AD-A106 130 PURDUE UNIV LAFAYETTE IN SCHOOL OF MECHANICAL ENGINEERING F/G 20/4
LASER VELOCIMETER MEASUREMENTS IN TURBULENT AND MIXING FLOWS. P--ETC(U)
JUN 81 W H STEVENSON, H D THOMPSON F33615-77-C-2010

UNCLASSIFIED AFAPL-TR-79-2009-PT-3 NL

1 OF 1
AD A
106130

END
DATE
FILMED
11-81
DTIC

LEVEL (12)

AD A106130

AFAPL-TR-79-2009
Part III

LASER VELOCIMETER MEASUREMENTS IN TURBULENT AND MIXING FLOWS

W.H. STEVENSON
H.D. THOMPSON
T.S. LUCHIK

SCHOOL OF MECHANICAL ENGINEERING
PURDUE UNIVERSITY
WEST LAFAYETTE, INDIANA 47907

JUNE 1981

Final Technical Report for Period March 1977-December 1980

AERO PROPULSION LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

This technical report has been reviewed and is approved for publication.

Roger R. Craig
Project Engineer

Frank D. Stull, Chief
Ramjet Technology Branch
Ramjet Engine Division

FOR THE COMMANDER

William G. Beecroft, Deputy Director
Ramjet Engine Division

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFAPL-TR-79-2009 Pt. III	2. GOVT ACCESSION NO. AD-A100130	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) LASER VELOCIMETER MEASUREMENTS IN TURBULENT AND MIXING FLOWS-FINAL REPORT		5. TYPE OF REPORT & PERIOD COVERED Final: 1 March 1977 - 31 December 1980
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) W.H. Stevenson, H.D. Thompson, and T.S. Luchik		8. CONTRACT OR GRANT NUMBER(s) F33615-77-C-2010
9. PERFORMING ORGANIZATION NAME AND ADDRESS School of Mechanical Engineering Purdue University West Lafayette, Indiana		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 2308-S1-02
11. CONTROLLING OFFICE NAME AND ADDRESS Aero Propulsion Laboratory (AFWAL/PORT) Air Force Wright Aeronautical Labs. (AFSC) Wright-Patterson Air Force Base, OH 45433		12. REPORT DATE June 1981
		13. NUMBER OF PAGES 33
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Turbulence measurements
Laser velocimeter
Bias errors (in laser velocimetry)
Numerical Analysis
Recirculating Flows

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

Experimental and analytical studies of subsonic flow over a backward facing 2-D step and in a cylindrical simulated dump combustor were conducted. A laser velocimeter was used to obtain mean velocities and turbulence quantities. A method for detecting and eliminating velocity bias errors in such measurements was developed. The 2/E/FIX computer code used for numerical modeling predicted the mean velocity field satisfactorily, but was less effective in computing turbulence quantities.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

FOREWARD

This final report was submitted by the School of Mechanical Engineering of Purdue University under Contract No. F33615-77-C-2010 and covers the period 1 March 1977-31 December 1980. The research was sponsored by the Aero Propulsion Laboratory, Air Force Wright Aeronautical Laboratories, Wright Patterson AFB, Ohio, under Project No. 2308 with Roger R. Craig AFWAL/PORT as Project Engineer. Warren H. Stevenson and H. Doyle Thompson of Purdue University were technically responsible for the work.

TABLE OF CONTENTS

SECTION		PAGE
I.	INTRODUCTION	1
II.	SUMMARY OF PREVIOUSLY REPORTED RESULTS	3
	1. Laser Velocimeter System	3
	2. Bias Error Investigation	6
	3. Flow Over a Backward Facing Step	12
III.	FEASIBILITY OF USING FLUORESCENT TRACER PARTICLES IN TURBULENT MIXING STUDIES	19
	1. Background	19
	2. Feasibility Study	19
IV.	MEASUREMENTS IN THE AXISYMMETRIC TUNNEL	21
	1. Background and Experimental Procedure	21
	2. Experimental Results	23
V.	CONCLUSIONS AND RECOMMENDATIONS	32
REFERENCES		33

LIST OF ILLUSTRATIONS

FIGURE		PAGE
1.	Laser Velocimeter System	4
2.	Data Acquisition System	5
3.	Step Geometry Showing Measurement Points	8
4.	Effect of Data Rate on Mean Velocity at Point A	9
5.	Effect of Data Rate on Mean Velocity at Point B	9
6.	Effect of Data Rate on Mean Velocity at Point C x = 25 Hz Sampling Rate o = 250 Hz Sampling Rate	11
7.	2-D Flow System	13
8.	Measured and Computed Mean Velocity Profiles at x/h = 2	15
9.	Measured and Computed Mean Velocity Profiles at x/h = 8	16
10.	Measured and Computed Turbulence Kinetic Energy Profiles at x/h = 4	18
11.	Geometry of Axisymmetric Test Section	22
12.	Axial Velocity Profiles	24
13.	Decay of Centerline Velocity	25
14.	Centerline Turbulence Intensity - Axial Component	26
15.	Turbulence Intensity Profiles - Axial Component	27
16.	Turbulence Intensity Profiles - Tangential Component	28
17.	Reynolds Stress Profiles	29
18.	Turbulence Kinetic Energy Profiles	30
19.	Integrated Mass Flux Profiles	31

SECTION I

INTRODUCTION

The primary objective of this research program was to investigate the application of laser Doppler velocimetry to flows typical of those encountered in ramjet devices. Such flows are characterized by the sudden expansion of a turbulent flow which produces a recirculation zone. Turbulence levels varying from near zero to rather large values are found as one moves through the shear layer separating the primary flow from the recirculation region.

Although laser velocimetry is a well established technique for flow measurement, a number of questions remain regarding measurement accuracy and data interpretation when applied to highly turbulent flows. A number of "bias" errors have been postulated which must be accounted for in such flows. One in particular - the velocity bias - has been a source of considerable controversy, since numerous investigations have resulted in conflicting conclusions as to the magnitude and even the existence of this effect. Therefore a careful study of the velocity bias question represented a major part of the research effort.

The overall research effort was divided into five parts as noted below.

1. Design and construction of a specialized laser Doppler velocimeter, data acquisition system, and flow facility [1].
2. Investigation of bias errors in highly turbulent flows [2,3].
3. Detailed analysis and measurement of flow over a backward facing (two-dimensional) step [2,4].
4. Examination of the feasibility of using fluorescent particles in turbulent mixing studies.
5. Mapping of the flow field in an axisymmetric dump combustor model (cold flow).

The previous interim technical reports [1-4] cover Items 1-3 in detail. A summary of that portion of the research effort is presented in Section II . The remainder of this final report describes results obtained in the research devoted to Items 4 and 5.

SECTION II

SUMMARY OF PREVIOUSLY REPORTED RESULTS

1. LASER VELOCIMETER SYSTEM

Since a careful investigation of bias errors formed a major part of the research effort, a special laser Doppler velocimeter (LDV) system was designed and fabricated [1]. A schematic of the LDV optics is shown in Fig. 1. The design allowed precise control of probe volume characteristics including fringe spacing and beam diameter. Acousto-optic (Bragg cell) modulators in both beam paths allowed a net frequency shift to be imposed ranging from 5 to 75 MHz. A 10 MHz shift was used for most of the experimental measurements. This allowed complete resolution of the sign on the velocity vector in all regions where negative velocities were present.

The entire optical system was mounted on a mill table driven in x, y, and z by stepping motors where x is the mean flow direction (horizontal), y is the vertical direction, and z is along the optical axis of the LDV system. Traverse ranges were 152 mm in x and z and 254 mm in y. Position accuracy was ± 0.1 mm. The optical system could be rotated about its axis to measure any velocity component in the x-y plane.

The data collection, storage, and processing system is illustrated in Fig. 2. It consisted of a Thermo-Systems, Inc. (TSI) Model 1980 counter type processor and an IMSAI 880 microcomputer tied to the University's CDC 6600 computer which handled the data analysis. With this system it was possible to acquire velocity data from individual Doppler burst signals at rates up to 4800 samples per second (limited by the microcomputer).

Seeding was provided by a TSI Model 3076 liquid atomizer followed by a TSI Model 3072 evaporation-condensation unit. This supplied a monodisperse aerosol about 1 μm in diameter. The aerosol was injected directly into the flow system blower upstream of the test section. Seeding densities sufficient to produce

