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(2)

## REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

AD-A210 355

1b. RESTRICTIVE MARKINGS

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT
Approved for public release;
distribution unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S)

5. MONITORING ORGANIZATION REPORT NUMBER(S)
AFOSR-TR- 89-0986

6a. NAME OF PERFORMING ORGANIZATION
Stanford University
Department of Mechanical

6b. OFFICE SYMBOL (If applicable)

7a. NAME OF MONITORING ORGANIZATION
AFOSR

6c. ADDRESS (City, State, and ZIP Code)
Engineering
Stanford California 94305

7b. ADDRESS (City, State, and ZIP Code)
BLDG 410
BAFB DC 20332-6448

8a. NAME OF FUNDING / SPONSORING ORGANIZATION
AFOSR

8b. OFFICE SYMBOL (If applicable)

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
F44620-74-C-0016

8c. ADDRESS (City, State, and ZIP Code)
B DG 410
BAFB DC 20332-6448

10. SOURCE OF FUNDING NUMBERS

| PROGRAM ELEMENT NO. | PROJECT NO. | TASK NO. | WORK UNIT ACCESSION NO. |
|---|---|---|---|
| 61102F | 2307 | A4 | |

11. TITLE (Include Security Classification)
SEPARATED FLOWS, TURBULENCE PRODUCTION MECHANISMS AND FREE SHEAR LAYERS

12. PERSONAL AUTHOR(S)
S.J. Kline/ J.H. Ferziger

13a. TYPE OF REPORT
FINAL

13b. TIME COVERED
FROM 12/1/73 TO 11/30/78

14. DATE OF REPORT (Year, Month, Day)
Jan 79

15. PAGE COUNT
37

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

| FIELD | GROUP | SUB-GROUP |
|---|---|---|
| | | |
| | | |

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)

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

DTIC
ELECTE
JUL 19 1989
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89 7 19 037

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION
unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL

22b. TELEPHONE (Include Area Code)
767-4987

22c. OFFICE SYMBOL
NA

DD Form 1473, JUN 86

Previous editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

AFOSR-TR- 89-0986

FINAL REPORT

to

U. S. Air Force Office of Scientific Research

on Contract

AF-F44620-74-C-0016

for Period

1 December 1973 to 30 November 1978

# Separated Flows, Turbulence Production Mechanisms And Free Shear Layers

from

Thermosciences Division
Department of Mechanical Engineering
Stanford University

Principal Investigators:
S. J. Kline
J. H. Ferziger

January 22, 1979

# I. INTRODUCTION

## The Integrated Program: General Objectives

The work ~~performed~~ under Air Force Contract AF-F44620-74-C-0016 forms part of an integrated, long-term program in complex turbulent flows and related convection heat transfer. The complete program is coordinated by the HTTM Group at Stanford University[*].

A very large fraction of all difficulties in complex turbulent flow fields arises from lack of the ability to predict the behavior of two phenomena: turbulence and flow separation. The Stanford HTTM Group centers work on these two problems.

The program is called integrated because of the spread of research over the range of problems in these fields. During the period covered by AF-F44620-74-C-0016, ongoing research included work on the following topics: experimental studies of fundamental flow physics; development of computational models and programs at several levels of complexity; development of design data and design procedures for some technologically critical applications[†]; production of data and computation methods for flow over curved surfaces with blowing and suction; development of instruments and instrument procedures pertinent to these tasks. Usually, several phases of research on each topic have been progress.

Applied problems of special interest to DOD include diffusers for both combustors and after-turbine sections in jet engines, flight vehicle inlets, cooling of high-temperature turbine blades, and coordination of an international effort to contront computational procedures in complex turbulent flows with carefully screened data of a wide variety. Many commercial applications also exist.

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[*] Faculty in the HTTM Program are S. J. Kline, J. H. Ferziger, J. P. Johnston, R. J. Moffat, and W. C. Reynolds.

[†] The HTTM Group views its task as long-range research and does not normally undertake development tasks that are more suited for work in industry or government laboratories. Whenever appropriate, work in HTTM is carried up to the stage of design utility, however, and transfer to application is facilitated not only by publication but also by an industrial affiliates program and by consulting. A current example of particular interest to DOD is consulting on Ram Jet flows for UTC, Sunnyvale.

Because of the integrated nature of the program, work from a variety of sources reinforces the specific activities under AFOSR support. For this reason, studies under other support are mentioned at some places in this report. A list of publications specifically from Contract AF-F44620-74-C-0016 is attached as Appendix A. A list of honors and special recognition of the work during the period 1973-78 is attached as Appendix B. In order to provide a clearer picture of the total program, a complete list of publications from the HTTM Group is attached as Appendix C.

F44620-74-C-0016

## II. WORK ACCOMPLISHED UNDER CONTRACT ~~AF-F-66420-74-C-0016~~

Work accomplished is reported below in six major categories.

A. Studies of the structure of turbulent shear flows, with particular emphasis on the processes of turbulence production in a boundary layer.
B. Computation of separated and separating flows.
C. Improved correlations and prediction methods for several classes of diffuser flows.
D. Experiments on and correlative methods for prediction of the zone of flow detachment for turbulent boundary layers.
E. Experiments on and computation of turbulent reattachment.
F. Establishment of calibration procedures for hot-film and hot-wire anemometers, including disclosure and quantification of serious errors for most film probes.

### A. Structure of Turbulence in Boundary Layers

At the beginning of the contract reported, work was being completed on several phases in a series of studies on the structure of turbulence in boundary layers. This work was begun in 1956-57 -- nearly coincident with the start of AFOSR support under predecessor contracts. These studies formed a central portion of the work under AFOSR support from 1957 through 1974, but involved less effort during 1974-78, for reasons noted below. An increased work fraction in this area has been proposed for AFOSR support during the 1978-80 period.

The studies under AFOSR support were the first to reveal the underlying structure of turbulence production in boundary layers. They have had a very large influence on both the understanding of the physics of turbulence production and the nature of experimental research in the phenomenon of turbulence. This influence was specifically acknowledged in the most extensive review on the topic by W. W. Willmarth in 1975, as noted in item 1, Appendix B.

In essence, these studies showed that turbulence production is not a steadily running, random process -- as implied by the original analysis of O. Reynolds; it is, rather, a highly intermittent phenomenon resulting from observable, quasi-coherent flow structures that repeat, stochastically, over time and space. A very large portion of current experimental research in turbulence throughout the world is concerned with further documentation and increased understanding of these quasi-coherent structures.

The HTTM Program also pioneered the combined time-streak, hydrogen-bubble-marker visualization method in order to study this problem (and for production of teaching films). The 1978 paper by S. J. Kline provides a summary of the history of such visual studies and their implications in turbulent flow structure.

The AFOSR work on turbulence structure has received several scientific awards. In 1968 the George Stephenson medal of the British Institution of Mechanical Engineers was awarded to this work. In 1978 the Institute for Scientific Information listed the 1967 paper from this work as a "citation classic"; this implies it has "left its mark on the whole field" -- see item 2, App. B.

Specific publications on this work phase emanating from Contract AF-F44620-74-C-0016 include:

- "Combined Dye-Streak and Hydrogen-Bubble Visual Observations of a Turbulent Boundary Layer" (with G. R. Offen), J. Fluid Mech. 62, Part 2, 223-239 (1974).
- "Experiments on the Velocity Characteristics of 'Bursts' in the Interactions between the Inner and Outer Regions of a Turbulent Boundary Layer" (with G. R. Offen), Report MD-31, December, 1973.
- "A Proposed Model of the Bursting Process in Turbulent Boundary Layers" (with G. R. Offen), J. Fluid Mech. 70, Part 2, July, 1975.
- "The Role of Visualization in Study of the Structure of the Turbulent Boundary Layer," invited keynote address and Procs. AFOSR-Lehigh Conference on Structure of Turbulent Boundary Layers (May, 1978).

