0.625



T=1.07



T=0.758



T=1.46

Figure 5 Secondary vortex ejection (side view, dye placed on surface). Sequence continued from previous page.

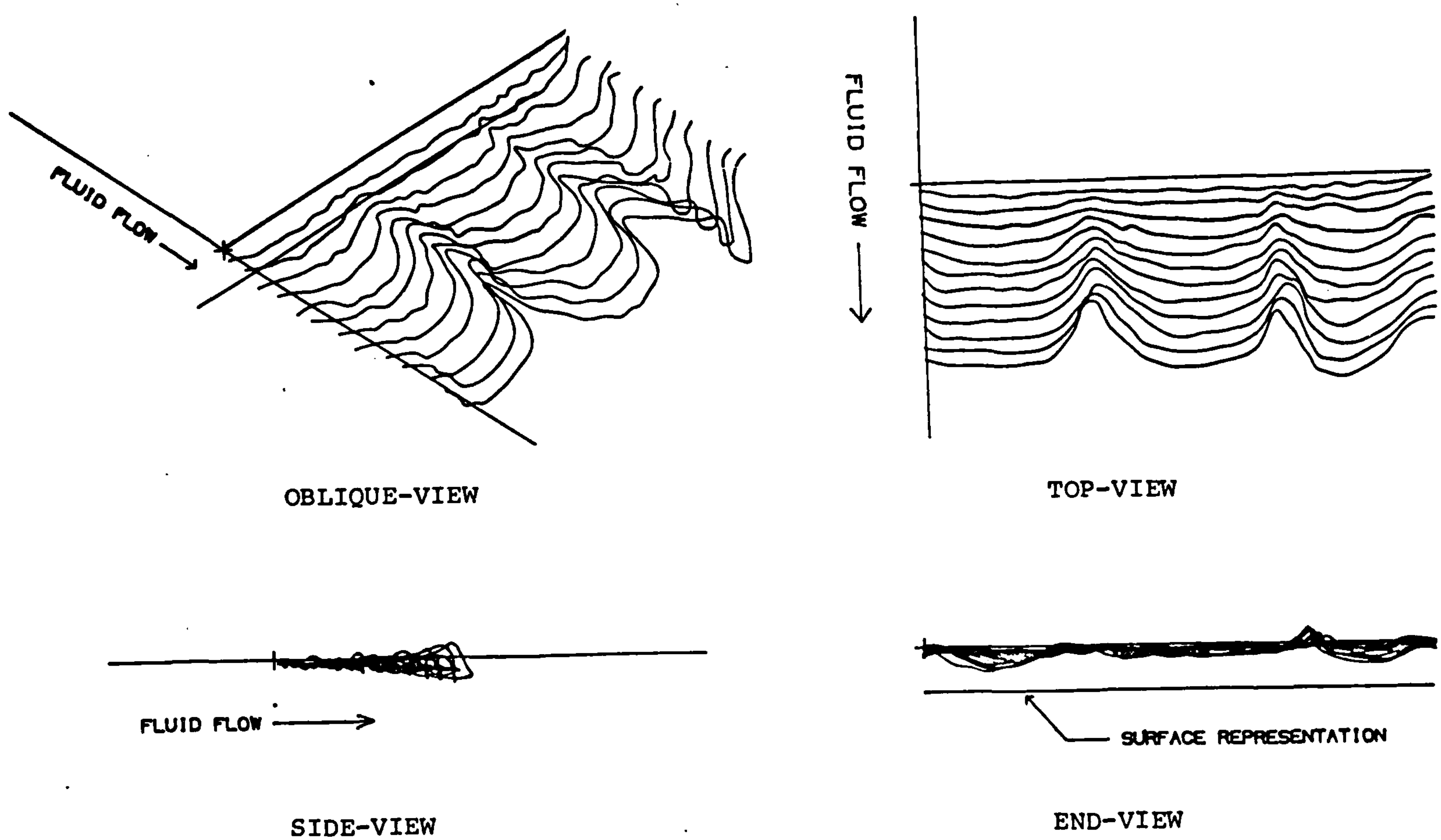


Figure 6 Four-view computer generated display of bubble-line motion and deformation.