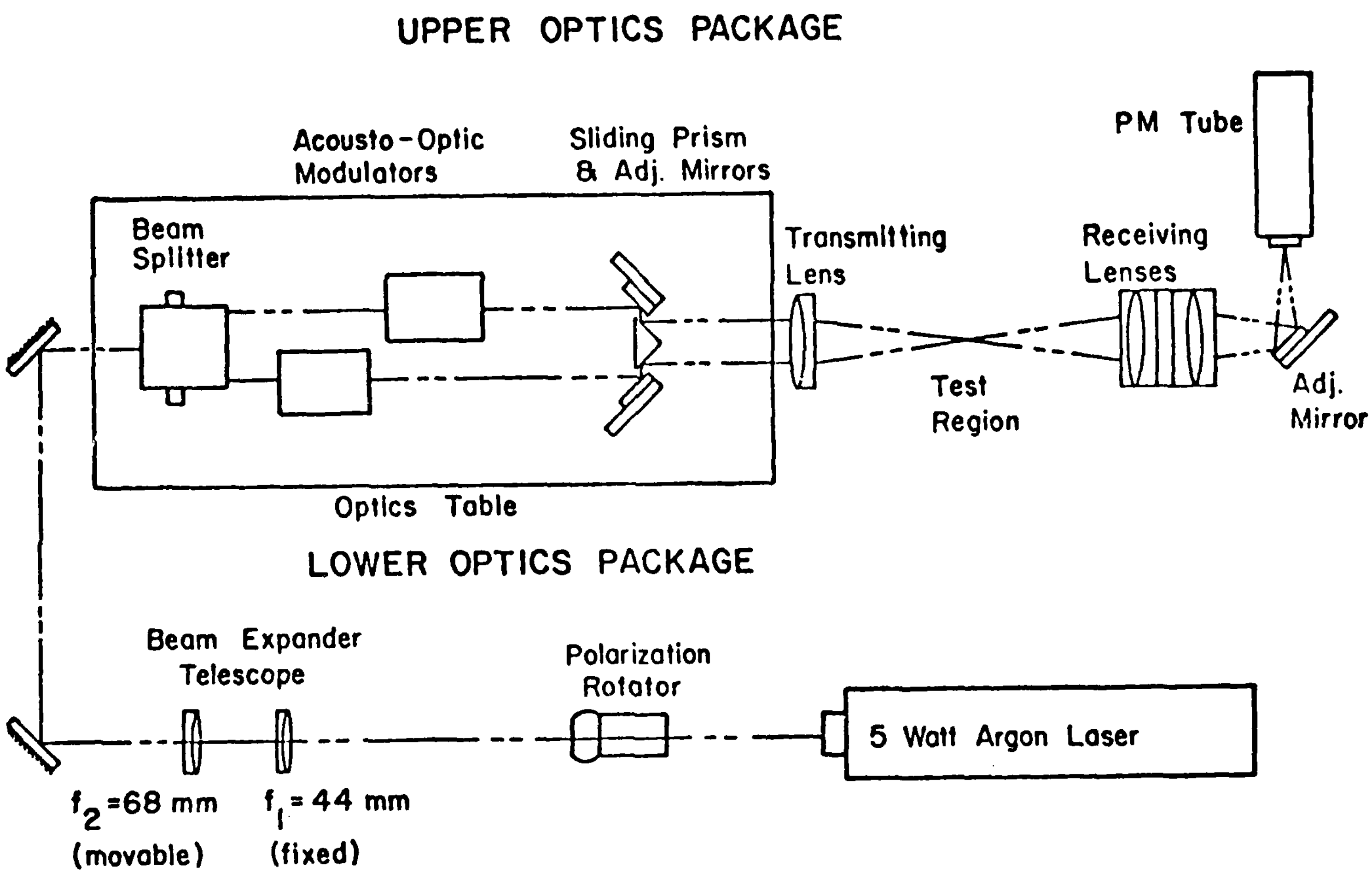


Figure 1. Laser Velocimeter System

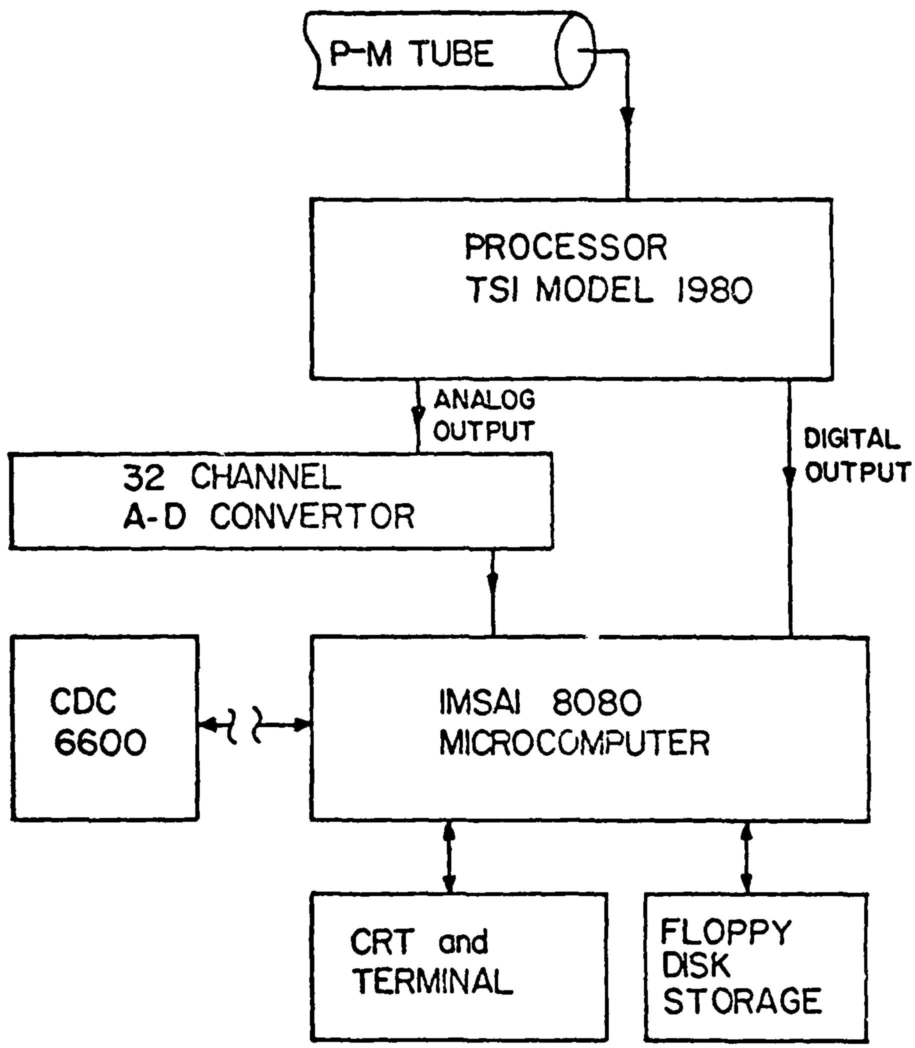


Figure 2. Data Acquisition System

upwards of 20,000 Doppler burst signals per second were easily achieved with this system. DOP was used as the seeding agent.

The LDV system described has proved to be very satisfactory. With the exception of some minor problems with the processor it has been quite reliable. Due to the deliberate flexibility in the optical system design which allows precise control of probe volume characteristics, a careful initial alignment of the optics is required [2,3]. Once aligned, however, the system is quite stable.

2. BIAS ERROR INVESTIGATION

When LDV data are obtained from individual seeding particles as they randomly pass through the probe volume, questions arise as to how the data set collected over a period of time in a turbulent flow is to be interpreted. It has been postulated, for example, that a simple average of the data will not yield the correct mean velocity. A major part of the research effort was therefore directed toward the detection and measurement of such "bias" errors [2,3].

The velocity bias effect alluded to above can be viewed in simple terms as arising from a preferential weighting of the data set toward higher velocities. This would occur because more fluid (and thus a greater number of scattering particles) is carried through the probe volume at higher velocities than at lower velocities. Although this is conceptually reasonable, the complex nature of turbulent flow has prevented a rigorous analytical modeling of the problem and previous experimental investigations have not been definitive. A major reason for the difficulty in obtaining unambiguous experimental results has been that alternative velocity measurements made, for example, with hot wire anemometers are also subject to unknown errors at high turbulence levels. Therefore comparisons between LDV and other data are not necessarily meaningful.

In the present study a direct measurement of the velocity bias was made using only LDV data to avoid any need for comparison with other measurements. The basic approach was to vary the data sampling conditions between the limits of particle controlled sampling as is normally used in LDV work and equal time interval sampling of the velocity. Obviously the latter data set, when averaged, should yield the true mean velocity provided the data set is large enough and is taken over a time period long enough to eliminate any effects of flow structure. Random (particle controlled) sampling was accomplished by reducing the seeding density so that the average data rate was well below the capability of the data acquisition system.* Equal time interval sampling was achieved by making the seeding density, and thus the processor data rate, very large, while limiting the sampling rate with the microcomputer. In this case a new data point was acquired each time, and as soon as, the microcomputer released its inhibit on the TSI processor after storing the previous data point.

Measurements were made at various points in the shear layer behind a rearward facing step. Test section geometry is shown in Fig. 3. Figures 4-6 show mean velocities obtained as described above. In Fig. 4 the measurement point A was upstream of the step where the turbulence level was relatively low (about 1%). Therefore no velocity bias was expected and, as the figure shows, the computed mean velocity was not influenced by sampling conditions. The data in Fig. 5 were obtained at measurement point B of Fig. 3 and in this case sampling conditions had a marked effect on the mean velocity obtained by averaging the data. Equal time interval sampling occurred at the high particle rate toward the right Fig. 5. The actual microcomputer sampling rate was 250 Hz or one sample every four milliseconds. At the left end of the plot the samples were taken randomly as the TSI processor validated particle signals. Obviously a velocity bias was present under these conditions. The solid circle represents the result of applying the one-dimensional bias correction of

*Data rate as employed here refers to the number of Doppler signals per second processed and validated by the TSI processor when it is not being controlled by the microcomputer.