The first three papers add information to understanding of the flow structure that produces turbulence. In particular, they elucidate details of the relationship between wallward motions (sweeps) and outgoing motions (bursts) near the wall; earlier work under AFOSR support had provided information primarily concerning bursts. These three papers also assess the relations between various measuring techniques employed by different observers.

The fourth paper summarizes central aspects of the work and calls for improved coordination among the active research groups. This call resulted in a first special workshop for the purpose -- at Stanford in July 1978. This workshop was sufficiently successful that plans have been made for another workshop to continue the work in summer of 1979 at Michigan State[*].

These invitational workshops have as a goal the resolution of three questions concerning the state of the art in turbulent shear layer structure among the leading research groups:

- On what points do the various research groups find consistent results" (What is relatively clear and undisputed?)
- On what points do different observers or different measuring techniques give apparently conflicting results?
- What experiments might best clarify points remaining in No. 2? (Preferably these will be set in terms of more than one hypothesis to avoid mental attachment to fixed ideas.)

We view clarification of these questions as particularly significant at this time in order to increase the rate of progress in understanding turbulent shear flows.

## B. Computation of Separated and Separating Flows

In 1973 work was being completed on the first computer program to predict "fully stalled" flow[†]. Because of the promising results of that first study, both for increased understanding and for engineering design, work on computation of separated and separating flows has received particular emphasis during 1973-1978.

As suggested in the 1973 proposal, the work on separated flows has yielded rapid progress on both understanding and predictive capacity concerning both separated and separating flows (and also the zone of detachment -- Section D following).

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[*] Proposal submitted by R. Falco to L. Ormand of AFOSR to support the 1979 workshop.

[†] This flow pattern was disclosed, its extent determined, and its details mapped under earlier research in HTTM, primarily under AFOSR support; see particularly reports PD-1, PD-5, PD-8, and MD-19, Appendix C.

The first report on fully stalled flow was that of Woolley and Kline. The complete work appears in MD-33. A shortened version has been published in the Journal of Fluids Engineering (see Appendix A). This study provides a research code for prediction of flow in a fully stalled, two-dimensional, plane-walled diffuser, a previously unsolved problem. More important, it gives the key to what goes wrong in general when predicting separated flows using the classical procedures of Prandtl's boundary layer theory in a strict sense. In particular, MD-33 shows that the rapid growth of the viscous zone as the flow nears detachment* must be accounted for at first-order (not second-order, as in the classic procedure), if accurate computations are to be achieved.

In the work of J. White (MD-35, 1975), the method of Woolley is applied successfully to the case of axisymmetric flows. The methods of Woolley and White are useful not only for computation of fully separated flows but also for providing very fast and flexible methods of computing incompressible flow in unstalled diffuser passages. Since they also allow very flexible boundary conditions to be solved with consistent input for the computer, they are useful in both the design and inverse problems and, as a result, have found considerable use in industry for passage design.

Although Reports MD-33 and MD-35 provide solutions for fully stalled flows, they do not provide computational methods for the most frequent optimum design problem in diffusers -- optimum pressure recovery at fixed length. That optimum lies in the zone of flow first revealed in the late 1950's in the HTTM Program and called "transitory stall". This zone of flow involves gross unsteadiness produced by self-excited oscillations arising from intermittent separation. In 1976, a new computation procedure was created by S. Ghose (Report MD-36) to cover the zone of optimum recovery at fixed length. The procedure assumed quasi-steady flow and hence did not cover the full zone of transitory stall, but it does predict successfully well beyond the location of peak recovery. This will allow optimization of passages not previously possible via computation. The method was sufficiently accurate that it created the need for improved data in the region of optimum recovery at fixed length, in order to provide better checks and "fine-tuning". In 1978 Ghose extended that work to provide the basis for

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*For clarity we now prefer the word 'detachment' for the zone where the mean flow deviates from the body surface. We use 'separation' to denote the total process or zone including recirculation.

computation of truly unsteady flow in passages including transitory stall. By the end of 1978, the procedure for unsteady flow was still being improved and checked and had not yet been published.

The work reported in MD-36 provided several further advances in the state of the art for computation of separated flows, beyond MD-33 and MD-35. It developed a much improved method for handling the interaction between the viscous and non-viscous zones when a flow nears or passes through detachment; it provided improved correlations for handling shear layers passing through detachment; and it made further improvements in computing passages with non-planar walls.

## C. Improved Correlations and Prediction Methods for Diffusers

In 1975 two additional phases of work were commenced to further extend and exploit the advances noted in the preceding section. The first study, by J. Bardina, has two goals: (i) providing unified computational procedures for planar and axisymmetric diffusers (including both conical and annular); (ii) improving the computing codes to make them appropriate for production use by design engineers. By 30 November 1978 the first goal had been accomplished. This work included two fundamental advances in mathematics -- an extension of Plemelj's integral to three dimensions and the use of Green's second integral theorem to provide a theoretically sound computational algorithm. The earlier alrogirhms by Woolley and White were correct and usable but did not have equally sound theoretic bases and were less efficient in axisymmetric cases. A paper for possible publication was written on the mathematical advances in late 1978.

In the summer of 1978, work on Mr. Bardina's goal (ii) led to an improved correlation for optimum performance in a variety of annular configurations*. The improved correlation has not yet been published, but was transmitted in late 1978 to some industrial firms with immediate applications. The work on goal (ii) of this phase is scheduled for completion in 1979.

The second phase, by R. Childs, has as a goal the extension of the methods for computing diffuser flows to high subsonic Mach numbers. The work is coordinated with an effort by R. Presley of the NASA-Ames Research Center, who is developing codes for the related supersonic sections of aircraft inlets. (This work has been supported in part by NASA.) By 30 November 1978, an approximate

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*This correlation is an extension of the classic correlation of Sovran and Klomp, Fluid Mechanics of Internal Flow, Elsevier Press, 1968.

method of very high speed and sufficient accuracy had been developed; programming it as a computer code had begun. Completion is anticipated for the 1978-1980 work period.

One desired goal was not reached under this general topic -- the computation of diffusers with strongly curving walls. High accuracy has not been attained, owing to the fact that wall curvature has a strong effect on the turbulence production and turbulent shear stresses in the boundary layers, and hence on flow detachment[*]. This effect is not correlated and cannot be computed at present. This has led to extensive, careful studies in HTTM of the effects of convex and concave wall curvature, under separate sponsorship, by Professors J. P. Johnston and R. J. Moffat. This separate but closely related work is being brought under AFOSR sponsorship in the 1978-80 work period. The work includes coordinated study of both flow physics and heat transfer; it will have direct applications in diffusers, turbine blade cooling for high-temperature jet engines, and many other design situations.

## D. Studies of Turbulent Flow Detachment

1. The work of Ghose, Report MD-36, described in Section B above, created a need for data of improved accuracy in the zone of optimum recovery at fixed length. Older data were not sufficient to 'fine tune' the theory to its full capability. The needed, more accurate data were proposed in another phase of work in the HTTM Group. This phase studies the fundamental physics and applications in design of the phenomenon of transitory stall (funding is supplied by Project SQUID). The data produced from this work have already been used, under AFOSR sponsorship, to further improve and develop theory. In particular, the effects of all four walls and of variable inlet-shear have been added to the program of Ghose, discussed in Section C above. Improvements in the subroutines have also been made. Publication of a first set of results in this phase of the work, by S. Ashjaee and others, should occur during the 1978-80 period[†]. Interaction between theory (with AFOSR support) and data (with SQUID support) within the total HTTM Program has been highly synergistic -- both projects have

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[*] This effect has only recently been recognized; it is qualitatively predictable from the knowledge of structures described in Seciton A above.

[†] A first publication was prepared by J. Ashjaee and J. P. Johnston in late 1978.

progressed far faster and better as a result. An improved understanding of the physics of transitory stall is emerging. Computational accuracy has been improved. An understanding of asymmetric effects in the boundary layers and in the wall shapes is being accumulated and is of considerable importance in design.