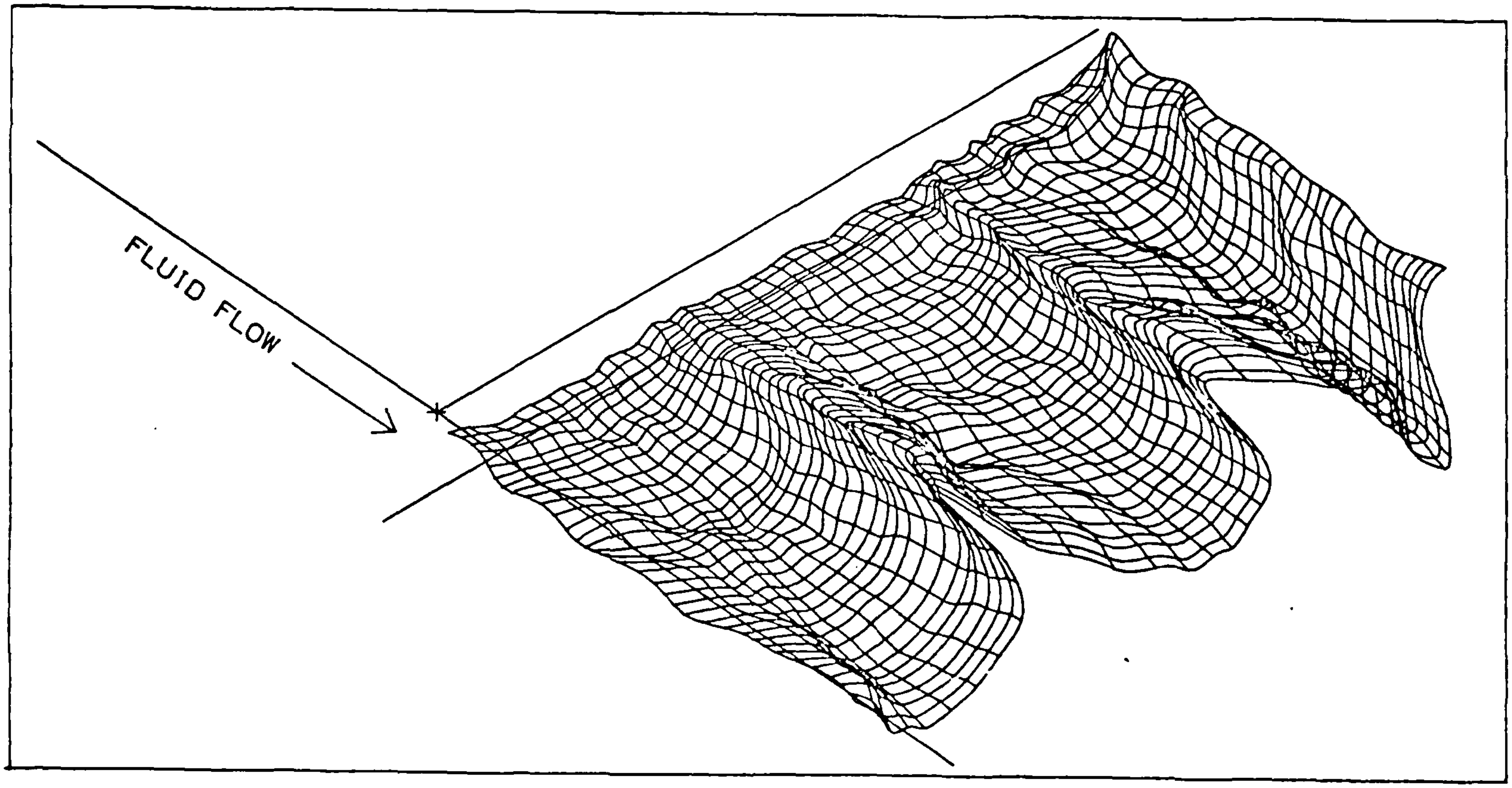


Figure 7 Oblique-view of the "surface" generated in time and space by the bubble-line motion.