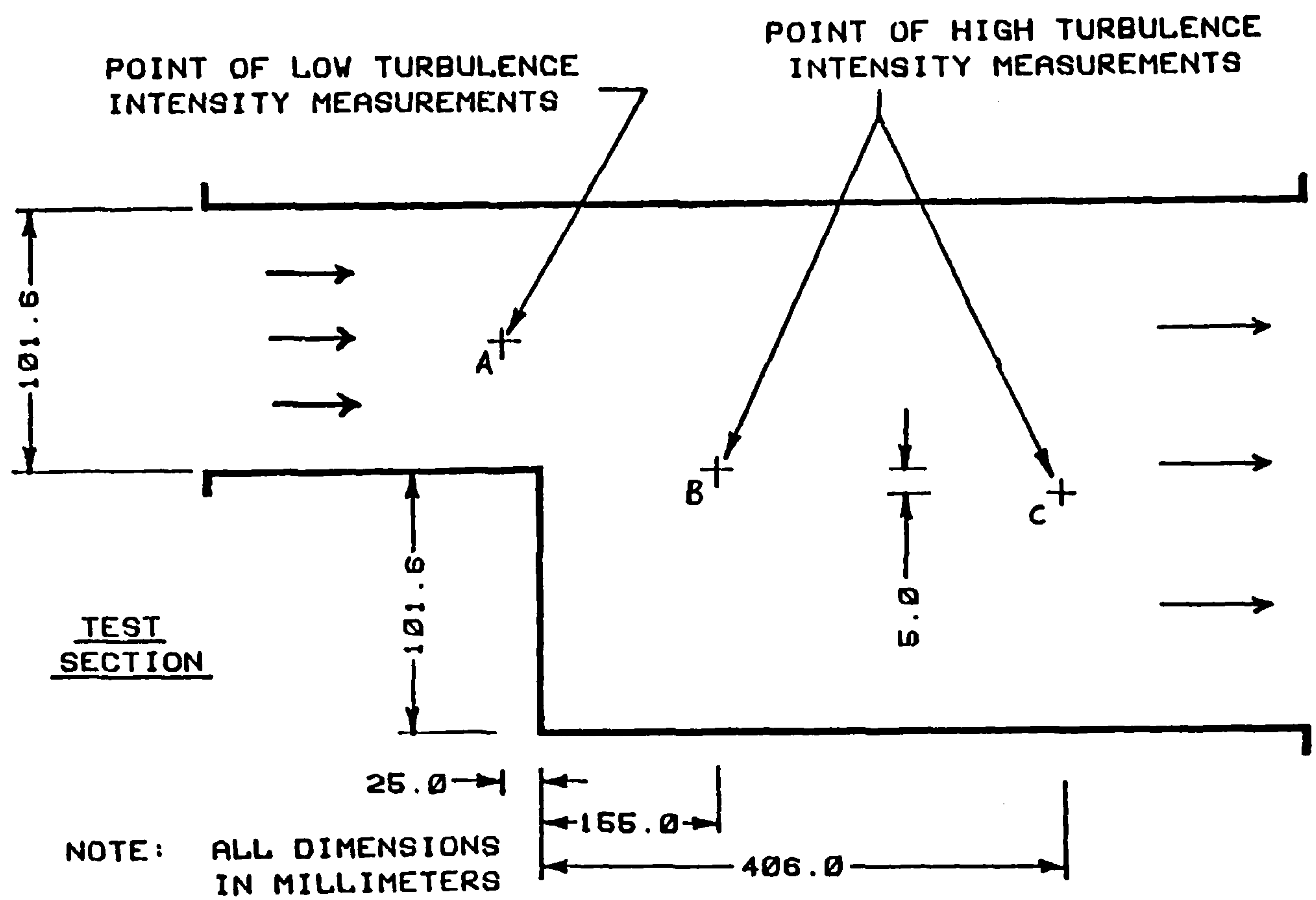


Figure 3. Step Geometry Showing Measurement Points

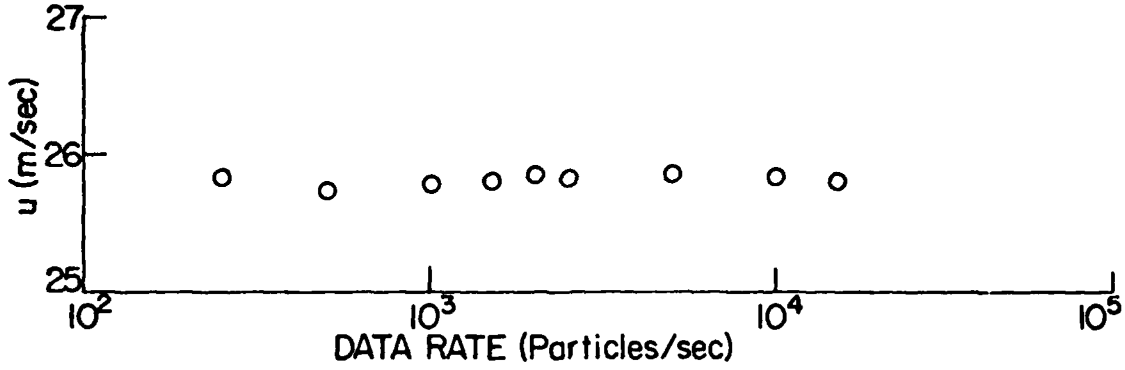


Figure 4. Effect of Data Rate on Mean Velocity at Point A

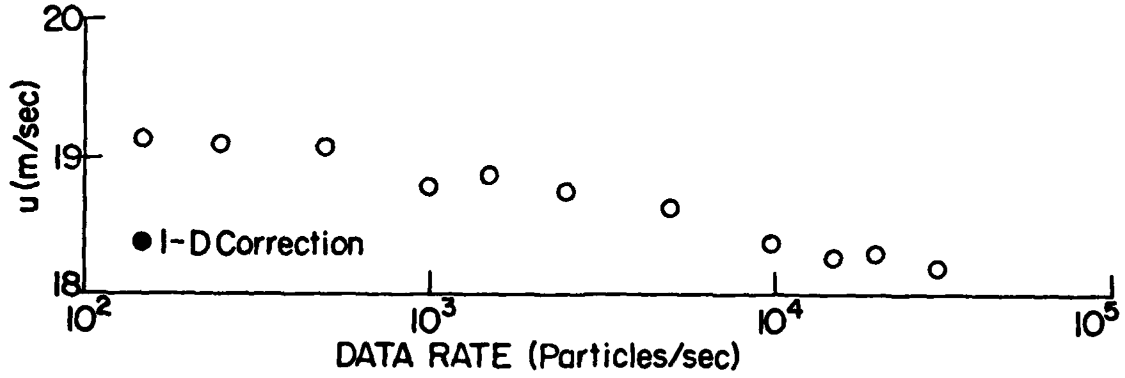


Figure 5. Effect of Data Rate on Mean Velocity at Point B

McLaughlin and Tiederman [5]. At this turbulence level (20%) the correction yields a mean velocity in fairly good agreement with the presumably unbiased value corresponding to the data at the right of the plot.

Figure 6 shows data obtained at measurement point C. Here two different sampling rates were used - 25 and 250 Hz. Little difference is found in the results except near the left end of the plot where the 25 Hz data is somewhat lower. The general behavior is the same as in Fig. 5, indicating a velocity bias. Application of the McLaughlin-Tiederman 1-D correction resulted in a significant over-correction of the data at this turbulence level (35%). This is to be expected because of the known limitations of the 1-D correction.

Each point plotted in Figs. 4-6 represents the average value of approximately 9000 individual velocity samples. The histograms based on the total data sets exhibited the usual near gaussian behavior. The few points outside a $\pm$ 3σ band were discarded before averages were computed. Data for velocities near zero were treated separately when using the 1-D correction, since the correction blows up otherwise. A frequency shift of 10 MHz was employed to allow resolution of negative velocities and signal validation was based on an 8/16 cycle comparison as is common when using a counter type processor. Therefore the data were obtained under conditions typical of LDV measurements in flows of this type. It should be noted that the results presented here are only a sample of a larger body of data obtained during this study, all of which exhibited the same behavior.

Since the measured mean velocity is obviously dependent on particle seeding density and sampling conditions, the amount of velocity bias error in a set of data will not be known in general. By using a heavy seeding density and a low sampling rate it is possible to eliminate data bias as shown here. However, this is often difficult in practice. An attempt was made to see if plotting the data from Fig. 6 in terms of a non-dimensional data rate (particle data rate/sampling rate) produced a universal curve.

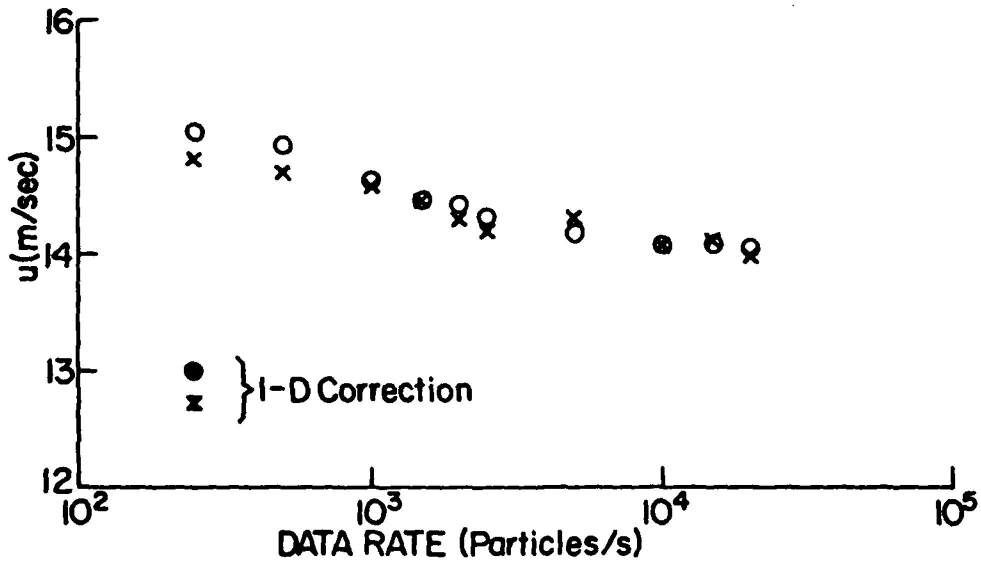


Figure 6. Effect of Data Rate on Mean Velocity at Point C
x = 25 Hz Sampling Rate
o = 250 Hz Sampling Rate

Unfortunately this was not the case, although the curves for the two sampling rates did converge to the unbiased velocity when this non-dimensional parameter exceeded 100. This cannot be used as a general criterion without further study, however.

3. FLOW OVER A BACKWARD FACING STEP

The flow over a two-dimensional backward facing step has been the subject of numerous investigations reported in the literature. In only a few cases have experimental data been compared to analytical results due to the difficulty of modeling the governing equations numerically. A comprehensive experimental and analytical study of such a flow was carried out during the present research program. This flow was chosen for several reasons. It is similar to the flow in an axisymmetric dump combustor geometry but is more tractable for study both analytically and experimentally. Flow conditions range from nearly laminar upstream to turbulent in the shear layer behind the step, with the turbulence intensity varying from low to high values. Also a well defined recirculation layer is present. Thus the step flow provided a good environment for the bias error study and a good test of the LDV system performance in general.

The measurements were carried out in the two-dimensional flow system illustrated in Fig. 7. Channel walls were made of 1/2 in. Plexiglas and air flow was supplied by an 1100 cubic feet/min radial blower. Flow straighteners and screens upstream of the step produced a reasonably uniform velocity profile at the test section inlet with a measured turbulence intensity on the order of one percent. The flow channel was 101.6 mm (4 in.) by 101.6 mm upstream of the step, which was 101.6 mm high. Thus the aspect ratio (ratio of channel width to step height) was unity. A larger aspect ratio would have been desirable to reduce sidewall boundary layer effects, but the channel height was chosen to give a reasonable scale for the shear layer and the width could not be made greater without limiting the scanning range of the LDV system.