2. In early 1978, we conceived of a way of using the detachment model of Sandborn and Kline* to develop a procedure in a design mode that would not only indicate incipient detachment with improved accuracy, but would also allow specification of "stall margin". Such a "stall margin" could then be used in a design either to control the next entire pass of computation for the passage or at each marching step through a passage by machine interaction as the computation proceeds. Designers with whom we have consulted agree that there is no procedure more badly needed in many designs for both internal and external aerodynamics. In order to develop this idea, an addendum to the work order of Contract AF-F44620-74-C-0016 was created in early 1978. By 30 November 1978, the work under this addendum was well advanced, and the probability of achieving the desired procedure during 1979 is high.

In pursuing this work, we have developed a significantly improved coordinate set for studying flow detachment of turbulent layers. Using those coordinates, we are able to show that incipient separation is confined to a narrow zone of parameters for smooth walls without suction or blowing and with only mild wall curvature. It will be relatively simple to program that result. Study of the effect of suction and blowing in the same coordinates is under way at the end of the contract period. We anticipate completion of the study in the first half of 1979.

## E. Studies of Turbulent Reattachment

### 1. The Backward-Facing Step

In Report MD-37, completed in mid-1978, J. Kim, S. J. Kline, and J. P. Johnston report the results of a study of flow over a backward-facing step. Principal objectives of the study were to increase understanding of the reattachment process and of the reattached layer. Three step sizes were studied. A universal

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*"Flow Models in Boundary Layer Stall Inception," TASME 83D, 3 Sept. 1961. This paper combines physical ideas developed under AFOSR support with related analysis by V. A. Sandborn.

non-dimensional shape of the pressure rise was found. A zonal prediction method was created, extending the ideas developed in the work reported under Section B above to include reattachment. The output matches available data adequately.

The structure studies in this work revealed important information concerning the relation of the large eddies (structure) in the separated free-shear layer and the boundary layer on the wall downstream from turbulent reattachment. In particular, the reattached turbulent layer had a decidedly non-equilibrium character. The structure of the layer showed typical turbulent boundary layer structures part of the time, but other eddies an order of magnitude larger during the rest of the time. The larger eddies came into the reattached layer from the free-shear layer over the separated, recirculating zone. These larger eddies died away only very slowly, that is, after 50 or more boundary layer widths downstream from reattachment.

Computationally, the result of this structure is surprising. The well-known correlation for eddy viscosity by F. H. Clauser fails entirely; it spreads the data rather than collapsing them. J. Kim was able to find an improved correlation that does collapse the data within about 10% (typical of good correlations for turbulent layers). This correlation then provides the basis for accurate computation of the first two flows for which it was 'calibrated', as well as a third geometry measured by another observer, J. Eaton. In addition, the new correlation provides accurate computation of the Tillman Ledge Flow[*], a case that was not predicted correctly (even qualitatively) by any of the 28 theories covered in "Computation of Turbulent Boundary Layers -- 1968 AFOSR-IFP-Stanford Conference."[†]

This result is of great interest computationally. The reattached layer appears to be a very small, one might say negligible, extrapolation of prior cases computed well by the Clauser correlation as a turbulence model. Nevertheless, it fails to provide true <u>prediction</u>. Because of this type of failure to extrapolate, P. Saffman suggested a few years ago that the methods of closure in computing turbulent flows would more appropriately be called <u>postdictive</u>. MD-37 is a particularly compelling illustration of Saffman's point. It also points up the importance of underlying flow structure. When the structure changes, one may need a new correlation. This and other cases emphasize the need for <u>local</u> modeling

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[*] Case 1500, Vol. II, Proc. of AFOSR-IFP-Stanford Conference.

[†] IFP was a predecessor program now incorporated in the HTTM Program.

of turbulence. This need is currently being promoted within the research community and will be studied in detail in the conference on computation of complex turbulent flows tentatively scheduled to be held at Stanford in 1980, under AFOSR sponsorship.

One might logically ask, do the more complex turbulence models (particularly the one-equation and two-equation models) suffer the same difficulties as the eddy viscosity model, when compared to the reattached flow reported in MD-37? We believe that they would suffer these difficulties from an understanding of the sources of physics inserted into those model equations. In discussing this question with Prof. Brian Launder, of UC-Davis, one of the foremost developers of such models, we found that he had already checked and had found they do indeed suffer this difficulty. Hence we have not made specific checks ourselves. This suggests that the correlation reported in MD-37 might have important uses in other flows. At 30 November 1978, that possibility remained to be studied.

## 2. The Reattachment Zone

The work reported in MD-37 showed that existing instrumentation created unacceptable levels of uncertainty in the zone of reattachment. This problem arises from transient flow reversals which are not properly handled by pitot or hot-wire probes. To overcome this difficulty, a new type of instrument has been designed, constructed, and calibrated during 1977-78. It is a simple, inexpensive, three-element probe. A central wire (or film) is heated with constant current, and two other wires, up and downstream, are operated as resistance thermometers. In this way, the fraction of forward (and backward) flow can be measured. The instrument is cheap and reliable. It dissects the reattachment zone roughly ten times more accurately than pre-existing visual studies (see, for example, Abbott and Kline, 1962, App. C). By 30 November 1978, initial sets of data were completed and checked these already allow measurement of the effect of $R_{\delta *}$ at the separation that lies within the scatter (uncertainty interval) in prior studies.

During the 1978-80 work period we plan to extend these measurements to include several types of two-point velocity correlations, and both more details and more cases of reattachment. We shall also use it to study the detachment zone where similar problems of measurement occur. It will be possible to use the apparatus constructed under Project SQUID funding (see work of Ashjaee, Section D above) for these studies; this will avoid the need for construction of an apparatus with AFOSR funds.

## F. Calibration of Hot-Wires and Hot-Films for Velocity Fluctuation Measurements

Good procedures for calibration of hot-wires and hot-film probes for mean flow have long existed. However, procedures for calibration of measurements of velocity fluctuation have not existed. Since a number of researchers, including ourselves, had questions concerning possible errors created by the existence of substrate in the hot-film probes, we felt it was important to create a direct, accurate calibration procedure for velocity fluctuation measurement.

In 1974, we conceived the idea of using fully developed channel flow in which three fluctuation quantities $(\overline{uv}, u', v')$ of the flow can be established via the momentum theorem from measurements of wall pressure. This idea has been used to check and calibrate the common probes of both commercial manufacturers, DISA and TSI. The results are given in Reports TMC-3 and TMC-4.

In essence, we find hot-wires are accurate up to the expected frequencies, to the uncertainty in our calibration procedure established by statistical replication, that is, 1%. However, in the process of calibration and checking, we found that the standard procedure used for yaw correction (and for finding the yaw constant) was inadequate. The deficiency created measured errors as large as 14% in some cases. An improved procedure for finding the yaw constant of a given probe has been developed and shown to effectively eliminate this error.

The hot-film probes present a different picture. Large errors in RMS values of fluctuation velocities were measured for most hot-film probes. These errors ranged from 25% to 75%; output is always below true value. These numerical values (25-75%) are specific to an overheat ratio of 1.4 in air at 25-100 ft/sec. At lower overheats the error decreases, but not fast enough to allow for measurements of reasonable accuracy. The worst offender is the cone probe, which unfortunately is also the most widely used probe in the industry. Errors in liquids will be much lower, but have not been measured.

The only exception to these errors is the solid film fiber probes; all other film probes have large RMS errors when used to measure velocity fluctuations according to the procedures recommended by manufacturers and in the published literature. Study of the results of the various probes plus simple theoretic studies allowed us to show that the errors are due to the presence of the substrate. They arise from the frequency-dependent conduction heat-flows to and from the substrate at the edges of the hot-films.

As a result of these reports, both the principal manufacturers are seeking remedies to the problems uncovered. Further publication by HTTM with one of the manufacturers is being considered for 1979 on methods for overcoming the problems.

