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EXPERIMENTAL STUDY OF THE OPERATING CHARACTERISTICS OF PREMIXING-PREVAPORIZING FUEL/AIR MIXING PASSAGES

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San Diego, California

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GLOSSARY

<table>
<thead>
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<th>Description</th>
</tr>
</thead>
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<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>ALEC</td>
<td>Advanced Low Emission Combustor</td>
</tr>
<tr>
<td>LPP</td>
<td>Lean Premixed, Prevaporized</td>
</tr>
<tr>
<td>LDV</td>
<td>Laser Doppler Velocimeter</td>
</tr>
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<td>SDL</td>
<td>Spectron Development Laboratories</td>
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</table>
INTRODUCTION

The program described in this report had as a goal the characterization of fuel sprays to be utilized in calibrating and verifying an analytical model of a premixing-prevaporizing passage of a lean burning combustor.

NASA's Advanced Low Emission Combustor Program (ALEC) was initiated to apply modern techniques of combustion science and analysis to the problems of achieving significant reductions in gas turbine pollutant emissions while maintaining high performance and durability for a wide range of aviation fuels. From this program, the lean premixed-prevaporized (LPP) combustor has evolved as the primary candidate for the program goals.

The LPP combustor is similar to conventional combustor concepts except that, prior to combustion, the fuel and air are mixed and the fuel vaporized in a fuel preparation section; hence the term premixed and prevaporized. This premixing and prevaporization is necessary to achieve the uniformity and control over local stoichiometry for low pollutant emissions, and low levels of flame radiation and pattern factors conducive to improved durability and performance for a variety of fuels.

In order to assist the design of the LPP combustor and reduce the associated development risks, an analytical model of the fuel preparation process is desirable. Such a model would permit low cost computer screening of premixing passage concepts and reduce time consuming, expensive experimental evaluation of high potential candidates. Such a model is currently being developed. The model computes the fuel-air distribution, degree of fuel vaporization, residual droplet size, distribution and air velocity, pressure and temperature profiles at the exit of the fuel preparation section, given the inlet air flow conditions and fuel spray characteristics.

Under the present program, data was collected on fuel spray and air flow characteristics at several points within a fuel preparation duct to calibrate and verify this analytical model. A well controlled test rig capable of producing repeatable fuel sprays was utilized in the research program. The rig was designed to operate to pressures of 10 atmospheres and to inlet temperatures of 750K.

The use of advanced non-intrusive (optical) measurement techniques for fuel spray characterization is seen as a significant contribution of this program. The data set obtained is the first acquired by this method at high pressures and temperature and is significantly more detailed than any previously obtained.
EXPERIMENTAL DESIGN

2.1 DESIGN PHILOSOPHY

Combustion research, relating to the operational characteristics of both innovative systems and the more well-established devices such as gas turbine combustors, requires instrumentation which can provide measurements in extremely severe environments. In an environment where pressures may reach 600 psi and temperatures over a thousand degrees Celsius, mechanical devices such as hot wire anemometers designed to function in much less severe conditions quickly fail or become highly inaccurate. Furthermore, instrumentation requiring a mechanical sampling technique perturb the environment which is to be measured. This perturbation reduces their accuracy and reliability. One particular area where instrumentation needs have become critical is in the measurement of particle (droplet) size and velocity for fuel sprays during fuel/air preparation and combustion. Devices which utilize optical measurements of the desired parameters are non-intrusive and thus can operate in severe environments with no perturbation of the flow field.

An instrument which has undergone extensive development during the past ten years, and has shown its utility in a wide variety of applications, is the Laser Doppler Velocimeter (LDV). Using a laser as a coherent light source, this instrument has been used to measure particle velocities in fluids. These applications have ranged from low speed water flows through supersonic wind tunnels to large oil and gas flames. The velocity measurement is obtained by determining the Doppler shift of light scattered from particles passing through the laser beam. This program has used a well-developed version of one type of Laser Doppler Velocimeter (LDV) optical system which incorporated highly refined signal analysis and electronic instrumentation to determine not only particle velocity but also particle size. This system has been tested with excellent results in small wind tunnels for the measurement of droplets in water sprays.