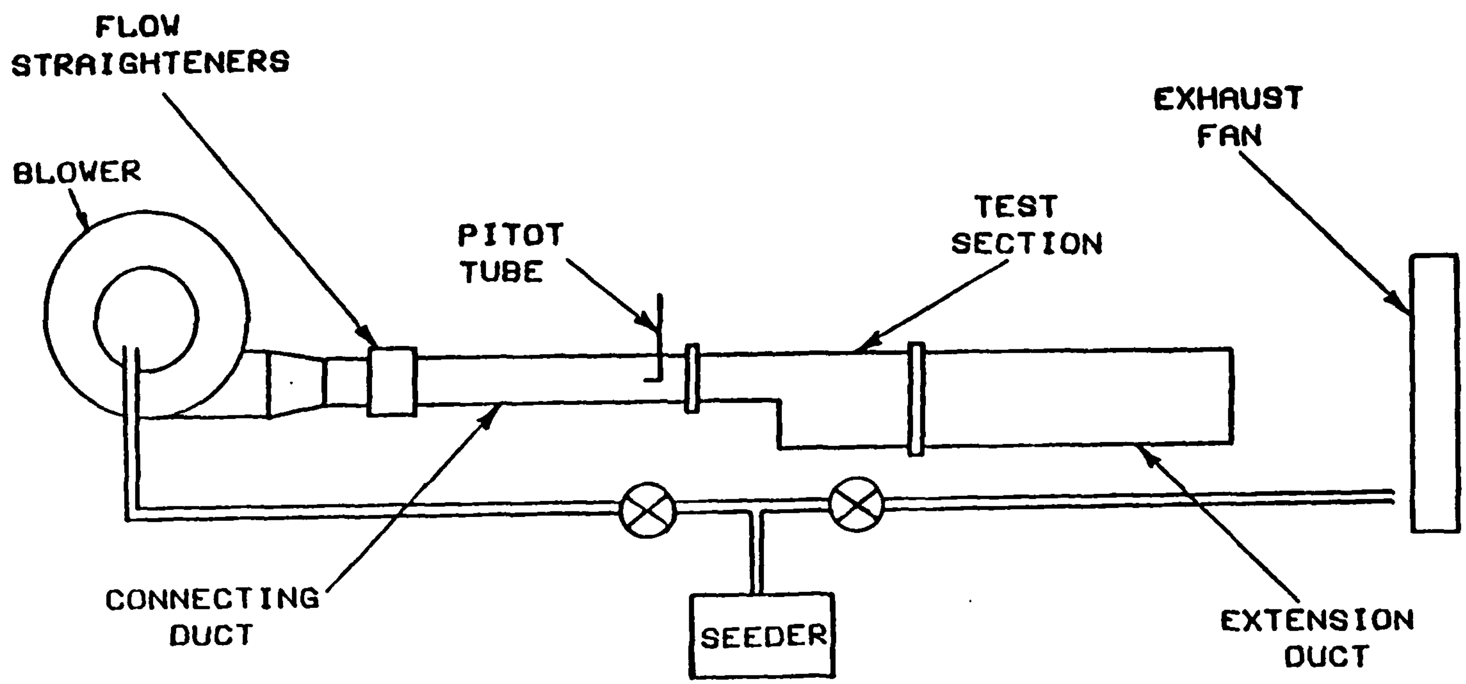


Figure 7. 2-D Flow System

Seeding was achieved by directing the aerosol into the blower inlet. This resulted in a particle data rate of at least 15,000 Doppler bursts per second at all points in the flow including the recirculation zone. Measurements were made on the center plane of the tunnel in a grid pattern consisting of 180 points spaced 0.1 step height vertically (10.1 mm) and 1 step height horizontally beginning at the step. The last vertical row of measurement points was 9 step heights downstream. (Reattachment of the shear layer occurred at about 7 step heights). Additional spanwise measurements were also made upstream and downstream of the step to insure that no abnormal flow behavior existed.

At each grid point 4500 velocity samples were taken at each of three component directions to the horizontal (0° and $\pm$ 30°). Using the method of Logan [8], this allowed computation of $\bar{u}$, $\bar{v}$, $\overline{u'^2}$, $\overline{v'^2}$, $1/2(\overline{u'^2} + \overline{v'^2})$ and $\overline{u'v'}$. In other words the mean velocity components, turbulence intensities, turbulence kinetic energy, and Reynolds stress could be derived from the measurements.

Numerical analysis of the flow was based on the 2-D CHAMPION 2/E/FIX computer code of Pun and Spalding [6], which is based on the k-ε turbulence model of Launder and Spalding [7]. The measured velocity profile and turbulence level upstream of the step were used as inputs to the program. Also, the turbulence model constant C_2 (dissipation rate coefficient) was derived from the measured reattachment length. A complete discussion of the analytical and experimental results is given in [4]. Only a summary of typical findings is presented here.

Figure 8 shows a comparison of measured and computed mean velocity profiles 2 step heights downstream of the step (x/h=2). There is quite good agreement except in the area where reverse flow occurs. It is quite likely that this is due to three-dimensional effects in the base region which have been noted by other investigators. Figure 9 shows a similar comparison at x/h=8 which is beyond reattachment. Here the difference between experiment and analysis is greater, although the two profiles

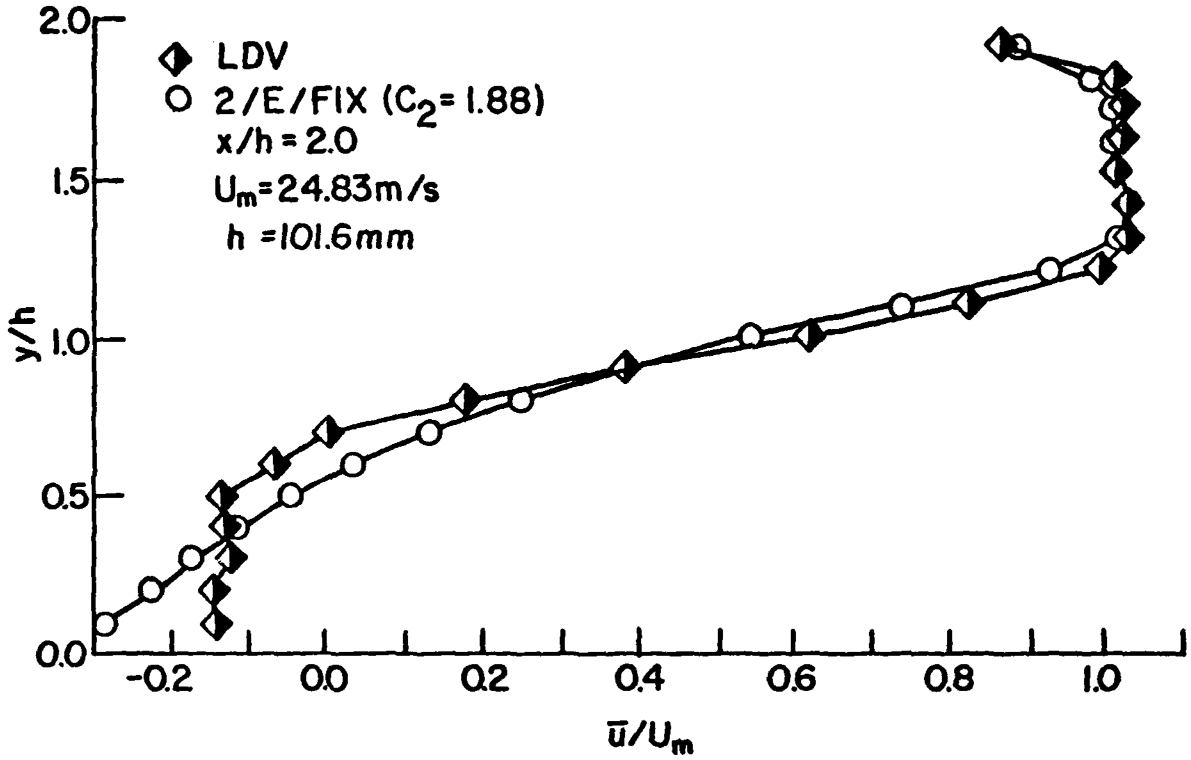


Figure 8. Measured and Computed Mean Velocity Profiles at x/h = 2

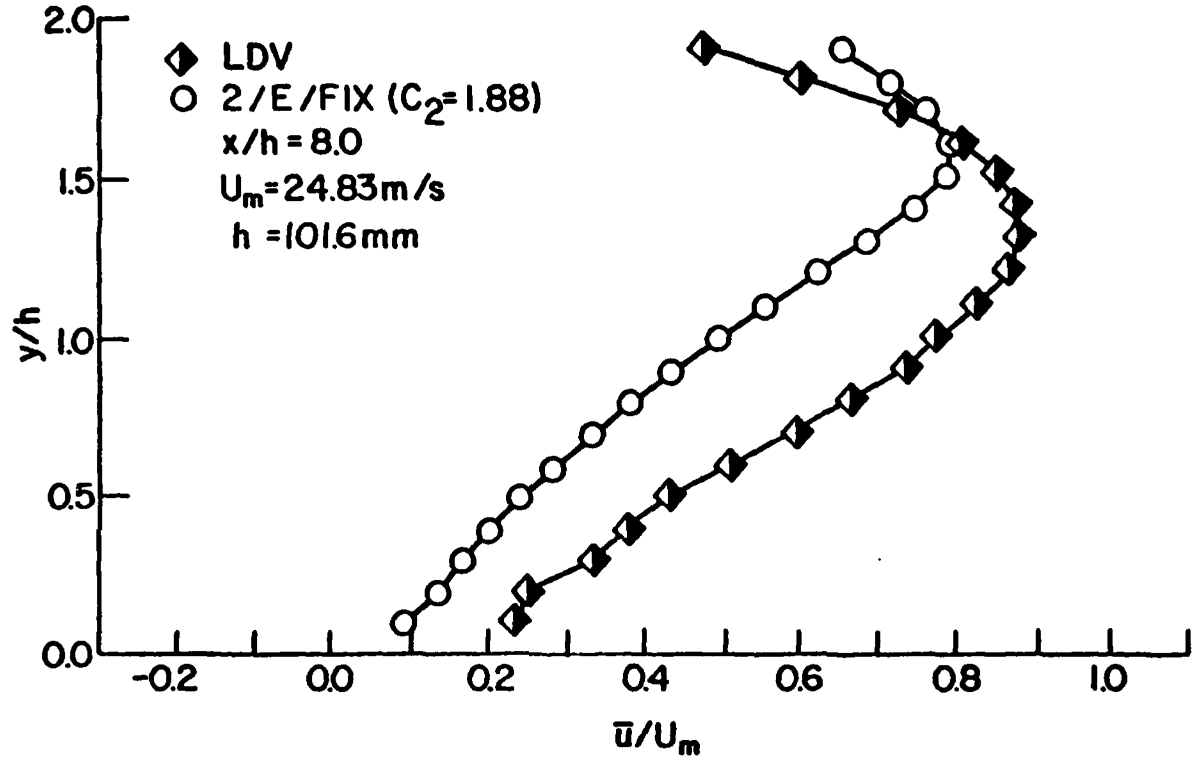


Figure 9. Measured and Computed Mean Velocity Profiles at x/h = 8

exhibit the same general behavior. The difference is attributable at least in part to sidewall boundary layer development.

Figure 10 shows a comparison between calculated and measured turbulence kinetic energy profiles at x/h=4. Again there are differences, although the general trend is similar. The difficulty of obtaining accurate values of $\overline{v'^2}$ from the equations of Logan [8] due to the necessity of subtracting two large numbers of similar magnitude is a factor here as is the strong grid dependence of the computed values.

A check of the dependence of the computed values of mean velocity and turbulence intensity on the spacing between points in the computational grid was made. Matrices of 11x11, 21x21, and 41x41 grid points were selected. (Results presented above were all for a 21x21 grid). It was found that computed mean velocity profiles (both $\bar{u}$ and $\bar{v}$) were relatively insensitive to grid mesh size, but there was a marked effect on turbulence kinetic energy profiles. Results for the three grids were qualitatively similar (except near the step), but differed in magnitude. It appears that a finer mesh is needed for computing turbulence parameters, but the excessive computation time (over one hour for the 41x41 grid) makes this impractical.

