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AFWAL-TR-82-2076 Part IV



LASER VELOCIMETER MEASUREMENTS AND ANALYSIS IN TURBULENT FLOWS WITH COMBUSTION

Part IV - Two-Component Cold-Flow Measurements

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Final Report for Period January 1981 - October 1984

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

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FOR THE COMMANDER

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streamwise and radial velocity and turbulence intensity measurements were made. Reynolds stresses were computed. The work previously reported in Parts I, II, and III of this report is briefly reviewed.

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# FOREWORD

This final technical report was submitted by the School of Mechanical Engineering of Purdue University under Contract No. F33615-81-K-2003 and covers the period 1 January 1981 - 2 October 1984. The research was sponsored by the Aero Propulsion Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson AFB, Ohio, under Project No. 2308 with Dr. Roger R. Craig AFWAL/PORT as Project Engineer. Warren H. Stevenson and H. Doyle Thompson of Purdue University were technically responsible for the work.





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## SECTION I

# INTRODUCTION

This is the final report on Air Force Contract No. F33615-81-K-2003, Project No. 2308 for the experimental and analytical study entitled, "Laser Velocimeter Measurements and Analysis in Turbulent Flows with Combustion." References 1 thru 13 are a direct result of the research. Additional work on the design, construction and preliminary measurements from a two component LDV system are reported in Section III of this report. The research is an extension of a previous Air Force contract, No. F33615-77-C-2010, Project No. 2308.

The major results of this research are briefly summarized in Section II.

#### SECTION II

## SUMMARY OF MAJOR RESULTS

#### 1. STUDENT SUPPORT AND THESES:

Three MSME theses were completed with support from this contract. They are listed here and as References 1-3.

- Luchik, Thomas Stephen, "A Laser Velocimeter Investigation of Turbulent Flow in an Axisymmetric Sudden Expansion," MSME Thesis, Purdue University, May 1982.
- 2. Gould, R.D., "Laser Velocimeter Measurements in an Axisymmetric Sudden Expansion With and Without Combustion," MSME Thesis, Purdue University, May 1983.
- 3. Durrett, Russell P., "Laser Velocimeter Measurements in an Axisymmetric Sudden Expansion with a Correction for Tube Wall Aberrations," MSME Thesis, Purdue University, May 1984.

In addition, the Ph.D. work of R.D. Gould, now in progress, was partially supported from this contract.

# 2. REPORTS AND PUBLICATIONS

In addition to the three MSME theses listed above the following ten reports and publications are a direct result of the contract. References 4, 5 and 6 are the interim annual reports for the contract and References 7 thru 13 are conference papers and journal articles that have resulted from the research work. 4. Stevenson, W.H., Thompson, H.D. and Luchik, T.S., "Laser Velocimeter Measurements and Analysis in Turbulent Flows with Combustion," AFWAL-TR-82-2076, Part 1, September 1982.

STATES STATES

- 5. Stevenson, W.H., Thompson, H.D. and Gould, R.D., "Laser Velocimeter Measurements and Analysis in Turbulent Flows with Combustion," AFWAL-TR-82-2076, Part II, July 1983.
- 6. Thompson, H.D., Stevenson, W.H. and Durrett, R.P., "Laser Velocimeter Measurements and Analysis in Turbulent Flows with Combustion, Part III - A Correction Lens for Laser Doppler Measurements in a Cylindrical Tube," AFWAL-TR-82-2076, Part III, July 1984.
- 7. Stevenson, W.H., Thompson, H.D., Gould, R.D. and Craig, R.R., "Laser Velocimeter Measurements in Separated Flow with Combustion," Proceedings of the International Symposium on Applications of Laser Doppler Anemometry to Fluid Mechanics, Lisbon, Portugal, July 5-7 (1982). Also published in <u>Laser</u> <u>Anemometry in Fluid Mechanics</u>, LADOAN, Lisbon 1984 (eds. R. Adrian, D. Durao, F. Durst, H. Mishina and J. Whitelaw).
- 8. Stevenson, W.H., Thompson, H.D. and Craig, R.R., "Laser Velocimeter Measurements in Highly Turbulent Recirculating Flows," <u>Proceedings of the Symposium on Engineering Applica-</u> <u>tions of Laser Velocimetry</u>, pp. 163-170, ASME Winter Annual Meeting, Phoenix, AZ, November 1982.
- 9. Gould, R.D., Stevenson, W.H. and Thompson, H.D., "Laser

Velocimeter Measurements in a Dump Combustor," ASME Paper 83-HT-47 National Heat Transfer Conference, Seattle, WA, July 1983.