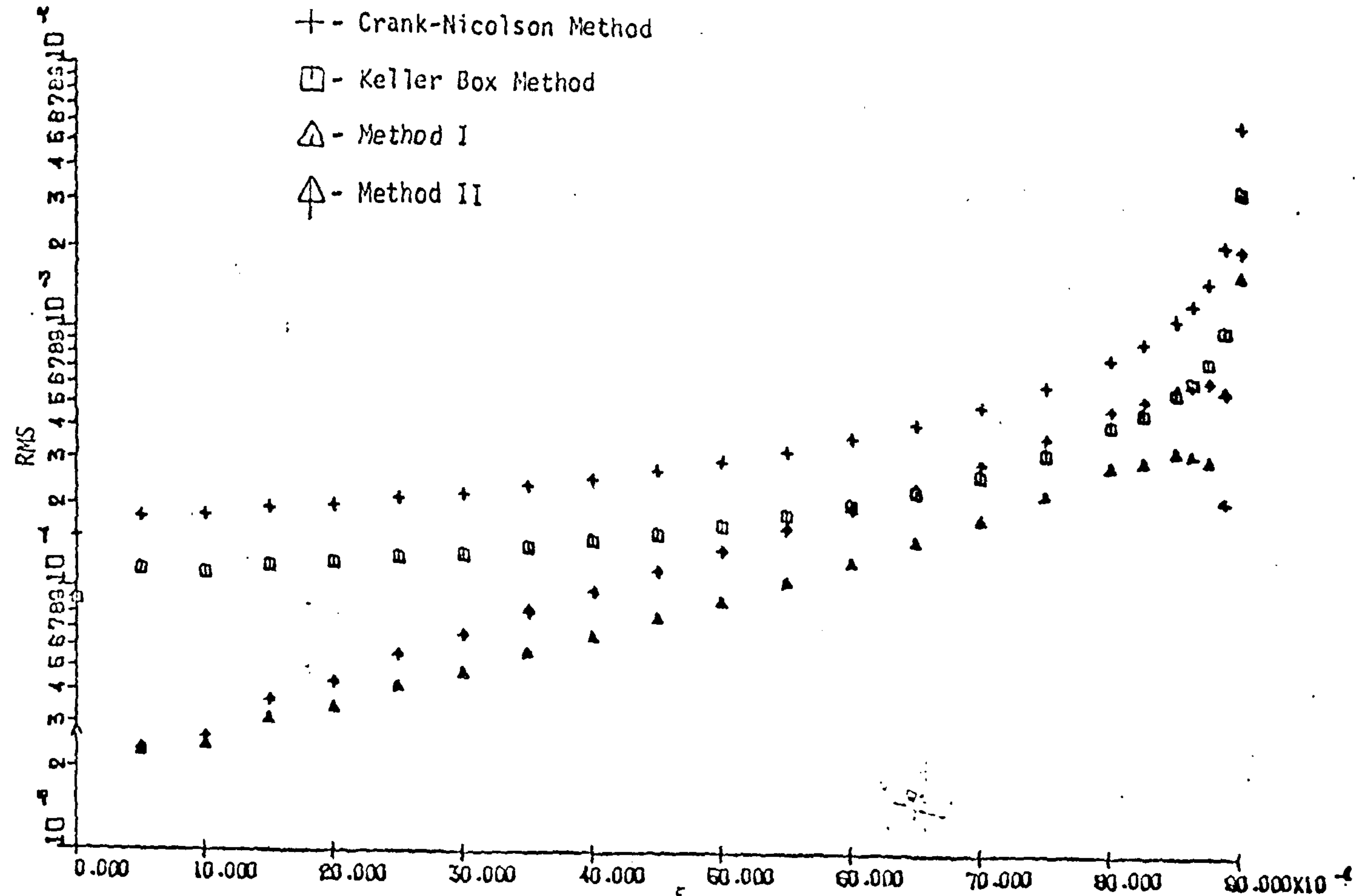


Figure 8. Comparison of RMS error for the Howarth flow problem

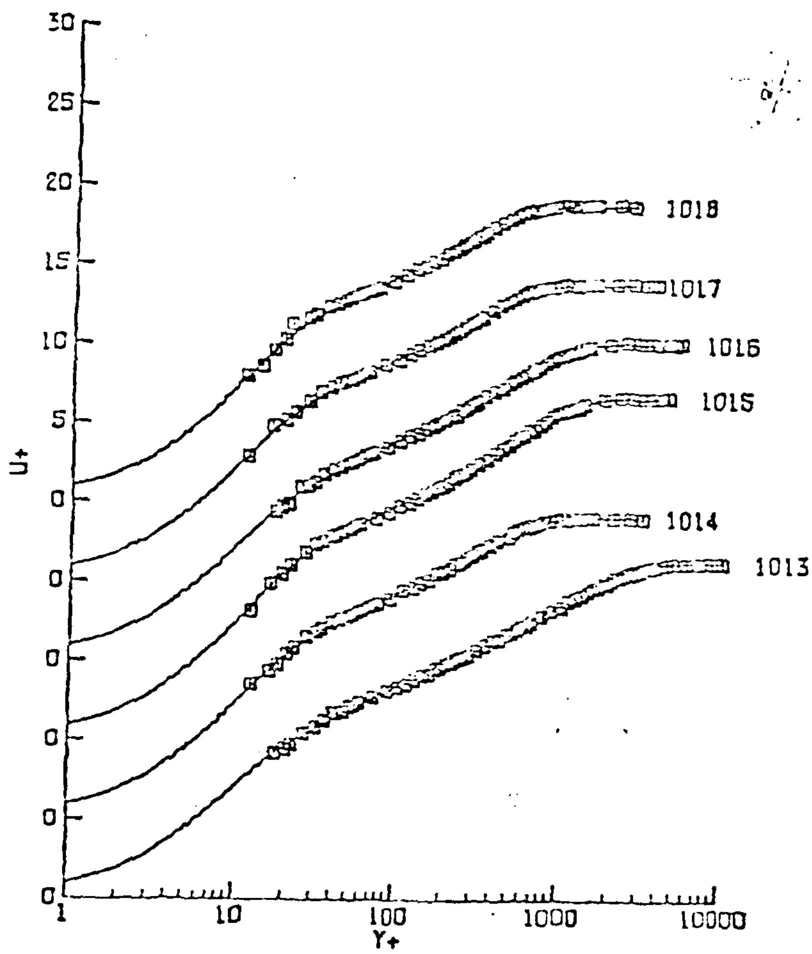


Figure 9. Velocity profile comparisons for two parameter optimization on S and K (with κ=0.44789) for mainstream turbulence flow.