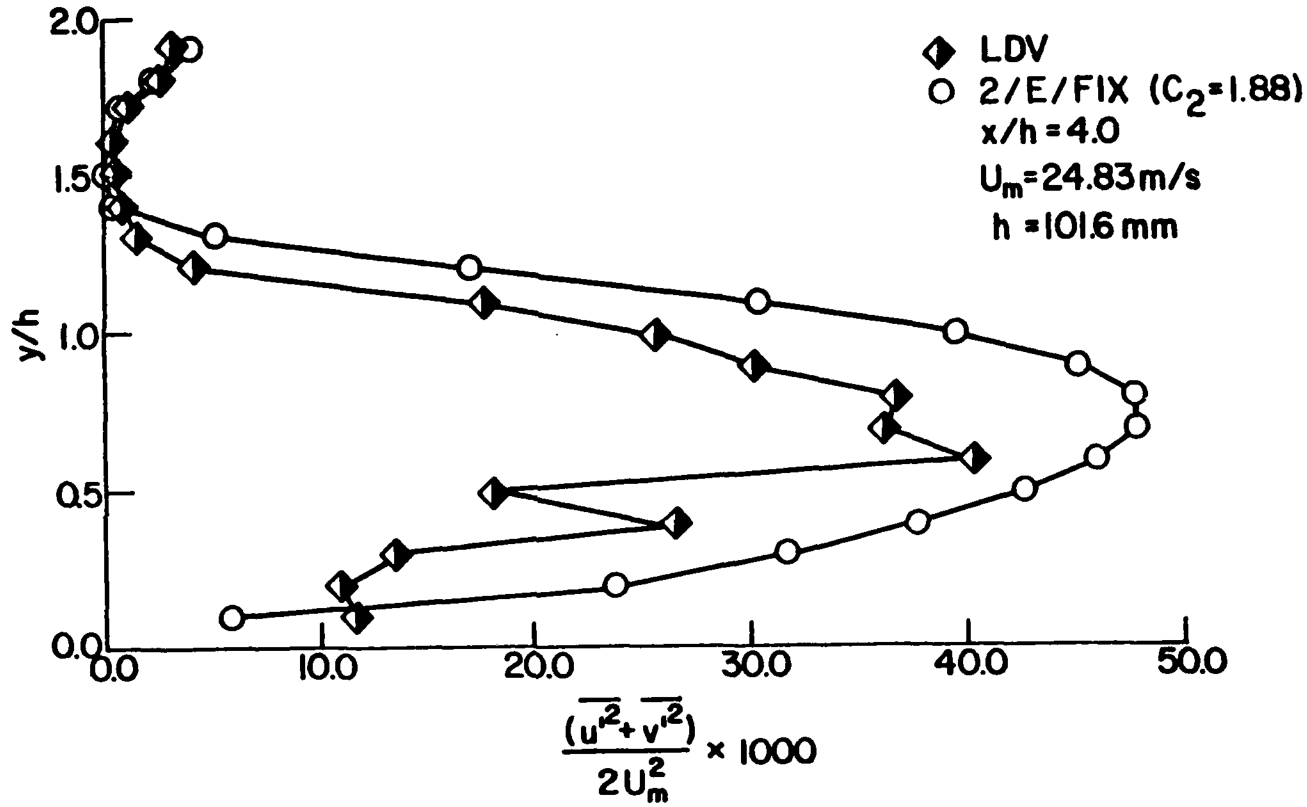


Figure 10. Measured and Computed Turbulence Kinetic Energy Profiles at x/h = 4

SECTION III

FEASIBILITY OF USING FLUORESCENT TRACER PARTICLES IN TURBULENT MIXING STUDIES

1. BACKGROUND

The concept of using fluorescence rather than scattering to provide the optical signal in laser velocimetry was suggested by Stevenson, et al. [9]. If a suitable fluorescent dye is dissolved in the liquid used to produce aerosol seeding particles, a "Doppler" signal equivalent to the normal one obtained with scattered light is observed. An optical filter in front of the photodetector blocks the scattered light at the laser wavelength, but transmits the longer wavelength fluorescence. Thus only signals from the fluorescent particles are detected.

This discriminatory feature of "fluorescence velocimetry" suggests that it might prove useful in studies of flows where mixing occurs. In the case of two concentric jets, for example, one jet could be seeded with fluorescent particles while the other was seeded normally. By using two detectors it would be possible to study the downstream velocity field and follow the development of the mixing process. Many other such examples where this capability would be useful are evident.

2. FEASIBILITY STUDY

In order to study the feasibility of the fluorescence technique, the two-dimensional flow facility described in Section IV was employed. A fluorescent solution of the dye Rhodamine 6G at 10^{-4} molar concentration in a 50-50 mixture of ethylene glycol and benzyl alcohol was used as recommended in [10]. This was atomized with the TSI Model 3076 atomizer. The evaporation-condensation generator could not be employed to produce a final monodisperse aerosol, since the dye deposited on the walls of the unit during the evaporation process and was therefore not present in the final aerosol. As a result the size distribution of the seeding particles was broader than desirable. Nevertheless it was hoped that the general concept could be investigated.

The original idea was to introduce the aerosol upstream of the backward facing step through a small tube parallel to the flow. By changing the location of the probe and making velocity scans downstream it would be possible to observe the turbulent mixing process as it developed. It was also hoped that some insight into the apparent three-dimensional nature of the flow in the recirculation region could be gained.

Unfortunately the experiment was not successful. The aerosol injection tube (I.D. = 0.06 in.) tended to produce large droplets rather than a fine aerosol. This was apparently due to one of three possible effects: (1) the backpressure imposed by the injection tube affected atomizer performance, leading to large droplets which clogged the tube, (2) the rapid expansion at the mouth of the injection tube caused the aerosol to condense out in the form of large droplets, or (3) the flow constriction at the injection tube caused coagulation of the aerosol. The line leading to the injection tube was heated to see if this would alleviate the problem, but there was no apparent change in performance.

It is possible that the rather broad size distribution in the initial output from the atomizer was the basic source of the problem. However, there was no convenient way of correcting this. It would have been possible to use a larger injection tube, but this would have affected the upstream flow significantly and made the results difficult to evaluate. Since the fluorescence method investigation was not a primary thrust of the research program, the experiment was abandoned. It should be continued in a later study if a means of producing an aerosol with all droplets below 1 μm can be developed.

SECTION IV

MEASUREMENTS IN THE AXISYMMETRIC TUNNEL

1. BACKGROUND AND EXPERIMENTAL PROCEDURE

The final aspect of this research program involved a limited set of LDV measurements in an axisymmetric dump combustor model. This Plexiglas model was based on an identical system at AFWAL and consisted of a cylindrical inlet section followed by a converging nozzle which entered a cylindrical downstream section (see Fig. 11).

Except for the difference in geometry the flow system was identical to that used for the 2-D backward facing step study described in Section II. Measurements in cylindrical tubes are typically somewhat more difficult than in flat walled test sections due to optical aberration effects which degrade Doppler signal quality. In order to minimize such problems, measurements were limited to points lying along the transverse diameter of the tube at several locations downstream of the throat. Doppler signals of good quality were obtained in all cases and the particle data rate was generally close to that observed in the 2-D study (20,00 per second). One exception was in the recirculation zone, where the data rate was much lower. This was not the case in the 2-D study. It is possible that the 3-D flow in the recirculation zone behind the step as noted in Section II was responsible for feeding seeding particles into the zone in that case, whereas such a flow was absent in the axisymmetric geometry.

Based on the results of the biasing study, all data were taken with a high particle data rate and a low data sampling rate so that equal time interval sampling could be approached. A sample set of 4500 data points was collected at each measurement condition. As explained previously, measurements were made at 0° and $\pm 30^{\circ}$ to the horizontal axis at each location. The reference velocity at the center of the nozzle exit was 25.65 m/sec based on pitot tube measurements. LDV measurements could not be made in the nozzle exit plane due to the finite beam angle.

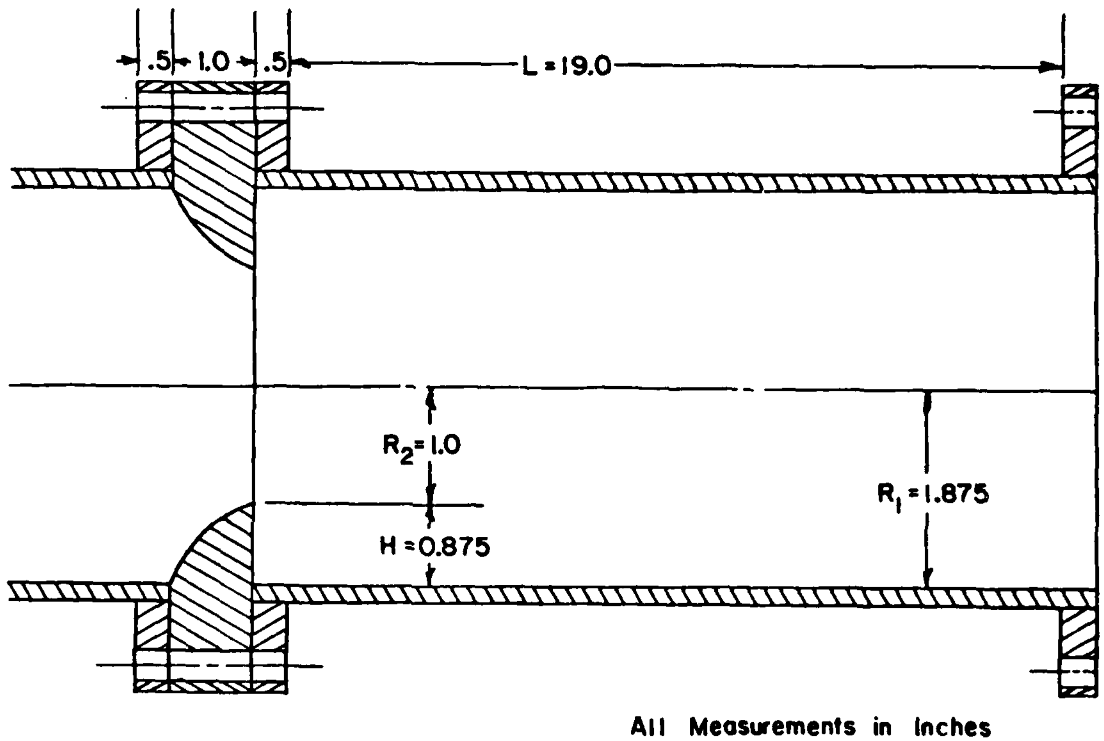


Figure 11. Geometry of Axisymmetric Test Section

2. EXPERIMENTAL RESULTS

Figure 12 shows the transverse axial velocity profiles obtained at four downstream axial positions. The behavior is as expected, with reattachment occuring near $x/R_2=7$ ($x/H=8$). No significant deviations from symmetry were observed when selected points were checked on both sides of the tube centerline. Figure 13 shows the decay of the mean velocity at the centerline. The corresponding local turbulence intensity is shown in Fig. 14. The peak near $x/R_2=13$ had also been observed in earlier measurements made at AFWAL.

Figures 15 and 16 illustrate the measured axial and tangential turbulence intensities. Again the results are reasonable, with the large excursion evident in the tangential case being due to the difficulty of accurately determining $\overline{v_\theta'^2}$ by the technique of Logan. Figure 17 shows the Reynolds stress profiles. Again accuracy is a problem, but the general behavior is as expected. The same comment applies to the kinetic energy profiles in Fig. 18.