- 10. Durrett, R.P., Gould, R.D., Stevenson, W.H. and Thompson, H.D., "A Correction Lens for Laser Doppler Velocimeter Measurements in a Cylindrical Tube," AIAA Paper No. 84-0429, 1984.
- 11. Stevenson, W.H., Thompson, H.D. and Craig, R.R., "Laser Velocimeter Measurements in Highly Turbulent Recirculating Flows," <u>Journal of Fluids Engineering</u> <u>106</u>, pp. 173-180 (1984).
- 12. Durrett, R.P., Gould, R.D., Stevenson, W.H. and Thompson, H.D., "A Correction Lens for Laser Doppler Velocimeter Measurements in a Circular Tube," <u>AIAA Journal</u> 23, pp. 1387-1391 (1985).
- 13. Durrett, R.P., Stevenson, W.H. and Thompson, H.D., "Radial and Axial Turbulent Flow Measurements with an LDV in an Axisymmetric Sudden Expansion Air Flow," to be published, ASME Winter Annual Meeting, Nov. 17-22, 1985.

#### 3. MAJOR ACCOMPLISHMENTS

The objective of this research has been to provide an increased understanding of the turbulent flow field in a dump combustor. The program has been primarily experimental, with some analytical modeling and comparison. It is an extension of previous work documented in References 14 thru 24. The following have been accomplished:

- A survey and analysis of the related literature. See References 1 thru 13.
- 2. The identification of bias errors that arise in LDV measurements and the development of measurement techniques to eliminate those bias errors. See References 17, 20 and 23. The identification of and elimination of bias errors has been a matter of continuing concern throughout both this and the previous research contracts. Major advances have been made. There remain some experimental situations for which it is neither possible to apply the bias elimination procedures that have been developed, nor to accurately compensate for bias errors in the data. Further work should be done in this area.
- 3. The development of a unique single-component LDV system, with variable beam angle and dual Bragg cell frequency shifters. The system could be rotated around the beam axis, permitting independent velocity component measurements at any desired angle in the plane perpendicular to the laser beam axis. See References 1 and 4.
- 4. The systematic determination of  $\overline{U}$ ,  $\overline{U}_{\phi}$ ,  $\overline{u^2}$ ,  $\overline{u_{\phi}^2}$  and  $\overline{u}$   $u_{\phi}$  in an axisymmetric sudden expansion. Measurements were made throughout the recirculation region, the reattachment region, and in the recovery region. Logan's method (Ref.

25) was used to extract the desired velocity, turbulence and shear stress values from the individual measurements. Measured results were compared to computations. See Reference 1 and 4.

- 5. Measurements of  $\overline{U}$  and  $\overline{U'}^2$  in the recirculating and reattachment region of a combusting flow. The hot-flow results are compared to biased and unbiased cold-flow data and to computations. See References 2, 4, 7, and 9.
- 6. The modification of the CHAMPION/2/E/FIX Computer program to handle reacting flow with the step geometry used herein. The treatment of the boundary conditions required considerable modification. An extensive parametric study was conducted. This work was supported in part by NASA. See References 5 and 26.
- 7. The development of a correction lens system to correct for probe volume abberations caused by the circular tube wall. The correction lens prevents the probe volume from wandering when the LDV optics are rotated, and allows the LDV system to be used to traverse the flow field vertically. This in turn permits the measurement of the radial velocity component and also allows simultaneous radial and axial component measurements to be made with a 2-D LDV system. See References 3, 6, 10, and 12.
- 8. The compilation of benchmark cold-flow measurements just downstream of the sudden expansion, and in the recirculation

zone. The correction lens was used for these measurements and care was taken to eliminate bias errors. Measurements were made to determine  $\overline{U}$ ,  $\overline{U}_r$ ,  $\overline{u^2}$ ,  $\overline{u_r^2}$  and  $\overline{u^2}_r$ . See Reference 13.

9. The development, design, and construction of a two-component LDV system with improved data recording and storage capabilities. Limited preliminary measurements in a cold-flow rig have been made. The system design and preliminary data are described in Section III of this report.

# Section III

#### THE TWO COMPONENT SYSTEM

This section describes the two-component LDV system and presents some preliminary experimental data obtained in a coldflow sudden expansion geometry.