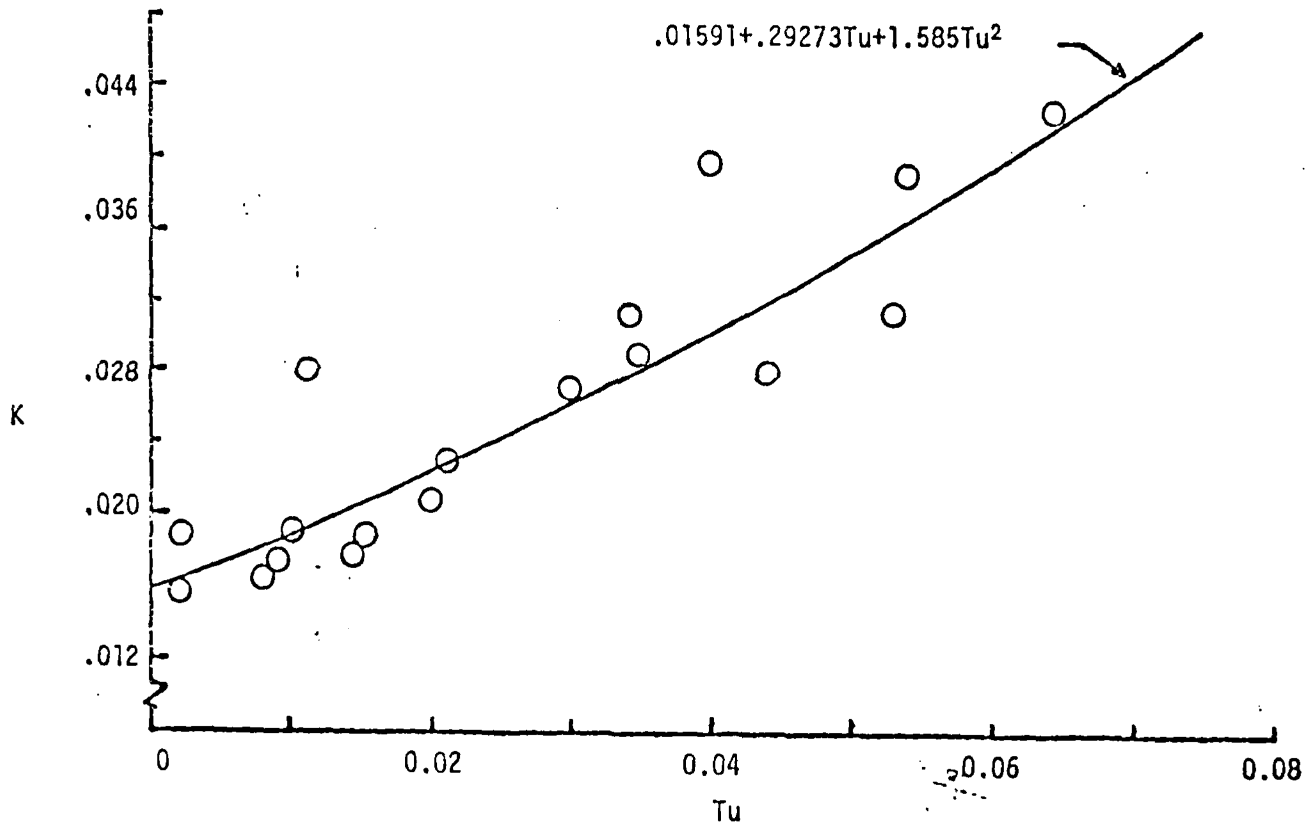