## Appendix A

## REPORTS AND PUBLICATIONS PRODUCED FROM WORK UNDER THE CONTRACT

Final Report

Contract AF-F44620-74-C-0016

1. Woolley, R. L., and S. J. Kline, "A Method for Calculation of a Fully Stalled Flow," Report MD-33, Thermosciences Div., Dept. of Mech. Engrg., Stanford Univ., November 1973.
2. Offen, G. R., and S. J. Kline, "Combined Dye-Streak and Hydrogen-bubble Visual Observations of a Turbulent Boundary Layer," J. Fluid Mech. 62, Part 2, 223-239 (1974).
3. Offen, G. R., and S. J. Kline, "Experiments on the Velocity Characteristics of 'Bursts' in the Interactions between the Inner and Outer Regions of a Turbulent Boundary Layer," Report MD-31, Thermosciences Div., Dept. of Mech. Engrg., Stanford Univ., December, 1973.
4. Offen, G. R., and S. J. Kline, "A Proposed Model of the Bursting Process in Turbulent Boundary Layers," J. Fluid Mech. 70, Part 2, July 1975.
5. White, J. W., and S. J. Kline, "A Calculation Method for Incompressible Axisymmetric Flows, Including Unseparated, Fully Separated, and Free Surface Flows," Report MD-35, Thermosciences Div., Dept. of Mech. Engrg., Stanford Univ., May, 1975.
6. Ghose, S., and S. J. Kline, "Prediction of Transitory Stall in Two-Dimensional Diffusers," Report MD-36, Thermosciences Div., Dept. of Mech. Engrg., Stanford Univ., December, 1976.
7. Kim, J., S. J. Kline, and J. P. Johnston, "Investigation of Separation and Reattachment of a Turbulent Shear Layer: Flow over a Backward-Facing Step," Report MD-37, Thermosciences Div., Dept. of Mech. Engrg., Stanford Univ., April, 1978.
8. Woolley, R. L., and S. J. Kline, "A Procedure for Computation of Fully Stalled Flows in Two-Dimensional Passages," Procs. ASCE-IAHR/AIHR-ASME Joint Symposium on Design and Operation of Turbomachinery, Vol. I, June 12-14, 1978; also to be published in TASME, J. Fluids Engrg.
9. Ghose, S., and S. J. Kline, "A Numerical Method for Calculating the Performance of Two-Dimensional Diffusers Operating in the Transitory Stall Regime, Including Prediction of Optimum Recovery," Procs. ASCE-IAHR/AIHR-ASME Joint Symposium on Design and Operation of Fluid Machinery, Ft. Collins, Colo., June 12-14, 1978.
10. Kline, S. J., and S. Ghose, "On Computation of Separated Diffuser Flows," Memorial Volume (Festschrift) for A. Walz, 1978.
11. Kline, S. J., "The Physics of Flow in Diffusers," Published notes of ASME Fluid Dynamics Institute, Dartmouth, August 1978.

12. Kline, S. J., "The Design of Diffusers," Published notes of 1978 ASME Fluid Dynamics Institute, Dartmouth, August 1978.

13. Young, M. F., S. J. Kline, and R. J. Moffat, "Calibration of Hot-Wires and Hot-Films for Velocity Fluctuations," Report TMC-3, Thermosciences Div., Dept. of Mech. Engrg., Stanford Univ., March 1976.

14. Taslim, M. E., S. J. Kline, and R. J. Moffat, "Calibration of Hot-Wires and Hot-Films for Velcoity Fluctuations," Final report, TMC-4, Thermosciences Div., Dept. of Mech. Engrg., August 1978.

15. Kline, S. J., "The Role of Visualization in Study of the Structure of the Turbulent Boundary Layer," Invited keynote address, Procs. AFOSR-Lehigh Conference on Structure of Turbulent Boundary Layers, May 1978.

16. Kline, S. J., J. H. Ferziger, and J. P. Johnston, OPINION - "The Calculation of Turbulent Shear Flows: Status and Ten-Year Outlook," TASME, J. Fluids Engrg., March 1978.

17. Ferziger, J. H., and S. J. Kline, "Levels of Turbulence Prediction," Procs. NASA-Ames Conference on Numerical Methods in Fluid Mechanics, July 1978.

18. Kline, S. J., W. C. Reynolds, F. A. Schraub, and P. W. Runstadler, "Turbulence Structure: The History of a Citation Classic," to be published in Current Content (see Appendix B).

## Appendix B - Awards and Honors

Final Report Contract AF-F44620-74-C-0016

During the contract period, 1 December 1973 through 30 November 1978, five specific honors in the form of awards and citations were conferred on work performed under this AFOSR contract and predecessor contracts. Only specific significant awards or citations are listed. Many invited lectures, consulting tasks, and other events of a nominally 'honors' type have been cited in year-end reports, and are not repeated here.

1. The most extensive review thus far published on the structure of the turbulent boundary layers, by W. W. Willmarth[*], gives special credit to the work of the Stanford Group. Nearly all this work was done under AFOSR support. In particular, Prof. Willmarth says,

> ". . . The research work on the visualization of boundary layer flow at Stanford University is summarized in three papers: Kline et al. (1967), Kim et al. (1971), and recently Offen and Kline (1974). As will become apparent later, the research at Stanford University has very considerably increased our understanding of the structure of turbulent boundary layers."

> ", , , As mentioned above, visual observations of coherent structures in the fully developed turbulent boundary layer were first reported at Stanford University by Kline and his colleagues. The first phase of their work (covering the period 1963-1967) was reported in Kline et al. (1967). This paper contained a description of the streaky sublayer discussed in Section IV,E. It also presented a description of an identifiable randomly occurring process (that we now call a burst) in which sublayer streaks were observed to gradually "lift up," then suddenly oscillate, followed by bursting and ejection. Unfortunately, there is not space to describe many of the details of their observations in this review. Perhaps a summary of the randomly occurring process that they identified can be obtained from a sketch. Figure 29, from Kline et al. (1967), is a sequence depicting the above process, from typical side views of a dye streak as seen in motion pictures. The arrow follows a prominent portion of the ejected streak. The oscillation occurs in the third sketch, and bursting and ejection with considerable contortion of the dye streak in the fourth and fifth sketch."

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[*] Advances in Applied Mechanics, Vol. 15, 1975.

2. In 1978, the Institute for Scientific Information notified us that our 1967 paper[*] had been classified as a citation classic and asked us to prepare a history of the work and its significance, for publishing in Current Contents A paragraph from the Institute's letter explaining the meaning of this citation follows. A description of Current Contents from the Institute's letter also follows.

- "What is a Citation Classic?

  Most papers in the sciences and social sciences contain cited references. Simply stated, a large number of citations to a paper usually indicates that the cited work significantly contributed to the development of scientific knowledge in its field. A paper that is very highly cited frequently has left its mark on the progress of the whole of science. We have coined the name "citation classic" to refer to such papers, which are identified by means of raw citation counts from our Science Citation Index® and Social Sciences Index™ data base."

- Current Contents is an information service which reproduces the contents pages of recent journal issues. Its six weekly editions cover the following disciplinary areas: (1) life sciences; (2) physical and chemical sciences; (3) agriculture, biology, and environmental sciences; (4) engineering, technology, and applied sciences; (5) clinical practice; (6) social and behavioral sciences. Since your Citation Classic is likely to appear in more than one edition, it will have a potential readership of 250,000 scientists.

3. In a summary "Diffuser Data Book"[†] for its military-industrial clients, the Creare Corporation of Hanover, New Hampshire, gives special credit to the work in the Stanford Group in organizing the field of diffuser flows and setting the modern basis for understanding and correlating diffuser performance. The technical history section of that manual is appended as Attachment 1. This work was commenced under NACA sponsorship and continues to be extended under AFOSR sponsorship since 1958.

4. In 1975 Prof. J. P. Johnston was awarded the R. T. Knapp Award of the Fluids Engineering Division of the ASME. The work cited was supported in part by AFOSR and in part by the National Science Foundation.