The primary use of the LDV instrumentation is to characterize the spray from various fuel injectors at several sets of operating conditions. The spray is characterized by measuring the droplet size and velocity at a set of points in several planes downstream of the injector. In order to achieve data that is meaningful, the test conditions (air flow, temperature, pressure, etc.) must remain constant during the measurement period and be repeatable from one test session to the next. This type of stability is especially important when comparing spray distributions from different injectors. The rig must also provide access for complete instrumentation to allow for flow measurement. The completed rig, as described below, allows for repeatability and stability. In addition, it has provision for instrumentation and fuel burnoff.
2.2 RIG DESIGN

The "rig" includes the fuel/air preparation section, burnoff combustor, air pressure regulation valve and supporting subassemblies. Basically the constraints were:

- The air inlet preparation section has been designed to produce uniform flat profiles of total pressure, total temperature and velocity at the inlet plane to the fuel injection section.

- The fuel injection section and fuel/air mixing section have a rectangular cross section with inside dimensions of 7.62 cm by 7.62 cm.

- The fuel injection section is designed to produce uniform flat profiles of total pressure, total temperature and velocity immediately upstream of the fuel injector location. It is also designed to accommodate various types of fuel injectors. (The injectors are mounted on a spool piece (2.5 cm high) and inserted into the flow path.)

- The fuel/air mixing section is designed to avoid autoignition and flashback over the conditions of the tests. It was designed to allow for optical measurements 7.5 cm, 15 cm, and 30 cm downstream of the fuel injector. This was accomplished with a stationary window and the addition of blank spool pieces to move the injector and fuel/air mixing section further upstream of the window. The spools were 7.5 cm, 15 cm and 30 cm high.

- The rig is designed to operate at temperatures of 450 to 750K, 20.0 to 80.0 m/sec reference velocity, equivalence ratios of 0.3 to 0.5 and pressures up to 10 atm.

- Flow distortions due to ports and instrumentation were minimized.

The rig was assembled in a manner shown in Figures 1 and 2. An A-frame support is used to support the rig vertically so that gravity will not disturb the radial symmetry of the spray distribution. The major components and dimensions of the rig are called out in the sketch of the rig in Figure 3.

The liquid fuel injector flange assembly is shown in Figure 4 and 5. It was designed to allow for changes in the type of injector under study. The fuel enters the air strut from both sides to prevent coking. Instrumentation ports were installed 180 degrees opposed. The injector for the first test has an ID = 0.085 cm and protrudes about 0.64 cm from the strut. This design produced a narrow spray cone and a distribution of fine droplets. Others designs without the sharp edge around the injector produced larger droplets and a less uniform combustion in the afterburner. (Standard gas turbine injectors cannot be used on the rig because the spray angle is generally too wide. They would have deposited fuel on the wall within centimeters of the injector.) All optical measurements were made with the injector shown in Figure 5.
Figure 1. Overview of Cell Showing LDV, Rig, Fuel Cart, and Air and Fuel Control Console

Figure 2. Rig Installed With Inlet and Exhaust Lines
Figure 3. Fuel Atomization Rig Mounted on A-Frame
Figure 4. Liquid Fuel Injector Flange Assembly

Figure 5. Closeup of Fuel Injector Nozzle
The laser measurement section is the most complex assembly in the rig. It is pictured in Figures 6 to 10. This section includes the laser beam window and ports, the laser beam dump, the off-axis detector window and ports and two auxiliary optical ports for other instrumentation. To prevent major flow disturbances plates were installed flush with the inner walls of the flow path at each measurement section. Slots were machined in these plates prior to the optical measurements. The laser measurement section contains pressure and temperature instrumentation. The beam dump port served the additional purpose of being a port for instrumentation wires.

The afterburner section (Fig. 11) contains the torch ignitor, natural gas pilot cone, dilution and cooling air port, combustor, transition duct (square to round) and water injector for final air cooling.