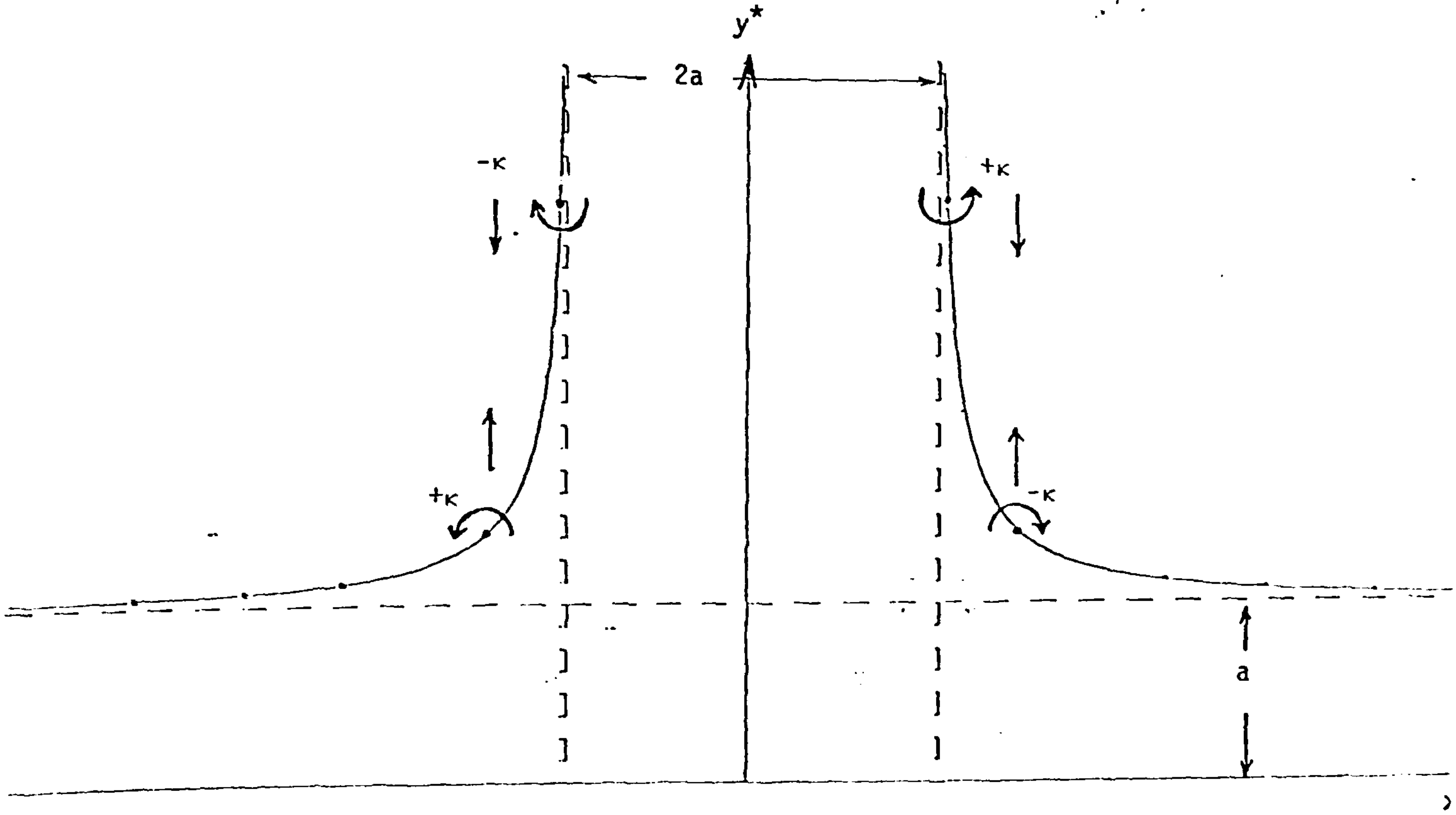