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[*] S. J. Kline, W. C. Reynolds, F. A. Schraub, and P. W. Runstadler, "Structure of Turbulent Boundary Layer on a Smooth Wall," J. Fluid Mech., 30, 741, 1967.

[†] P. W. Runstadler, F. X. Dolan, and R. C. Dean, Jr., Diffuser Data Book, Creare Corporation, 1976.

The citation for this award reads:

> "In recognition of an outstanding research accomplishment as reported in the paper: "Suppression of Shear Layer Turbulence in Rotating Systems."

5. In December 1975, Professor S. J. Kline was awarded the Fluids Engineering Medal by the Fluids Engineering Division of ASME. The citation, prepared by Dr. Gino Sovran, Head of Fluid Mechanics Research in the General Motors Research Laboratories, is appended as Attachment 2. This medal is not given annually; it is only awarded when the Executive Committee of Fluids Engineering Division of ASME believes the career contributions of an individual warrant the award. The medal had been awarded only twice prior to 1975 -- to H. W. Emmons and G. F. Wislicenus -- and has been awarded once since -- to A. H. Shapiro. As the attached citation indicates, much of the work noted was carried out under AFOSR support. Professor Kline remains the youngest recipient thus far by nearly a decade.

Attachment 1 for Appendix B

Final Report Contract AF-F44620-74-C-0016

From Diffuser Data Manual, Creare Corp., 1976

## 3 TECHNICAL HISTORY

The first known diffusers were designed to cheat the authorities.* In Rome (circa 100 A.D.) water was distributed to homes of the wealthy via an aqueduct system. The charge for the water was based upon flow rate, because the water ran continuously. At each outlet, the flow water was metered by an ajutage which amounted to a long flow-metering nozzle made of lead. Some enterprising Roman discovered that if he flared the adjutage, his flow rate increased without increasing his cost! Hence, from necessity and avarice, the diffuser was invented.

The rational appreciation and application of diffusers probably did not commence until the 18th century, when hydraulic engineers began to understand that a significant portion of pumping power can appear in a system as flow kinetic energy. Leonhard Euler (1707-1783) showed the mathematical relationship between flow kinetic energy, elevation and pressure.** From that theoretical cornerstone, diffuser technology has been constructed for over 200 years.

The history of diffuser technology seems remarkable, but is perhaps a typical example of how man's knowledge structures are really built. Until recent times, there were two divergent schools at work. The theoreticians have attempted to predict diffuser performance analytically, for two centuries and are still trying, but without much success.

The practical engineer built and tested diffusers for his particular needs. A few pragmatically oriented researchers tested families of diffusers. None of these empiricists made a systematic search, exploiting the theoretical tools as they could, in order to identify the key parameters and the characteristic behavior modes of the diffuser.

Those who have studied the history of hydraulics know that there was a classical period in the late 18th and in the 19th century when leading thinkers thought that theory alone was going to explain everything. At the turn of the 20th century, there were famous, now slightly amusing, arguments between the theoreticians and the pragmatists over such subjects as whether the bumblebee could fly. The existing theory could not explain the lift on a wing, but everyone with common sense knew that wings could lift the bumblebee. The early years of the 20th century produced a cadre of giants in fluid mechanics such as Prandtl and von Karman, Lancaster and G. I. Taylor, who bridged the chasm between the pure theories and the pragmatists. They showed for wings, for example, that a little bit of viscosity must be added as "spice" to the inviscid theory in order to make it replicate reality.

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*Rouse and Ince (1957), p. 28.

**Rouse and Ince (1957), p. 104.

One of the important tools of these new, undogmatic technologists was simple observation. We are moved by the image of Prandtl dallying in the gutter watching the runoff swirl, while his advanced theoretical fluid-dynamics class waits impatiently. Prandtl's image reminds us of an earlier giant, Leonardo da Vinci, who in his notebooks recorded many fluid phenomena, such as the Karman vortex street forming behind a rock in the river (we should call it the da Vinci vortex street; as often happens, the credit went to the theoretician rather than to the observer!).*

Figure 1 - Sketch of Vortex Street by da Vinci

Now, how did these many trends of intellectual development impact diffuser technology?

The diffuser had roughly the same history as all other devices of fluids engineering. In the late 19th century, theoreticians were at work upon the diffuser, but could not explain some obvious paradoxes raised by the experimentalists. The experimentalists, on the other hand, were lost in the n-dimensional "forest" of the complex physical realm of the diffuser. Each one charted a small path through this multi-dimensional function space, rarely crossing the paths charted by other researching explorers. Thus, the literature appeared to be confusing and contradictory. The engineer who attempted to build a design technolgy often concluded that "all those researchers are wrong; I must generate my own data". Hence, he would chart a little territory surrounding his point of interest in the n-dimensional "forest".

The situation was much like astronomy before Newton. All man could do was to make careful measurements of particular cases and catalog them logically for use by others. Libraries of records accumulated and the situation rapidly grew like a cancer, beyond man's ability to comprehend. Of course, Newton's laws collapsed all of this information into two simple equations, plus a catalog of heavenly bodies. Then the behavior of any astronomical element could be reconstructed by calculation from the distilled pith of the matter. Suddenly, the whole became comprehensible to even ordinary men.

Diffusers, like all other devices, felt the impact of the intellectual revolution sparked by Newton, et al.

We come into the early 20th century with the hydraulic theoretician failing to explain the nature of the diffuser, and the practical researcher and fluids engineer lost in the n-dimensional "woods". This situation actually persisted until the 1950's. The great watershed was crossed in 1955 by S. J. Kline in a pure da Vincian fashion. He recognized a classic diffuser paradox, which is as follows. Generally, flat diffusers of about $2\theta = 8°$ are close to optimum. However, a $2\theta = 16°$ diffuser has markedly lower recovery than an 8° diffuser. If space dictates a short diffuser, we are impelled to use the 16° in favor of the 8°. Theory says that we need

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*Rouse and Ince (1957), p. 46.

lose nothing, because we merely can put a thin splitter down the centerline of the 16° diffuser and make two 8°'s running in parallel. According to the potential theory, with Prandtl-type boundary layers appended, this scheme should work fine. But, when tried by numerous workers, it was found not to work at all. Kline asked "Why?", and set out to discover the answer by looking at the flow pattern.

He used a simple water table constructed from laboratory junk for a few hundred dollars. With this water table, he revealed the gross topography of the n-dimensional world of the diffuser. Suddenly, the reports of earlier explorers fitted into a pattern. He often found that their data were not contradictory, but just lay on opposite sides of cliffs in the topography.

Kline's diffuser world is shown in Figure 2. The principal discovery was that diffusers have, not one, but four principal modes of behavior. The transition between modes is at some places gradual and at others sudden. There is hysteresis. Some of the modes are strongly transient while others are essentially quiescent. Transient modes are interleafed between more quiescent ones. No wonder the unenlightened explorers did not recognize the pattern of this n-dimensional map for two centuries.

Since Kline's seminal focusing of the pattern, a large amount of effort has been guided by his structure. Much of this work has been done at Stanford University under Kline and his colleagues. Much has been done elsewhere by his disciples.

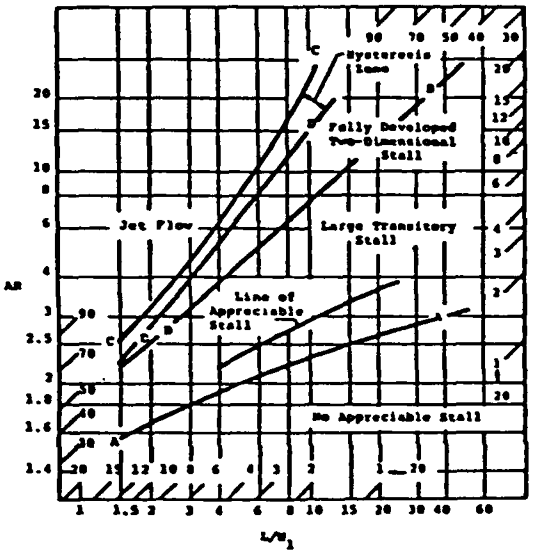

Figure 2 - Incompressible Straight Channel Diffuser Flow Regime Map (Fox and Kline (1962))

Another major discovery was that of Sovran and Klomp, who identified the key fluid variable that impacts diffuser performance--throat boundary-layer blockage. They proved that merely the simple idea of area blockage by boundary layer was a sufficient parameter for expressing the diffuser's strong response to the effects of the inlet boundary layer. The simplicity of this representation is remarkable and unexpected. One would think that the shape of the boundary-layer velocity profile, boundary-layer thickness distribution on the walls, etc. should have major influences. But, diffusers, like people, almost always confound our intuition.