## 1. THE LDV SYSTEM

A two-color, two-component LDV system operating in forward scatter has been developed. The initial application is simultaneous measurements of the axial and radial velocity components in an axisymmetric sudden expansion flow with and without combus-The LDV system includes Bragg cell modulators in the four tion. beam paths of the argon-ion laser to allow a net frequency shift of 5 MHz in both the green and blue beams. This permits an unambiguous measurement of negative velocities and also eliminates incomplete signal bias. The green beam optical probe volume has a waist diameter of 0.200 mm and is approximately 2 mm long. The blue beam has a probe volume waist of 0.250 mm and is approximately 1 mm long. The scattered light from the probe volume is separated using a dichroic filter so that approximately 80% of each color passes to its respective photomultiplier tube. Narrow bandpass filters are used to further filter unwanted signals before they are detected. A'schematic diagram of the LDV system is shown in Figure 1.

The flow without combustion is seeded with oil particles (DOP) approximately 1  $\mu$ m in diameter generated from a liquid



Figure 1. Two-Component LDV System.

atomizer followed by an evaporization-condensation unit. The flow with combustion will be seeded with 1  $\mu$ m diameter aluminum oxide particles generated from a TSI model 3400 fluidized bed generator or from a home-built cyclone- type seeder, depending upon which seeder gives the best results. No testing has been performed using aluminum oxide seed particles to date. From some preliminary testing using this LDV system (with seed particles generated from the liquid atomizer) maximum data validation rates were found to be approximately 15,000 and 5,000 samples per second for the green (axial) and blue (radial) components, respectively. >From preliminary tests, it appears that maximum "coincident" data ready rates range between 1000 and 2000 per second. For this case, biased velocity data results as will be shown later.

In an effort to obtain accurate unbiased velocity data two approaches will be investigated. The first approach will involve minor LDV system modifications with the goal of improving the blue beam signal quality and therefore increasing the blue beam data validation rate to > 10,000 samples per second. If this can be accomplished the experimental technique for eliminating velocity bias by inhibiting the counter processors for a fixed time interval between samples, approximating equal time sampling, will be used [8,9,20,24,27,28].

If the signal quality of the blue beam cannot be improved, an attempt will be made to develop a velocity bias correction scheme. The second approach involves validating two proposed

velocity bias correction schemes. The two correction schemes of interest are the McLaughlin-Tiederman 2-D weighting correction [29,30] and the Barnett and Bentley time between data correction [31]. The two-component "corrected" data will then be compared to independent unbiased one-component data obtained using the interval sampling technique to validate and modify each correction scheme.

The data collection and processing system consists of two TSI model 1990 counter-type processors (one for each channel), a TSI model 1998 interface with coincidence timing electronics and a PDP 11/40 mini-computer with DMA capability. A digitized thermocouple signal will also be interfaced through the TSI 1998 interface so that coincident velocity-temperature data can be obtained (Figure 2). With this system it is possible to acquire velocity data from individual doppler burst signals at rates up to 50,000 samples per second (limited by seed density). The mini-computer and counter processors are also interfaced so that sampling can be controlled. This is accomplished with a hardware clock controlling the data-inhibit handshaking signals. The software developed for this experiment is capable of burst (measurement sampled and stored as soon as it is validated) or interval sampling. It can also access the extended memory in the PDP 11/40 allowing up to 96K words of data to be stored for each sample.

The data reduction program calculates three types of statistics for each sample. These include the standard statistic, the



and manage, paralle analysis

Figure 2. Data Acquisition System.

McLaughlin-Tiederman 2-D weighted statistic and the time between data weighted statistic. Data points lying outside  $\pm 3 \sigma$  (selectable) are discarded and revised statistics are calculated. Histograms are constructed for both velocity components on the terminal and can be routed to the line printer for hard copies. The data can also be stored on the hard disk.

# 2. THE TEST RIG

The flow system utilized in this experiment is illustrated in Figure 3. Air is provided by a radial fan blower followed by a flow conditioning section consisting of honeycomb flow Fuel (gaseous propane) will be injected in the straighteners. duct immediately following the blower through a multi-port manifold to give a homogeneous fuel-air mixture. The test section consists of a converging inlet nozzle with an exit diameter of 76.2 mm followed by a 152.4 mm diameter downstream section. This inlet was chosen to give a uniform inlet velocity profile. The static pressure drop across the nozzle is used to monitor the inlet flow condition. The test section was extruded from optical quality fused quartz and allows measurements throughout the flowfield for x/h values ranging from 0.3 to 14. The test section design is shown in Figure 4.