Figure 10. K parameter correlation obtained from one parameter fits of the composite similarity profile to constant pressure test data with mainstream turbulence.



Vortex Path: $\frac{1}{x^{*2}} + \frac{1}{y^{*2}} = \frac{1}{a^2}$

Figure 11. Vortex for a pair of counter-rotating vortices at equal distances above a plane wall.

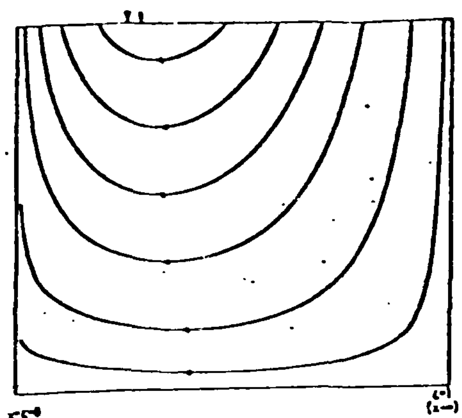


Figure 12(a). Boundary layer streamlines due to an upward moving vortex pair started at $X_o = Y_o = \sqrt{2}$ at t=0.65.

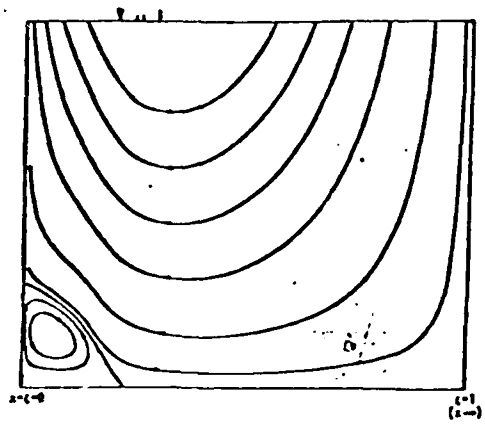


Figure 12(b). Same case as figure 12(a) t=1.775.

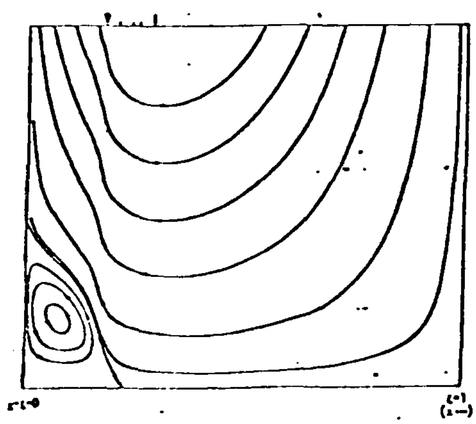


Figure 12(c). Same case as figure 12(a) at t=2.375.