The fact is that simple area blockage (i.e., $B_t = 1 - A_{eff}/A_{geom}$) is a sufficient parameter in most cases. It is the king among all the others: Mach number, Reynolds number, velocity profile, turbulence level, over most of the range of common engineering interest.

The work reported herein has been guided by the technology structure first visualized by Kline and has had a principal purpose of fleshing out that structure. Our contribution has been to extend the Mach number dimension up to choking. We have also produced systematic and highly precise data from over 5,000 diffuser tests (including varying the inlet length in order to vary throat blockage).

Attachment 2 to Appendix B

Final Report, Contract AF-F44620-74-C-0016

## Introduction of Stephen J. Kline, recipient of the Fluids Engineering Division Award, 1975

I have had the pleasure of knowing Steve Kline for many years, and the privilege of being a close observer of, and sometimes participant in, a great many of the activities of his outstanding professional career. It is therefore from first-hand knowledge that I will briefly outline these activities for you. They have been many-faceted -- involving fluid-mechanics research, fluids engineering, education, the ASME, and the interface between society and technology -- and I will cover them one at a time.

First of all, Steve Kline has made major contributions to fluid-mechanics research, most particularly in the areas of diffusers, separated flows, and turbulent shear flows. It was his research on subsonic diffusers that first gained him technical prominence, and his name is probably more closely associated with these devices than that of anyone else in the world. Through well-conceived, comprehensive and systematic experimentation, he determined that diffuser operation is characterized by a spectrum of flow conditions; he established the relationship between this spectrum and the geometry of the units; he determined the effect of inflow conditions on diffuser pressure recovery; and he defined the geometries for optimum performance.

This diffuser research revealed areas of fluid mechanics where existing knowledge was insufficient for rational fluids engineering, and these served as the basis for much of his subsequent work. Recognizing the importance of stall as an unresolved problem in fluid mechanics, he was one of the key organizers of the Stall Symposium; this was one of the first symposia hosted by the Fluids Engineering Division and was probably its largest and most successful. One year his paper, "The Nature of Stall," won him the Melville Medal for the Society's best technical contribution. His most recent and current activity is concerned with the calculations of turbulent flows containing large regions of separation.

Turbulent shear flows have been a subject of his intensive study; to identify the basic physical processes, he has used flow visualization to great advantage; he has shown the streaky flow structure that exists very near the wall in turbulent boundary layers, and the lift-off and periodic bursting of the low-velocity streaks. He has correlated the bursting with the longitudinal pressure gradient, and has proposed an explanation of the fluid physics involved. He conceived the unique conference on turbulent boundary layer prediction held at Stanford in 1968 -- sometimes euphemistically referred to as the "Kline Olympics." He sensed a need, and felt that the time was ripe. To establish the state-of-the-art, he created a simple but effective format in which the proliferation of existing calculation procedures could be evaluated by testing them in a controlled manner against a selected mass of uniformly processed experimental data. This conference stands as a landmark in the development of boundary layer technology and is a model that others have been emulating.

Steve Kline the fluids engineer! Steve has a keen awareness of the needs of industry for rational design information, and is constantly seeking to bring modern fluid mechanics into engineering practice so that fluid systems of improved performance can be built. In the area of diffusers, he developed design charts that have been used with great effect throughout the world for configuring diffusers for a variety of fluid-flow systems. Appreciating that the realities of engineering practice sometimes dictate diffuser geometries, he developed a design procedure for vane systems that can be used to produce respectable pressure recovery in diffusers that would otherwise be classified as "basket cases."

Having been involved in its organization, I can tell you that one of the primary motivations for the Stanford boundary layer conference was a concern for the practicing engineer. The literature contained a confusing array of prediction procedures, and of various types. Recognizing that the practicing engineer who needed to make a boundary layer calculation usually had neither the time nor the expertise to make his own critical assessment, an objective of the conference was the generation of information that would assist him in making the best selection for his particular needs.

Steve has also been active as an engineering consultant to industry. In one instance, he has been an important contributor to a long-term development by one of the country's major industrial companies that has vastly improved the efficiency of jet pumps.

In both the research and the engineering areas, his efforts have these common characteristics:

-- foresight in recognizing important problems before they are evident to others,
-- shrewdness in the planning of an effective line of attack,
-- skill in execution,
— perception in identifying and systematizing the basic concepts involved.

With considerable frequency he has been the "pathfinder," the one who forged the new paths that others subsequently recognized and followed.

Steve Kline the educator! The proper relationship between the teaching and practice of engineering has always been of concern to Steve Kline, and he has continually sought to improve the quality and utility of engineering education. Through the Internal Flow Program which he organized at Stanford he has trained a cadre of competent fluid mechanicians who are now spread throughout the technical establishments of this country.

His educational impact has not been confined to the college campus. Through the medium of motion pictures, his influence has been felt beyond those boundaries. His motion-picture records of flow-visualization experiments have been an effective instructional device, as well as a tool for research, and they have permitted practitioners in fluids engineering to gain increased understanding of fundamental flow phenomena. He is responsible for establishing the library of research films in fluid mechanics which exists in the ASME today. Throughout its existence, he was a member of the National Committee for Fluid Mechanics Films that produced so many excellent educational movies, and was himself responsible for the one on "Flow Visualization."

The fourth category is that of ASME activist and innovator. Steve's contributions to ASME have been many. He has been unselfishly dedicated to promoting the profession of engineering in general, and fluids engineering in particular. He and Bob Dean were the two people most responsible for the pioneering work that, in 1963, transformed the old Hydraulic Division into the Fluids Engineering Division. As a member of the Executive Committee, he contributed in a very dynamic and forceful manner to the definition of its goals and scope, and was one of its most energetic contributors. His concern for its growth and advancement has been continuous; he has always sought to identify changing needs and to suggest means for meeting them as they arose.

He was intimately involved with the transfer into ASME of the fluidics activity originated by the Harry Diamond Laboratories, and was instrumental in setting up the unique arrangement whereby the Fluidics Committee is jointly sponsored by the Fluids Engineering and Automatic Controls Divisions.

Most recently, he was one of the original members of the Freeman Scholar Committee. No one knows better than I the extent of his contributions in establishing the objectives and procedures for this new program, and the efforts he has expended in selecting the Scholars and in reviewing their manuscripts.

His work in ASME has gone beyond Divisional boundaries. At a time when the Society was reorganizing into its present format, he was an eloquent spokesman for a more influential role by the Technical Divisions in the determination of policies and practices. After the reorganization, he served on the Policy Board of the Basic Engineering Department. Later, he was an active and extensive contributor to the discussions that led to the definition of the Society's present Goals and Priorities.

The last area of contribution concerns problems at the interface between society and technology. Motivated by the anti-scientific attitude prevalent on college campuses several years ago, Steve was a leader in establishing the interdisciplinary program at Stanford on "Values, Technology and Society." Two of its purposes have been to improve the general education of undergraduate students, and to delineate and develop an understanding for the relationships between technology and human values. Some of the spin-off from this effort will be evident very shortly, so I need not elaborate further.