A standard butterfly valve with an electrical actuator was used to control rig backpressure. Because the valve was rated for 427°C service it was necessary to spray considerable quantities of water into the air stream just ahead of the valve. A thermocouple was used to monitor air temperature at the valve.

2.3 RIG CONTROL AND CONTROL INSTRUMENTATION

All optical measurements were made at air temperatures of 375°C. Variations over a six hour run were within 2.8°F. Air from high pressure compressors was directed through a heater to achieve the design operating temperature. The flow was controlled by a remotely actuated valve. Flow rates were measured using a standard ASME orifice run.

The fuel subsystem was designed to provide high pressure fuel at the design flowrate of 0.9 kg/s configurations. The fuel was filtered to prevent clogging of the fuel injector.

Nitrogen was used to purge the optical window ports and laser beam dump to maintain clarity. Needle valves were used to adjust nitrogen flow into the flow section. The total nitrogen flow was minimized to reduce the disturbance of the air flow in the measurement section. The primary purpose of this subsystem is to maintain high optical transmission through the quartz windows.

Overall rig instrumentation is detailed in Figure 12. Thermocouples in critical locations were routed to limiting pyrometers. Actual instrumentation channels recorded did not include all instrumentation shown. Many instruments were monitored by the test engineer to insure rig safety and not recorded.

The control panel with instrumentation readouts is shown in Figures 13 to 15.
Figure 6.

Laser Measurement Section

(The laser beam dump will be installed in the upper port. Transmissometer ports were welded into the lower ports at the time of these photos.)

Figure 7.

Top View of Measurement Section
Figure 8.
The Two Measurement Window Flanges Can be Seen in This View of the Measurement Section. (Nitrogen purge tubes are assembled.)

Figure 9.
Apertures for the Laser Beam are Visible Inside Window Flange. (The entire rig is supported on the brackets extending from both sides.)
2.4 TECHNIQUE

2.4.1 LDV Operating Procedure

The techniques used to obtain size and velocity information differed from standard LDV practice in one significant way: the detector measured the scattered laser light 90 degrees off axis (the laser beam defines the axis). This technique provided smaller probe volumes and fewer incidents of multiple droplet measurement. In this technique, two laser beams are used, but only one component of droplet velocity and size are measured at one time. The lens in front of the detector selects the signal from only the central part of the ellipsoid created by the intersecting laser beams. In this manner the probability for multiple droplets in the probe volume is considerably reduced. Data can be taken in regions where the drop density is so high that some detection techniques would not provide significant data. There was great concern that the results would be biased if approximately 90 percent of the data were rejected. Since this rejection does not occur with the off-axis detector the bias problem was reduced considerably.

SDL was subcontracted to take optical data using their equipment. Spectron set up the equipment at Solar in early September 1979. That equipment is
Figure 11. Afterburner Section. (Torch ignitor port is on the left while cooling air is introduced via the port on the right.)

represented in the sketch in Figure 16 and shown photographically in Figures 17 and 18. The data consist of size and velocity measurements of fuel droplets and the surrounding air.
Figure 12. Liquid Fuel Premix Rig Instrumentation
Figure 13. Main Control Panel for Test Rig

Figure 14. LDV Signal Conditioning and Control
Figure 15. Overall Control Panel With View Into Test Cell

Figure 16. Diagram of SDL Equipment for Off-Axis Measurement
Figure 17. Optical Bench for SDL Tests

Figure 18. Signal Processor for SDL Tests
Two types of measurements were made: visibility and Doppler period (see Appendix A for description). These were then converted to size and velocity of individual particles or droplets. From this information, several important parameters were then obtained. They are: linear mean diameter, size standard deviation, surface mean diameter, kurtosis, mean velocity, and turbulence intensity. These parameter as defined below.

In an effort to understand the interaction between the fuel droplets and the surrounding air, the velocities of both media were measured. The velocity of the air was obtained by seeding it with 3 \( \mu \)m glass beads using a fluidized bed and subsequently measuring the bead velocity.

2.4.2 LDV Data Recording Procedure

The positions where the measurements were taken are identified by the indices \((i,j)\) where \(i\) corresponds to the abscissae \((x)\) axis, and \(j\) corresponds to the ordinate \((y)\) axis as specified in Figure 19.