# 3. CORRECTION LENS

A correction lens to allow simultaneous axial and radial velocity measurements in a cylindrical tube has been designed and fabricated using the procedure described in Reference 12. The



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Figure 4. Test Section.

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planar-concave cylindrical lens that corrects for the aberration induced by the quartz test section has a radius of curvature of 3.3528 m, a thickness at its center of 17.93 mm and a refractive index of 1.52. The correction lens insures that the orthogonal probe volumes (green and blue) intersect to within 100  $\mu$ m along the length of the probe volume and to within 25  $\mu$ m along the diameter of the probe volume. This forces the scattered light from the different colored probe volumes to come from approximately the same point. The correction lens system is comprised of two lenses, one on the transmitting side and one on the receiving side of the test section as shown in Figure 5. This is due to the symmetry of the system. The lenses have to be moved away from the test section as the measurement point moves further off axis. A ray tracing program is used to determine the placement of the lenses and also gives the real probe volume intersection relative to the beam intersection if no test section or lens was present. Simultaneous axial-radial velocity measurements can be made out to a non-dimensional radius of approximately 85% with this system.

# 4. PRELIMINARY EXPERIMENTAL DATA

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A substantial amount of preliminary two dimensional data have been taken in an effort to validate the LDV system, the flow characteristics of the test rig, the correction lens performance and the data acquisition and reduction software. A free jet flow was used initially and later replaced by the more complicated axisymmetric sudden expansion flow. As mentioned earlier only

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non-reacting flow experiments have been run to date. The following data set was acquired using the 2-component LDV and data acquisition system described in the previous section.

The measurements were made in the axisymmetric sudden expansion flow (Figure 4) using the correction lens system. The inlet velocity was uniform with a value of 22 m/s corresponding to a Reynolds number of  $5.5 \times 10^4$  based on step height. Seeding was provided by the liquid atomizer described earlier. The burst sampling technique was used to obtain all the data presented here. Because the data are biased, owing to the sampling method used, the McLaughlin-Tiederman 2-D correction is also applied. This preliminary data set consists of measurements across the radius of the test section at 4 non-dimensional axial locations, namely x/H = 0.3, 2, 4 and 6.

Figure 6 shows the mean axial velocities (corrected and uncorrected) at the four axial planes. Notice that the corrected data has lower values of mean velocity in the shear layer where turbulence is high and has approximately the same value as the uncorrected velocity in regions of low turbulence. This is the expected result. These preliminary measurements are presented only to demonstrate LDV system performance. They are known to suffer from inaccuracy as a direct result of (1) the slowly oscillating shear layer characteristic of this flow field and (2) the burst sampling technique. The first problem occurs because the data was gathered at a high rate. This means the entire sample (n = 6000) was collected in a very short time (typically ( 2



sec) and the statistical parameters of the sampled data depend on when in the low frequency cycle the data is collected. The observed variation in the mean axial velocity due to this unsteadiness was up to 10%. This "inaccuracy" is much greater than the statistical error due to the finite number of samples taken. Typically, in a well-defined experiment, mean velocities are repeatable to better than 1%. The second source of inaccuracy (the burst sampling technique) is a velocity bias problem. Although the 2-D bias correction was applied, it was found to over correct the results in regions of high turbulence. This was confirmed by comparing unbiased one-component (axial) data to the 2-D corrected data. More work has to be done to determine the errors involved due to velocity bias and over-correction.

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Figure 7 shows the mean radial velocity component at the four axial planes. Not much can be said about the data except that the very low radial velocity in this flow field is responsible for more scatter. The low signal quality of the blue beam could also be responsible for some of this scatter.

Figures 8 and 9 show the axial and radial normalized turbulence intensities, respectively. The 2-D weighted data show the correct trends [9,27] relative to the uncorrected (biased) data and reach the same maximum values as other investigators have found [9,13]. Notice the shift in the locations of peak turbulence intensities depending on whether a standard or weighted statistic is used. These figures show the magnitude of error that can be caused by biased velocity measurements and

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illustrate that completely unbiased data are needed to improve existing time-averaged turbulence models.

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Figure 10 shows simultaneous Reynold's stress measurements made with the coincidence window set to 10  $\mu$ s (the minimum value on the TSI 1998 interface). Again, significant differences exist between the corrected and uncorrected statistic in regions of high turbulence. Also, more scatter is associated with this statistic, probably due to the low signal quality of the radial velocity component. However, the maximum values of normalized Reynold's stress agree well with other experimenter's values [13].

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