There, in brief, you have it -- a summary of the contributions that give insight into the character and capabilities of the man; his broad perspective, talents and interests; his impact on our profession. It is my great personal privilege to commend to the Executive Committee of the Fluids Engineering Division as a most worthy recipient of its highest honor, Stephen J. Kline -- fluid mechanics researcher, fluids engineer, educator, ASME activist and innovator, socio-technologist.

by Dr. Gino Sovran
Supervisor, Fluid Mechanics Research
General Motors Research Laboratories

Appendix C - AFOSR Report - 15 Jan. 1979

## Publications in Fluid Mechanics HTTM Group

Thermosciences Division
Department of Mechanical Engineering
Stanford University

| No. and Date | Author(s) | Title | Sources or Open Literature Reference |
|---|---|---|---|
| MD-1<br>3/57 | S. J. Kline | "Some New Mechanisms and Conceptions of Stall, Including the Behavior of Vaned and Unvaned Diffusers" | Out of Print. See MD-4 for Reference. |
| MD-2<br>5/58 | S. J. Kline<br>A. V. Lisin | "An Experimental Investigation of the Effect of Free Stream Turbulence on the Turbulent Boundary Growth" | NASA TN D-368 March 1960; out of print. |
| MD-3<br>6/58 | S. J. Kline<br>P. W. Runstadler | "Some Preliminary Results of Visual Studies on the Flow Model of the Wall Layers of the Turbulent Boundary Layer" | Out of print; J. Appl. Mech. TASME, Ser. D, Vol. 26, No. 2, Sept. 1959. |
| MD-4<br>6/58 | S. J. Kline | "On the Nature of Stall" (ASME 1959 Melville Prize Paper) | Out of print; J. Basic Engrg. |
| MD-5<br>6/61 | D. E. Abbott<br>S. J. Kline | "Theoretical and Experimental Investigation of Flow over Single and Double Backward-Facing Steps" | Thermosc. Div. TASME. See also "Similarity Analyses of Boundary Problem in Engrg.," A.G. Hansen, Prentice-Hall, 1964. |
| MD-6<br>10/60 | D. E. Abbott<br>S. J. Kline | "Simple Methods for Classification and Construction of Similarity Solution of Partial Differential Equations" | Out of print. |
| MD-7<br>12/61 | S. J. Kline<br>K. A. Meyer | "Visual Study of the Flow Model in the Later Stages of Laminar-Turbulent Transition on a Flat Plate" | Thermosc. Div. |
| MD-8<br>6/63 | P. W. Runstadler<br>S. J. Kline | "An Experimental Investigation of the Flow Structure of the Turbulent Boundary Layer" | Thermosc. Div.; see also MD-12. |
| MD-9<br>10/63 | C. M. Sabin | "An Analytical and Experimental Study of the Plane, Incompressible, Turbulent, Free Shear Layer with Arbitrary Velocity Ratio and Pressure Gradient" | J. Basic Engrg. TASME, Ser. D., Vol. 87, No. 2. |

| No. and Date | Author(s) | Title | Source or Open Literature Reference |
|---|---|---|---|
| MD-10<br>2/64 | F. A. Schraub<br>S. J. Kline<br>J. Henry | "Use of Hydrogen Bubbles for Quantitative Determination of Time-Dependent Velocity Fields in Low-Speed Water Flows" | Out of print. Jour. Basic. Engrg. TASME Ser. D., Vol. 87, No. 2. June, 1965 (see also ASME preprint FE-20) |
| MD-11<br>4/64 | R. W. Halleen | "A Literature Review on Subsonic Free Turbulent Shear Flow" | Thermosc. Div. |
| MD-12<br>3/65 | F. A. Schraub<br>S. J. Kline | "A Study of the Structure of the Turbulent Boundary Layer with and without Longitudinal Pressure Gradient" | TSD*. MD-8 & -12 summarized by J. Fl. Mech., 30, Pt. 4, 1967. |
| MD-14<br>8/65 | T. Uzkan<br>W. C. Reynolds | "A Turbulent Boundary Layer on a Wall Moving at the Free-Stream Velocity | J. Fl. Mechanics, 28 Part E, 1967. |
| MD-15<br>7/66 | C. K. Liu<br>S. J. Kline<br>J. P. Johnston | "An Experimental Study of Turbulent Boundary Layer on Rough Walls" | Out of print. |
| MD-16<br>8/66 | S. J. Kline | "Some Remarks on Turbulent Shear Flow" (1967 George Stephenson Prize Paper) | TSD. Proc. Inst. of Mech. Engrs. (Brit.) 1966 |
| MD-17<br>4/65 | R. M. Halleen<br>J. P. Johnston | "The Laminar Boundary Layer on a Rotating Circular Arc Blade" | Out of print. J. Basic Engrg. TASME, 88, Ser. D No. 1, March, 1966. |
| MD-18<br>5/67 | R. M. Halleen<br>J. P. Johnston | "The Influence of Rotation on Flow in a Long Rectangular Channel - An Experimental Study" | J. Fl. Mech., 56, p. 533 1972; also see J. Fl. Engrg. TASME, 95, p. 229 1973. |
| MD-19<br>8/67 | G. K. Chui<br>S. J. Kline | "Investigation of a Two-Dimensional Fully Stalled Turbulent Flow Field" | Out of Print |
| MD-20<br>1/68 | H. T. Kim<br>S. J. Kline<br>W. C. Reynolds | "An Experimental Study of Turbulent Production Near a Smooth Wall in a Turbulent Boundary Layer with Zero Pressure Gradient" | Thermosc. Div. |
| MD-21<br>6/68 | E. A. Hirst<br>W. C. Reynolds | "An Integral Prediction Method for Turbulent Boundary Layers Using the Turbulent Kinetic Energy Equation" | Thermosc. Div. |
| MD-22<br>8/68 | R. T. Lahey,Jr.<br>S. J. Kline | "Representation of Space-Time Velocity and Pressure Fluctuation Correlations by a Tentative Phenomenological Model" | Thermosc. Div. |
| MD-23<br>1/69 | S. J. Kline | "Turbulent Boundary Layer Prediction and Structure -- the State of the Art" | Thermosc. Div. |
| MD-24<br>5/70 | J. P. Johnston | "The Effects of Rotation on Boundary Layers in Turbo-Machine Motors | Thermosc. Div.: NASA SP-304, Pt. I, p. 207, 1974 |

| No. and Date | Author(s) | Title | Source or Open Literature Reference |
|---|---|---|---|
| MD-25<br>5/71 | T. Morrow<br>S. J. Kline | "The Evaluation and Use of Hot-Wire and Hot-Film Anemometers in Liquids" | Out of print. |
| MD-26<br>3/71 | R. T. Lahey, Jr.<br>S. J. Kline | "A Stochastic Wave Model Interpretation of Correlation Functions for Turbulent Shear Flows" | Thermosc. Div. |
| MD-27<br>10/70 | W. C. Reynolds | "Computation of Turbulent Flows -- State of the Art" | Thermosc. Div.; Adv. in Ch. E., Vol. 9, 1974. |
| MD-28<br>5/71 | O.K. Oseberg<br>S. J. Kline | "The Near Field of a Plane Jet with Several Initial Conditions" | Thermosc. Div. |
| MD-29<br>6/71 | D. Lezius<br>J. P. Johnston | "The Structure and Stability of Turbulent Wall Layers in Rotating Channel Flow" | Out of print.; J. Fl. Mech., Vol. 56, p. 533, 1972 |
| MD-30<br>6/71 | A. J. Wheeler<br>J. P. Johnston | "Three-Dimensional Turbulent Boundary Layers -- an Assessment of Prediction Methods" | Out of print; J. Fl. Engg. TASME, Vol. 95, p. 393, 1973. |
| MD-31<br>12/73 | G. R. Offen<br>S. J. Kline | "Experiments on the Velocity Characteristics of 'Bursts' and on the Interactions between the Inner and Outer Regions of a Turbulent Boundary Layer" | Thermosc. Div. |
| MD-32<br>8/72 | W. J. Wheeler<br>J. P. Johnston | "Three-Dimensional Turbulent Boundary Layers -- Data Sets for Two-Space Coordinate Flows" | Thermosc. Div. |
| MD-33<br>11/73 | R. L. Woolley<br>S. J. Kline | "A Method for Calculation of a Fully Stalled Flow" | Thermosc. Div. |
| MD-34<br>7/76 | J. P. Johnston | "Experimental Studies in Three-Dimensional Turbulent Boundary Layers" | Thermosc. Div. |
| MD-35<br>5/75 | J. W. White<br>S. J. Kline | "A Calculation Method for Incompressible Axisymmetric Flows, Including Unseparated, Fully Separated, and Free Surface Flows" | Thermosc. Div. |
| MD-36<br>12/76 | S. Ghose<br>S. J. Kline | "Prediction of Transitory Stall in Two-Dimensional Diffusers" | Thermosc. Div. |
| MD-37<br>4/78 | J. Kim<br>S. J. Kline<br>J. P. Johnston | "Investigation of Separation and Reattachment of a Turbulent Shear Layer: Flow over a Backward-Facing Step" | Thermosc. Div. |
| MD-38<br>5/78 | E. J. Kerschen<br>J. P. Johnston | "Modal Content of Noise Generated by a Coaxial Jet in a Pipe" | Thermosc. Div. |