The data of each task are presented in matrix form where the position, mean velocity, turbulence intensity, and linear mean diameter are specified. In the SPRAY series, the velocity and size distributions are also provided.

The heading of the test data matrix indicates the series and the position of the run. For instance, SPRAY 1 RUN 2-1 indicates that the measurements were taken at 30 cm plane and the position 2,1). The histogram that follows, plots the frequency of the particle of a certain size versus the corresponding size. This frequency is obtained by dividing the number of particles of a certain size by the total number collected. That is, frequency \( f_i = \frac{N_i}{N} \). The maximum frequency of the ordinate is then indicated. Typically, it is \( 0.1 \). The ordinate is then divided into five equal numbers of intervals.

The table below the graph shows the values that were used to construct the graph: the diameters of the particles and the number of particles with this diameter (count). Finally, there is a list of the size and velocity parameters of interest for this test.

The next graph shows the velocity versus size distribution. The maximum velocity (ordinate) is indicated, and again the ordinate is divided into five equal intervals. The table below indicates the velocity and turbulence intensity corresponding to each size.

The data and graphs are included in Section 3.

2.4.3 Definition of Size and Velocity Parameters

Let:

\[ D_i = \text{diameter of droplet } i, \]
SERIES: SPRAY 1 - 30 cm DOWNSTREAM NOZZLE PLANE
SPRAY 2 - 15 cm DOWNSTREAM NOZZLE PLANE
SPRAY 3 - 7.5 cm DOWNSTREAM NOZZLE PLANE

RUN : 16/PLANE AT LOCATIONS (REC, TRANS)

Figure 19. Test Matrix

\( N_i \) = number of \( i \) droplets collected,
\( U_i \) = velocity of droplet \( i \), and
\( N = \text{total collected droplets} \pm \sum N_i \).

17
The following can then be defined:

- Linear mean diameter: \( D_{10} = \frac{\sum N_i D_i}{N} \),
- Surface mean diameter: \( D_{20} = \left[ \frac{\sum N_i D_i^2}{N} \right]^{1/2} \),
- Volume mean diameter: \( D_{30} = \left[ \frac{\sum N_i D_i^3}{N} \right]^{1/3} \),
- Sauter mean diameter: \( D_{32} = \frac{\sum N_i D_i^3}{\sum N_i D_i^2} \),
- Standard deviation: \( S = \left[ \frac{\sum N_i (D_i - D_{10})^2}{N} \right]^{1/2} \),
- Kurtosis: \( \frac{\sum N_i (D_i - D_{10})^3}{\left[ \sum N_i (D_i - D_{10})^2 \right]^{3/2}} \),
- Mean velocity: \( \bar{U} = \frac{\sum N_i U_i}{N} \),
- Turbulence intensity: \( T = \left[ \frac{\sum N_i (U_i - \bar{U})^2}{N} \right]^{1/2} / \bar{U} \).

2.5 SPECIAL INSTRUMENTATION

Several special instrumentation probes were built to measure the performance of the rig prior to the fuel droplet measurements. Data obtained from the probes are presented in Section 3.

2.5.1 Temperature Uniformity in Measurement Plane

The optical droplet measurements were made in a plane perpendicular to the flow axis. That plane was called the measurement plane. Air temperature and pressure measurements were made in that plane to assure uniformity.

An instrumentation rake was built to install in the rig at the measurement plane. It contained 13 thermocouples to measure total gas temperature. The thermocouples were arranged in a cross pattern (see Fig. 20). They were routed through a cruciform shaped airfoil to reduce the disturbance of the air flow.

2.5.2 Fuel Injection Plane Measurement Probe

A probe was designed to measure pressure and temperature at the fuel injection plane. The basic design is shown in Figure 21. This probe was installed in a spool section and replaced the fuel injector module. The probe spool piece was equipped with wall pressure and temperature probes.
Figure 20. Measurement Plane Probe

Figure 21. Pressure/Temperature Probe for Fuel Plane
2.5.3 Probe for Flow Uniformity and Spillover Measurements

A sampling probe was designed and built for the flow uniformity and spillover measurements. The probe replaced the laser beam dump and received samples of the air or air/fuel mixtures at the laser measurement plane. Six samples could be made with the rig at operating conditions without moving the probe. The probe could be positioned into a total of four slots to achieve the 24 point grid (Fig. 22).