Consistency in the measured axial velocity profiles was checked by integrating them to obtain the mass flux profiles of Fig. 19. The velocity profiles were curve fitted using a second degree polynomial fit to the data and piecewise integration was performed using four point gaussian quadrature. If the nozzle exit velocity is constant with value U_o, all mass flux profiles should approach a value of 1.0 at the tube wall. Actual results ranged from 0.9 to 1.0. This discrepancy is within the limits of experimental and computational error. Measurements could only be made to within 7 mm of the wall which did not allow an accurate mapping of the thin boundary layer at the larger x/R_2 values.

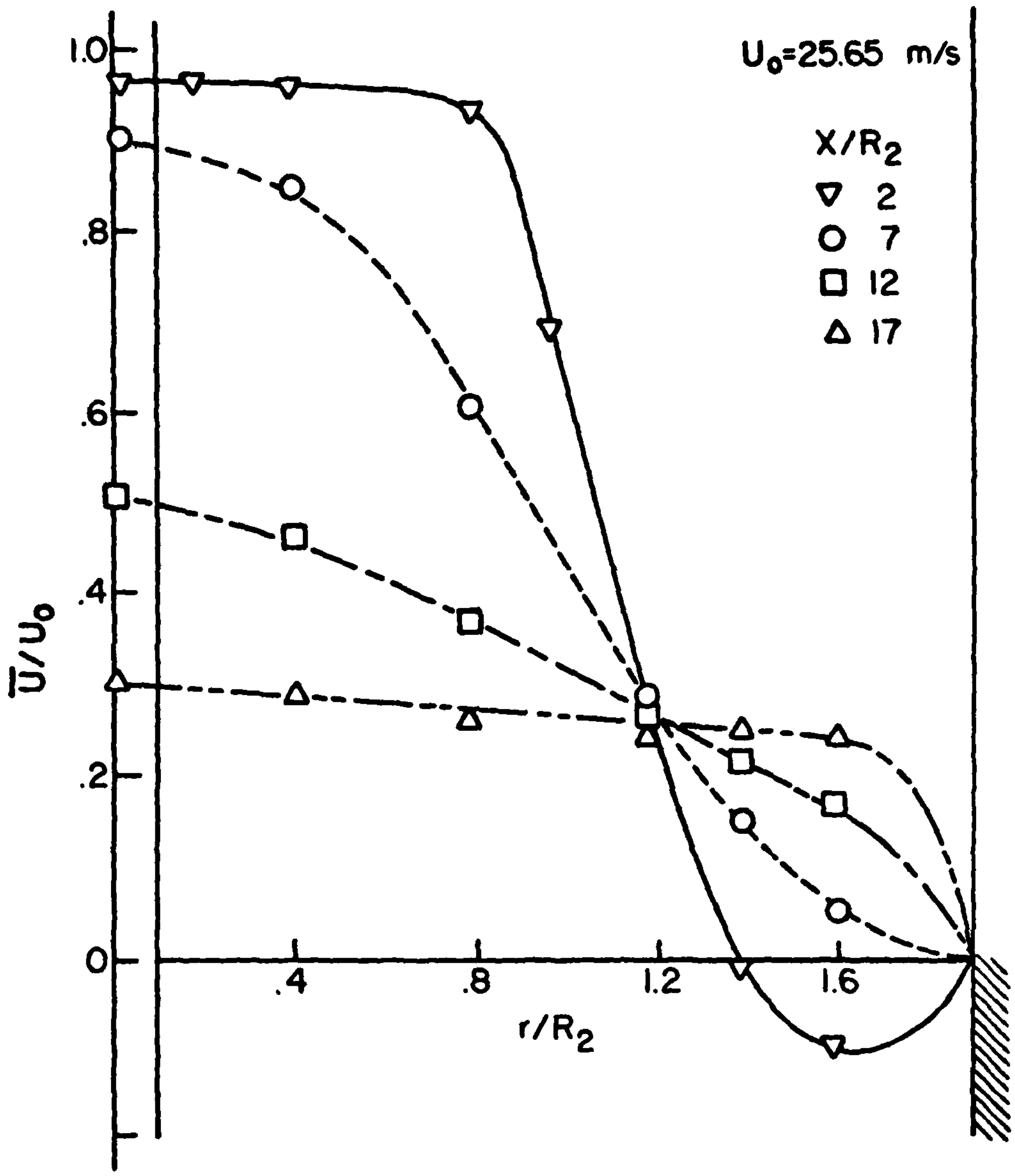


Figure 12. Axial Velocity Profiles

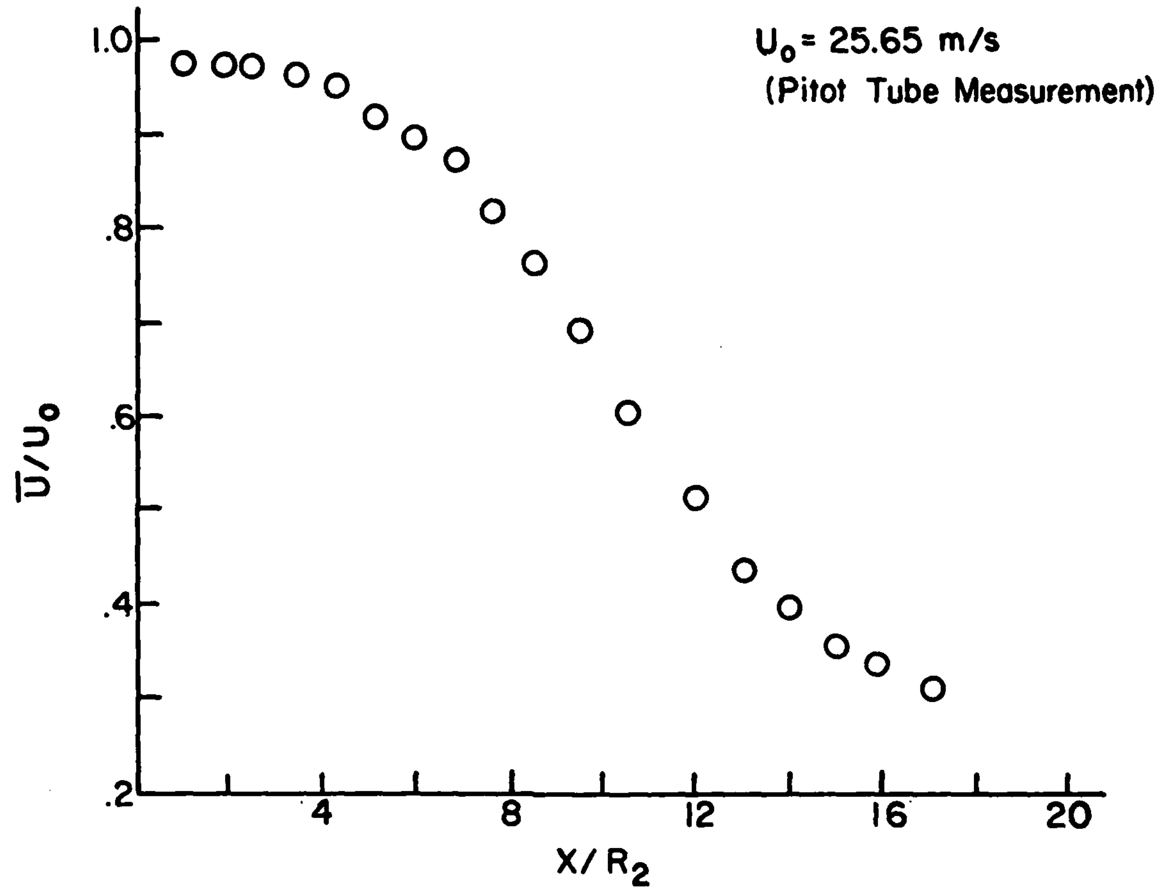


Figure 13. Decay of Centerline Velocity

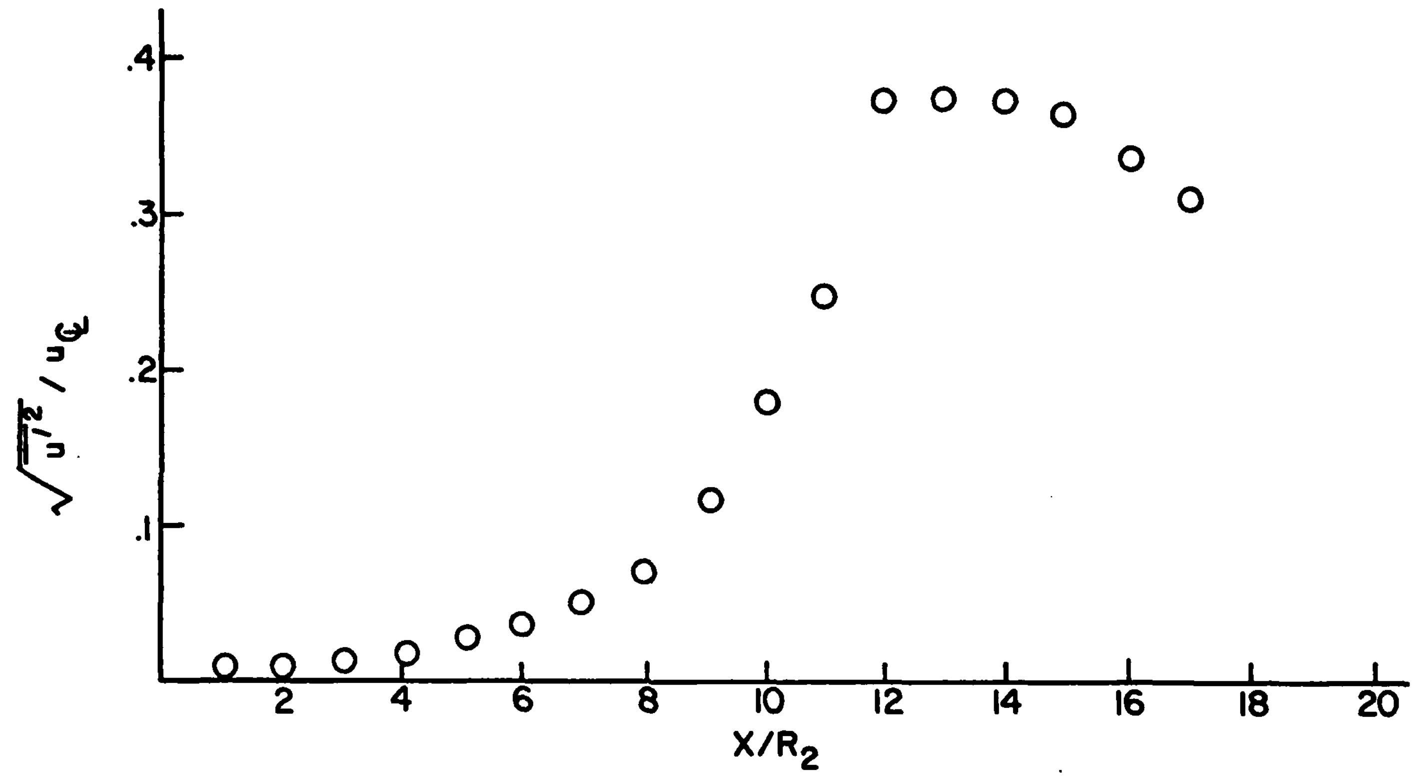


Figure 14. Centerline Turbulence Intensity - Axial Component

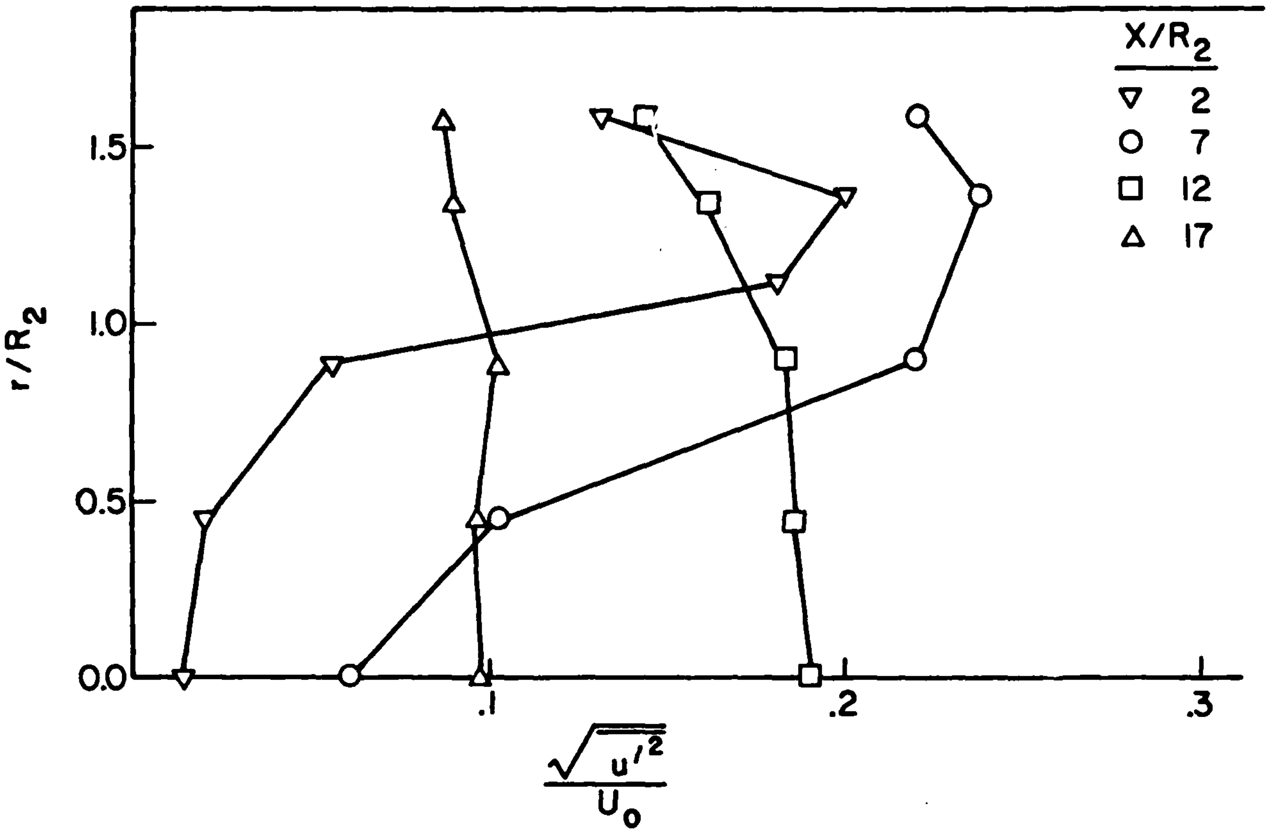
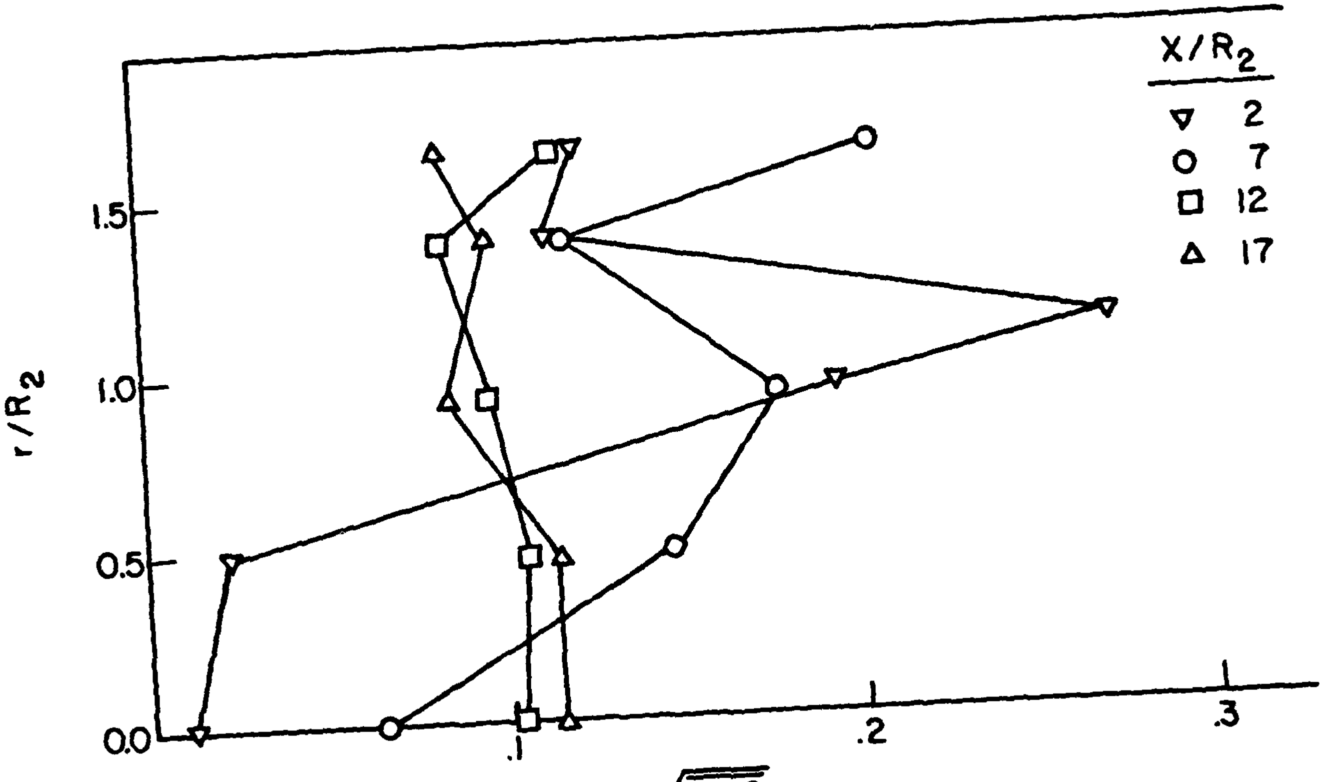