| No. and Date | Author(s) | Title | Source or Open Literature Reference |
|---|---|---|---|
| PD-1<br>9/55 | C. A. Moore<br>S. J. Kline | Investigation of Airfoils, Plates Grids and Rods for Boundary Layer Control in Subsonic Diffusers | Out of Print |
| PD-2<br>9/55 | C. A. Moore<br>S. J. Kline | Some Effects of Vanes and of Turbulence on Two-Dimensional Wide-Angle Subsonic Diffusers | Out of Print;<br>NACA TB 4080 |
| PD-3<br>4/57 | D. L. Cochran<br>S. J. Kline | The Use of Short, Flat Vanes for Producing Efficient Wide-Angle, Two-Dimensional Subsonic Diffusers | Out of Print;<br>NACA TB 4309 |
| PD-4<br>6/58 | S. J. Kline<br>D. E. Abbott | Optimum Design of Straight-Walled Diffuser | J. Basic Engrg., TASME, Ser. D, Vol. 81. No. 3, Sept. 1959. Also Thermosc. Div. |
| PD-5<br>3/60 | B. A. Waitman<br>L. R. Reneau<br>S. J. Kline | Effects of Inlet Conditions of Performance of Two-Dimensional Diffusers | Out of print; J. Basic Engrg., TASME, Ser. D., Vol. 83, No. 3, Sept. 1961. |
| PD-6<br>8/60 | R. W. Fox<br>S. J. Kline | Flow Regime and Design Methods for Curved Subsonic Diffusers | Out of Print;<br>J. Basic Engrg. TASME, Ser. D, Vol. 82, Sept. 1962 |
| PD-7<br>2/62 | O. G. Feil | Vane Systems for Very Wide-Angle Subsonic Diffusers | TSD; J. Basic Engrg. TASME, Ser. D, Vol. 86, No. 4 Dec. 1964 |
| PD-8<br>9/64 | L. R. Reneau<br>J. P. Johnston<br>S. J. Kline | Performance and Design of Straight Two-Dimensional Diffusers | TSD; J. Basic Engrg. TASME, Ser. D, Vol. 89, No. 1 March 1967 |
| PD-9<br>5/65 | C. J. Sagi<br>J. P. Johnston<br>S. J. Kline | The Design and Performance of Two-Dimensional Curved Subsonic Diffusers | TSD; J. Basic Engrg. TASME, Ser. D, Vol. 89, No. 4 December 1967 |
| PD-10<br>5/65 | A. B. Cocanower<br>S. J. Kline | A Unified Method for Predicting the Performance of Subsonic Diffusers of Several Geometries | TSD |
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| PD-18<br>9/74 | D. W. Roberts<br>J. P. Johnston | Development of a New Internal Flow Aeroacoustic Facility - Aerodynamic and Acoustic Experiments on Square-Edged Orifices | TSD |
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| IT-2<br>5/65 | D.H. Gage<br>M. Schiffer<br>S.J. Kline | The Non-Existence of a General Thermokinetic Variational Principle | Symposium Vol. on "Non-Equilibrium Therm<br>dynamics - Variational<br>Techniques & Stability"<br>Chicago Press, 1966<br>Also Thermosc. Div. |

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| LG-3<br>9/64 | W.C. Reynolds<br>M.A. Saad | Capillary Hydrostatics and Hydrodynamics at Low g | Thermosc. Div.; NASA Monograph |
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| TF-3<br>8/74 | S. Shaanan<br>J. H. Ferziger | A direct method of solution of Poisson equation accurate to fourth order. | Out of print. |
| TF-4<br>4/75 | W. C. Reynolds | Computation of turbulent flows. | Out of print. |
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| TF-7<br>5/75 | H. Lee Norris<br>W. C. Reynolds | Turbulent channel flow with a moving wavy boundary. | " |
| TF-8<br>5/75 | M. Acharya<br>W. C. Reynolds | Measurements and predictions of a fully developed turbulent channel flow with imposed controlled oscillations. | " |
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| TF-12<br>5/78 | P. Moin<br>W. C. Reynolds<br>J. H. Ferziger | Large-Eddy Simulation of Incompressible Turbulent Channel Flow | " |

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| AHT-2<br>9/1/61 | R. E. Lundberg<br>W. C. Reynolds<br>W. M. Kays | Heat Transfer with Laminar Flow in Concentric Annuli with Constant and Variable Wall Temperature and Heat Flux | Thermosc. Div. |
| AHT-3<br>4/12/62 | P. A. McCuen<br>W. M. Kays<br>W. C. Reynolds | Heat Transfer with Laminar and Turbulent Flow between Parallel Planes with Constant and Variable Wall Temperature and Heat Flux | |
| AHT-4<br>4/15/62 | E. Y. Leung<br>W. M. Kays<br>W. C. Reynolds | Heat Transfer with Turbulent Flow in Concentric and Eccentric Annuli with Constant and Variable Heat Flux | |
| AHT-5<br>7/1/62 | H. S. Heaton<br>W. C. Reynolds<br>W. M. Kays | Heat Transfer with Laimar Flow in Concentric Annuli with Constant Heat Flux & Simultaneously Developing Velocity and Temperature Distributions | Thermosci. Div. |
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# Publications
# Heat and Mass Transfer Program

## Thermosciences Division
## Department of Mechanical Engineering
## Stanford University

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| HMT-2<br>1967 | R. L. Simpson<br>W. M. Kays<br>R. J. Moffat | "The Turbulent Boundary Layer on a Porous Plate: An Experimental Study on the Fluid Dynamics with Injection and Suction" | Out of print |
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| HMT-12<br>1970 | D. W. Kearney<br>R. J. Moffat<br>W. M. Kays | "The Turbulent Boundary Layer: Experimental Heat Transfer with Strong Favorable Pressure Gradients and Blowing" | Out of Print |
| HMT-13<br>1970 | R. J. Loyd<br>R. J. Moffat<br>W. M. Kays | "The Turbulent Boundary Layer on a Porous Plate: An Experimental Study of the Fluid Dynamics with Strong Favorable Pressure Gradients and Blowing" | Out of Print |
| HMT-14<br>1971 | W. M. Kays | "Heat Transfer to the Transpired Turbulent Boundary Layer" | Out of Print |
| HMT-15<br>1972 | P. S. Andersen<br>W. M. Kays<br>R. J. Moffat | "The Turbulent Boundary Layer on a Porous Plate: An Experimental Study of the Fluid Mechanics for Adverse Free-Stream Pressure Gradients" | Out of Print |
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| HMT-17<br>1974 | A. F. Orlando<br>R. J. Moffat<br>W. M. Kays | "Turbulent Transport of Heat and Momentum in a Boundary Layer Subject to Deceleration, Suction and Variable Wall Temperature" | Thermosc. Div. |
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