In order to measure the percent of fuel vaporized in the measurement plane Solar followed the technique of Tacina\textsuperscript{1}. A catalytic reactor was built which was patterned after a design supplied by NASA. The catalyst used was 0.5 percent Pt on Gamma Alumina. The basic design was reasonably successful with problems occurring only in the heater. The electric heater element for the reactor was manufactured straight. To fit the reactor, the element was wound into a helical shape and inserted into the shell. The actual bend radius was smaller than that tolerated by the element resulting in an open circuit failure after each cycle. The design was altered by removing the strip heater and surrounding the core with a clamshell heater.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{sampling_probe.png}
\caption{Sampling Probe}
\end{figure}

2.6 FUEL EVALUATION TESTS

All fuel used during this study was drawn from a single 3800 l tank. Only this program used the fuel in that tank. The tank was pumped empty and then filled with commercial Jet A at the beginning of the test in June 1979. A sample of that fuel was taken on three separate occasions and tested in the Solar Chemistry Laboratory. The results of those three evaluations are shown in Table 1. There is some variation in the measured properties and these cannot be explained fully. It is possible that some fuel evaporation occurred between the first test and the subsequent two evaluations. The test rig had not been operated for a period of months when the third evaluation was made. A complete distillation curve was not measured during the third evaluation. All chemistry testings were performed by the same personnel using the same equipment and techniques.

Table 1
Fuel Sample Evaluation

<table>
<thead>
<tr>
<th></th>
<th>#1 7/79</th>
<th>#2 11/79</th>
<th>#3 4/80</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinematic Viskosity</td>
<td>1.55</td>
<td>1.46</td>
<td>1.55</td>
<td>(centistokes @ 100°F)</td>
</tr>
<tr>
<td>Gravity</td>
<td>43.2</td>
<td>43.7</td>
<td>40.3</td>
<td>Degrees API @ 60°F</td>
</tr>
<tr>
<td>Pour Point</td>
<td>-80</td>
<td>-72</td>
<td>88.6</td>
<td>°F</td>
</tr>
<tr>
<td>Flash Point</td>
<td>140</td>
<td>170</td>
<td>160</td>
<td>°F</td>
</tr>
<tr>
<td>Distillation BP</td>
<td>357</td>
<td>356</td>
<td></td>
<td>°F</td>
</tr>
<tr>
<td>10</td>
<td>390</td>
<td>379</td>
<td></td>
<td>°F</td>
</tr>
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<td>20</td>
<td>403</td>
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<td>430</td>
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<td></td>
<td>°F</td>
</tr>
<tr>
<td>90</td>
<td>484</td>
<td>460</td>
<td></td>
<td>°F</td>
</tr>
<tr>
<td>End PT</td>
<td>548</td>
<td>510</td>
<td></td>
<td>°F</td>
</tr>
<tr>
<td>% Recovery</td>
<td>98.5</td>
<td>98</td>
<td>95</td>
<td>%</td>
</tr>
<tr>
<td>Carbon Residues</td>
<td>0.28</td>
<td>0.08</td>
<td>0.095</td>
<td>%</td>
</tr>
</tbody>
</table>
3
MEASUREMENTS

The results presented in this section are divided into two sections: measurements of the rig flow characteristics without fuel droplets, and measurements concerning droplets in that flow field.

3.1 PRELIMINARY RIG MEASUREMENTS

This subsection describes the measurements of the flow temperature and uniformity of the rig without fuel being present. (The inlet air was preheated in an external heat exchanger.)

3.1.1 Temperature Uniformity

The air temperature was measured at the optical (LDV) measurement plane using the probe described in Section 2.5.1. The conditions for that test were:

- air temperature 744K
- air pressure 507 kPa
- reference velocity 40 m/sec

No fuel was injected during this test. The data from the thermocouples is shown in Table 2. The thermocouple numbers are referenced in Figure 23.