Figure 15. Turbulence Intensity Profiles - Axial Component



$$\frac{\sqrt{\overline{v_\theta'^2}}}{U_0}$$

Figure 16. Turbulence Intensity Profiles - Tangential Component

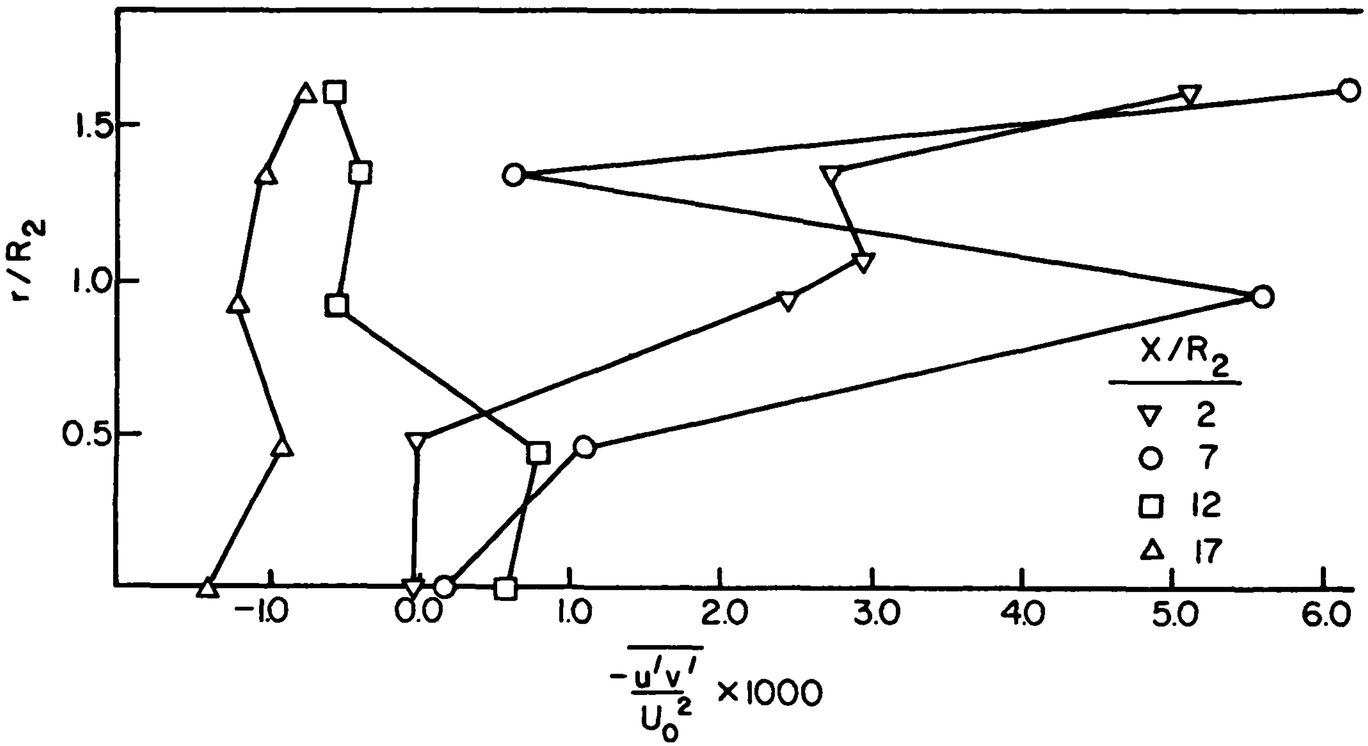


Figure 17. Reynolds Stress Profiles

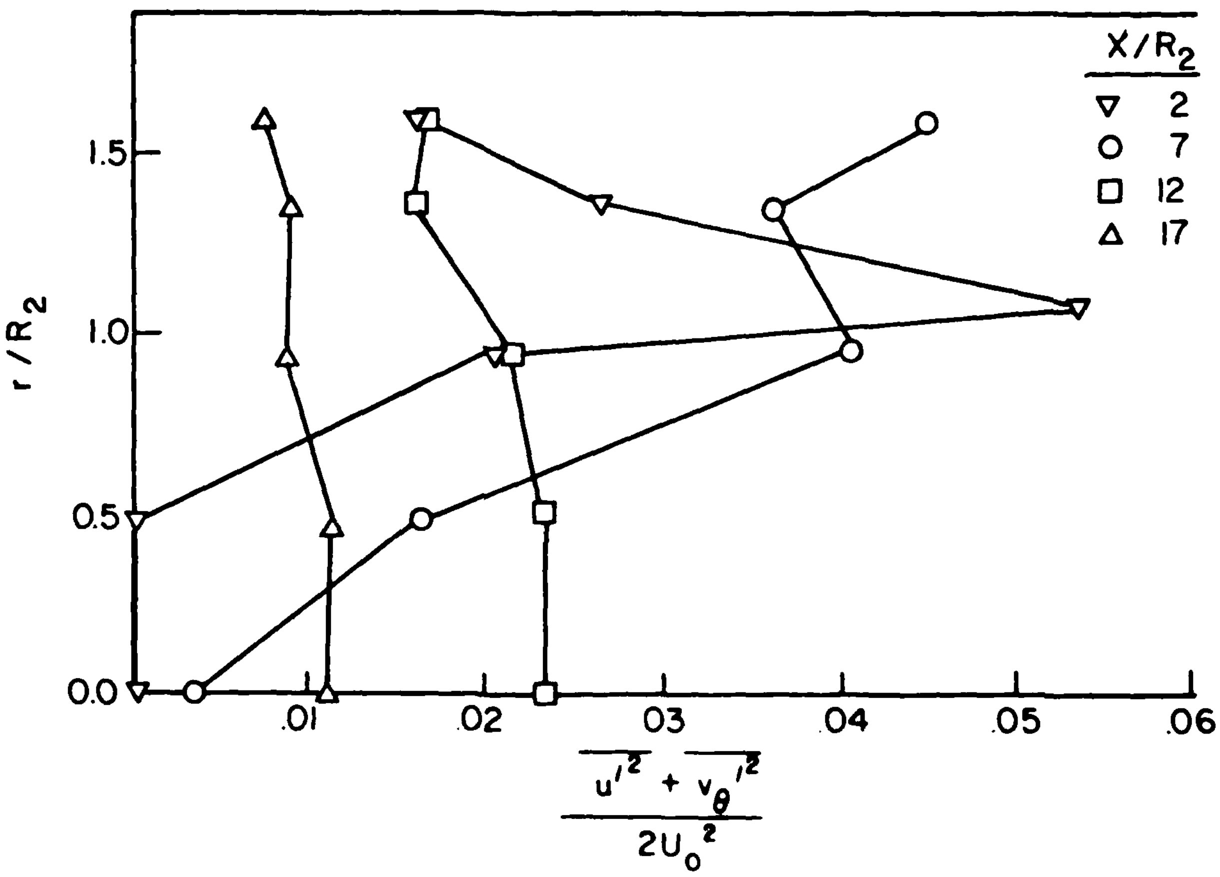


Figure 18. Turbulence Kinet[illegible] Ener[illegible] [illegible]

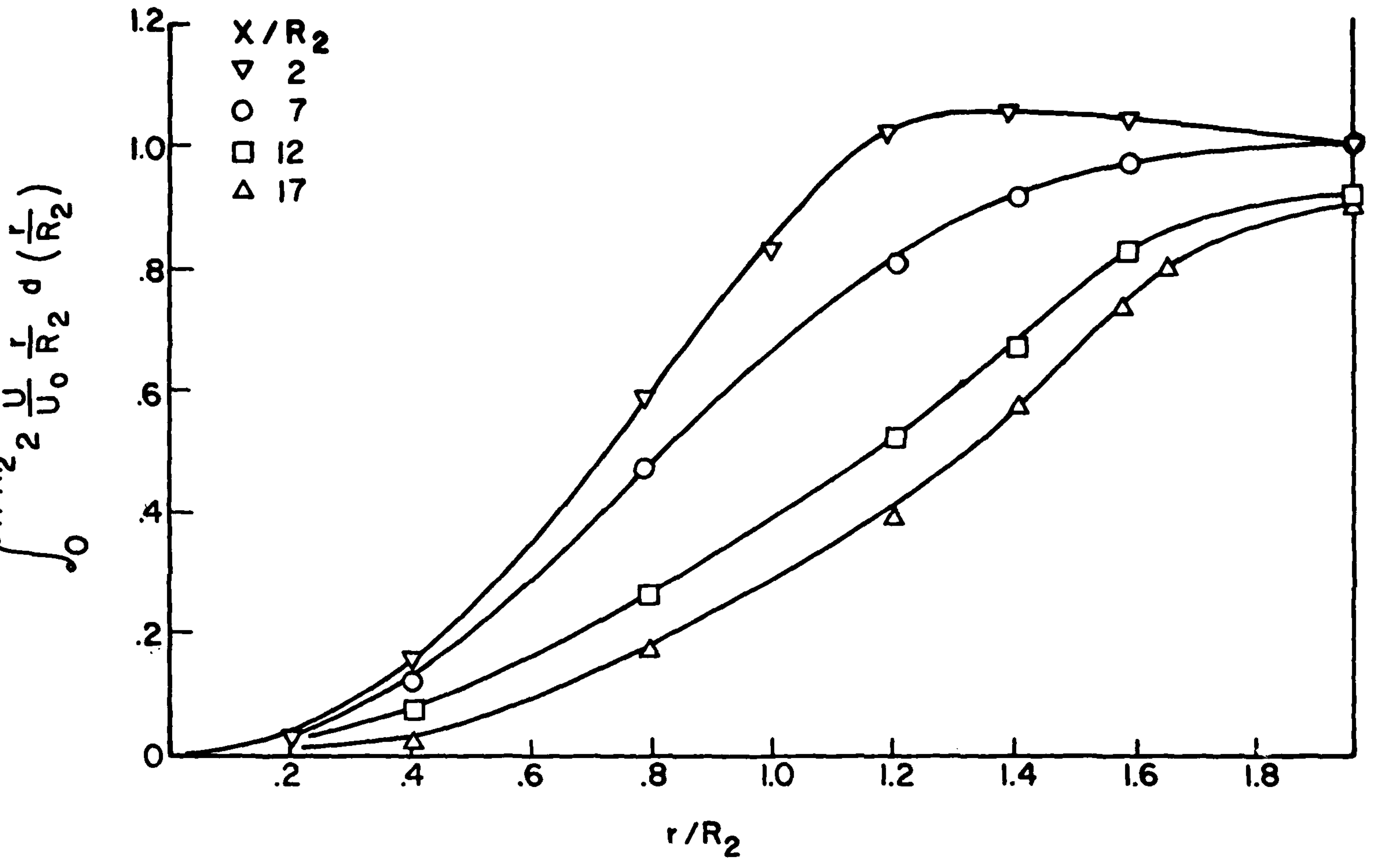


Figure 19. Integrated Mass Flux Profiles

SECTION V
CONCLUSIONS AND RECOMMENDATIONS

The LDV system designed for the study of bias errors and measurements in step flows has performed satisfactorily in all respects. The existence of velocity bias errors has been confirmed and an experimental method, based on a high seeding density and low sample rate, has proved effective in eliminating such errors in turbulent flow measurements. Detailed measurements of mean velocity profiles and turbulence parameters in both 2-D and 3-D step flow have been made with a one-dimensional LDV using the three component method of Logan. Although significant errors can occur in the derived parameters in which v' appears, the general results appear reasonable. Comparisons between measured mean axial velocities in the 2-D flow and numerical predictions based on the 2/E/FIX computer code are in relatively close agreement, with the difference at least partially attributable to 3-D effects in the recirculation zone which are not accounted for in the computer program. However, the 2/E/FIX code exhibited a sizable grid dependence with respect to computed turbulence quantities.

Several recommendations for future work can be made. Further study of the velocity bias problem should be carried out in an attempt to develop general analytical and/or experimental techniques for eliminating bias errors which are not dependent on a high seeding density. This is important, since in many cases of practical interest it is impossible to maintain the high seeding densities achieved here. Additional measurements in the axisymmetric model should be made, including radial velocity components. This will require a means of correcting for the serious optical aberration effects which exist when the LDV optical axis is not coincident with the tube diameter. It would be desirable to convert the LDV system to two-component operation so that the difficulties which occur when Logan's method of deriving turbulence quantities is used can be avoided. This would also allow a more reliable means of evaluating the performance of the 2/E/FIX code.

REFERENCES

1. Stevenson, W.H. and Thompson, H.D., "Laser Velocimeter Measurements in Turbulent and Mixing Flows," AFAPL-TR-79-2009, March 1979.

2. Stevenson, W.H., Thompson, H.D., Bremmer, R., and Roesler, T., "Laser Velocimeter Measurements in Turbulent and Mixing Flows - Part II," AFAPL-TR-2009, Part II, March 1980.

3. Roesler, T., Stevenson, W.H., and Thompson, H.D., "Investigation of Bias Errors in Laser Doppler Velocimeter Measurements," AFWAL-TR-80-2105, December 1980.

4. Bremmer, R., Thompson, H.D., and Stevenson, W.H., "An Experimental and Numerical Comparison of Turbulent Flow Over a Step," AFWAL-TR-80-2108, December 1980.

5. McLaughlin, D. and Tiederman, W., "Biasing Correction for Individual Realization of Laser Anemometer Measurements in Turbulent Flows", Physics of Fluids, 16, 2082 (1973).

6. Pun, W.M. and Spalding, D.B., "A General Computer Program for Two-Dimensional Elliptic Flows,: Imperial College Mechanical Engineering Department Report No. HTS/76/2 (1976).

7. Launder, B.E. and Spalding, D.B., "The Numerical Computation of Turbulent Flows," Computer Methods in Applied Mechanics and Engineering, 3, 269 (1974).

8. Logan, S.E., "A Laser Velocimeter for Reynolds Stress and Other Turbulence Measurements," AIAA Journal, 10, 933 (1972).

9. Stevenson, W.H., Santos, R., and Mettler, S.C., "A Laser Velocimeter Utilizing Laser Induced Fluorescence," Applied Physics Letters, 27, 395 (1975).

10. Stevenson, W.H., Santos, R., and Mettler, S.C., "Fringe Mode Fluorescence Velocimetry," AGARD Conference Proceedings No. 193 (1976).

END
DATE
FILMED
11-81
DTIC