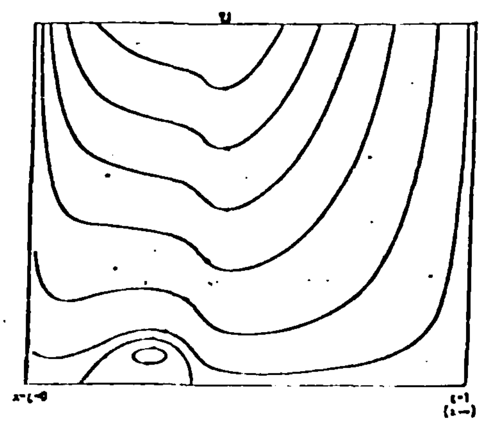
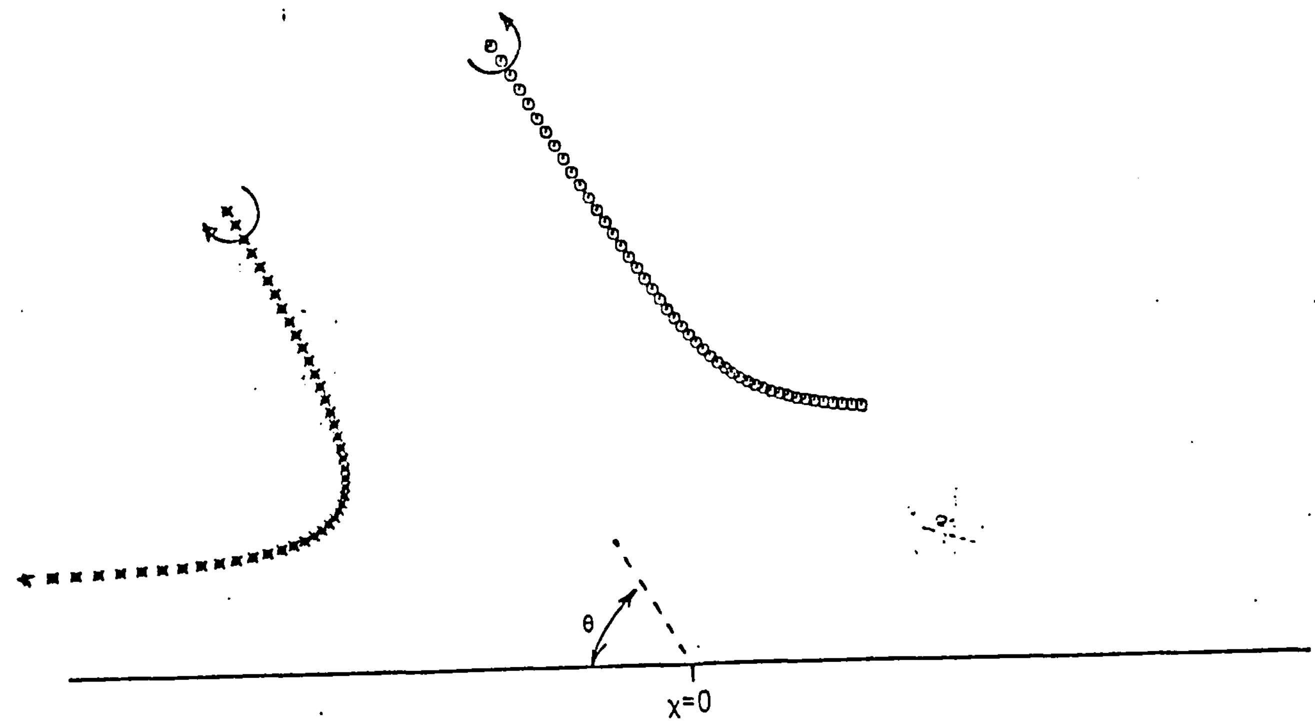


Figure 13. Boundary layer streamlines due to a downward moving pair started at X_o=3.28, Y_o=1.05 at t=1.225.

Figure 14. Trajectories of a pair of counter-rotating vortices approaching a wall at an angle.