One thermocouple failed, but the remainder indicated that an extremely uniform temperature distribution in the measurement plane had been achieved.

Temperatures were also measured at the fuel injection plane using the probe described in Section 2.5.2. The conditions at the time of that test were:

- air temperature 650K (nominal)
- air pressure 507 kPa
- reference velocity 40 m/sec

Data from that test are shown in Figure 24. The mean temperature was 656K with a standard deviation of 0.44K.
Table 2

Thermocouple Data

<table>
<thead>
<tr>
<th>Thermocouple Number</th>
<th>Temperature (°K)</th>
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<tbody>
<tr>
<td>1</td>
<td>741</td>
</tr>
<tr>
<td>2</td>
<td>741</td>
</tr>
<tr>
<td>3</td>
<td>Failed</td>
</tr>
<tr>
<td>4</td>
<td>741</td>
</tr>
<tr>
<td>5</td>
<td>741</td>
</tr>
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<td>6</td>
<td>741</td>
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<td>742</td>
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<tr>
<td>13</td>
<td>742</td>
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</table>

Figure 23. Diagram of Measurement With Thermocouple Numbers
3.1.2 Flow Uniformity

The uniformity and symmetry of the air flow in the mixing section was determined by injecting methane into the rig at a point in the center of the fuel injection plane. A probe (Fig. 25) was constructed in a square spool piece which replaced the fuel injector. Methane was injected into rig while the rig was being operated at

- Air temperature 650K
- Air pressure 5 atm
- Reference velocity 40 m/s

A sampling probe (Fig. 22) was constructed for use at the measurement plane. The rectangular mounting plate of that probe replaced the laser beam dump, 180 degrees opposed to the laser port. Each of the six probes could be sequentially attached to a hydrocarbon analyzer. When the rig was shut down the probe could be moved to any of four different positions. In this manner a grid of 24 measurement points was constructed in the optical measurement plane. Unburned hydrocarbons were measured at each of the 24 points. The methane injector was positioned at three different planes to measure the distribution of the methane at 7.5, 15 and 30 cm downstream of the injector. The results of the 72 point survey are shown in Figure 26. The data indicates that the distribution is slightly skewed toward one side. This is probably a result of a slight skew in the injector. Taking this into account, the concentration profiles show the flow uniformity within the test section is acceptable. Background levels of CH₄ were subtracted out before presentation. The sensitivity of the CH₄ measurement is ± 1 ppm overall range. Data gathering was repeated for the right hand column of the 30 cm plane.
Several pressures were measured at the fuel injection plane using the probe described in Section 2.5.2. The conditions at the time of the test were:

- air temperature = 650K
- air pressure = 507 kPa (5 atm)
- reference velocity = 40 m/sec

The pressure measurements had a mean of 400 kPa (gauge) with a standard deviation of 3.3 kPa. The pressure data sets exhibited good uniformity. The data are shown in Figure 24.

3.2 MEASUREMENTS WITH FUEL IN FLOW FIELD

All tests were accomplished with a Jet A fuel and except for one characterization test were performed at one set of operating conditions. These conditions were:

- air temperature = 750K
- air pressure = 75 psia
- air velocity = 40 m/sec
- mean equilibrium ratio = 0.4

The operation set points to achieve these conditions are shown in Table 3. The variations described the tolerance that the rig operator could maintain.
**Table 3**