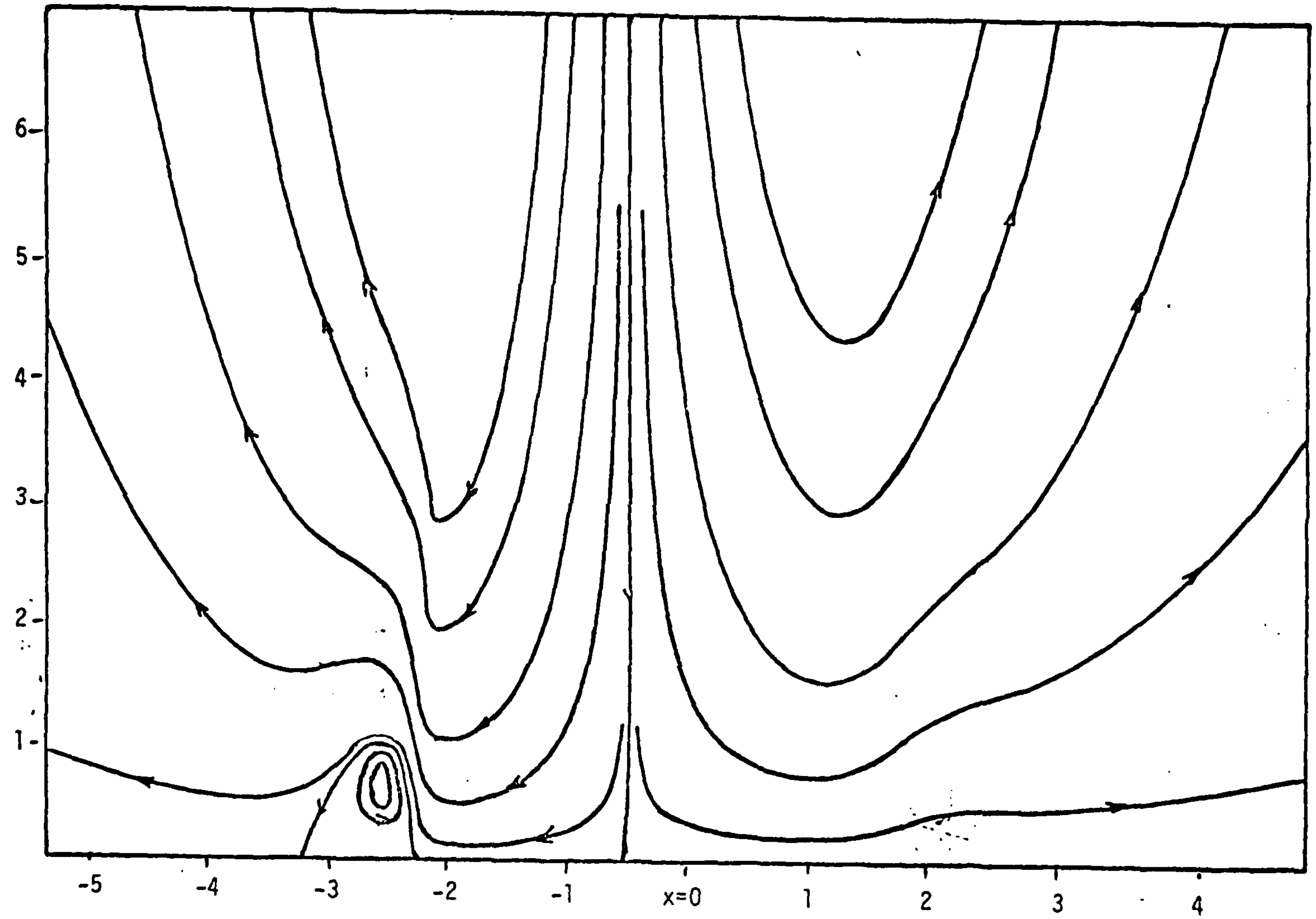


Figure 15. Instantaneous streamlines in the boundary layer for a pair of counter-rotating vortices approaching a wall at an angle of 80°. Note secondary vortex at x≈-3 and beginning of another separation at x≈2.5. Arrows indicate flow direction.