Set Points for Operating Conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Inlet temperature</td>
<td>700°F</td>
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<tr>
<td>Rig Pressure</td>
<td>58.2 psig</td>
</tr>
<tr>
<td>Orifice Temperature</td>
<td>727°F</td>
</tr>
<tr>
<td>Orifice Pressure</td>
<td>70 psig</td>
</tr>
<tr>
<td>AP Orifice</td>
<td>11.8 in. Hg</td>
</tr>
<tr>
<td>Downstream Throttle Temperature</td>
<td>280°F</td>
</tr>
<tr>
<td>Fuel flow In</td>
<td>133 Hz</td>
</tr>
<tr>
<td>Fuel Flow Total</td>
<td>88 Hz</td>
</tr>
<tr>
<td>Nitrogen Window Pressure</td>
<td>78 psig</td>
</tr>
<tr>
<td>Fuel Nozzle Pressure</td>
<td>300 psig</td>
</tr>
<tr>
<td>Fuel Pump Pressure</td>
<td>580 psig</td>
</tr>
<tr>
<td>Cooling Air Pressure</td>
<td>65 psig</td>
</tr>
<tr>
<td>Pilot Light Off T.C.</td>
<td>1700°F</td>
</tr>
<tr>
<td>Rig Overtemperature T.C.</td>
<td>450°F</td>
</tr>
<tr>
<td>Combustor Exit Temperature</td>
<td>In excess of 2200°F</td>
</tr>
</tbody>
</table>

### 3.2.1 Spillover Measurements

The tests were performed in the 7.5 cm measurement plane with the rig at the set position:

- **air temperature** = 650K
- **air pressure** = 5 atm
- **reference velocity** = 40 m/s
- **equivalence ratio** = 0.4

The probe shown in Figure 22 was used to collect the samples. This probe was used only in the middle two of the four possible positions. This was done primarily because of the narrow spray angle and the proximity of the probe to the fuel injector. The sample location numbering grid is shown in Figure 27.

The conditions of the rig and the emissions data received are shown in Table 4 for position B. Rig conditions are only printed out when changes in conditions were recorded. This order of presentation is the order in which the data was taken. The computer code used to generate the results is shown in Appendix B.

Problems were encountered on several occasions. The existence of the problems limited the amount of data available. In some positions, primarily probe Position C, insufficient flow as obtained to go past the isokinetic velocity. High "percent vaporized" numbers resulting from these data are not realistic and are excluded. The raw data are shown in Table 5 and 6.
<table>
<thead>
<tr>
<th>LASER WINDOW</th>
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</thead>
<tbody>
<tr>
<td>3   20  8  0</td>
</tr>
<tr>
<td>85  315 62 0</td>
</tr>
<tr>
<td>175 640 180 9</td>
</tr>
<tr>
<td>200 700 210 8</td>
</tr>
<tr>
<td>135 442 100 0</td>
</tr>
<tr>
<td>10  37  8  0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>7.5 CM PLANE</th>
</tr>
</thead>
<tbody>
<tr>
<td>130 225 125 15</td>
</tr>
<tr>
<td>195 350 208 35</td>
</tr>
<tr>
<td>210 390 220 40</td>
</tr>
<tr>
<td>220 400 208 40</td>
</tr>
<tr>
<td>210 360 190 35</td>
</tr>
<tr>
<td>150 250 130 15</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>15 CM PLANE</th>
</tr>
</thead>
<tbody>
<tr>
<td>145 200 140 43</td>
</tr>
<tr>
<td>170 215 140 52</td>
</tr>
<tr>
<td>175 220 130 47</td>
</tr>
<tr>
<td>180 215 125 49</td>
</tr>
<tr>
<td>180 210 128 55</td>
</tr>
<tr>
<td>155 185 110 54</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>30 CM PLANE</th>
</tr>
</thead>
<tbody>
<tr>
<td>145 200 140 43</td>
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<td>170 215 140 52</td>
</tr>
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<td>175 220 130 47</td>
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<td>180 215 125 49</td>
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<tr>
<td>180 210 128 55</td>
</tr>
<tr>
<td>155 185 110 54</td>
</tr>
</tbody>
</table>

FLOW UNIFORMITY TEST.
DATA IS PPM OF CH₄ AT EACH LOCATION WITH BACKGROUND SUBTRACTED OUT.

TORCH

Figure 26. Flow Uniformity Test Results
3.2.2 Description of Graphs and Tables

The data of the various series is presented in matrix form. The numbers indicated in each element correspond to the position, mean velocity, mean droplet diameter, and turbulence intensity, as appropriate. The corresponding positions in the combustor are indicated in Figure 19.

3.2.3 Data Collection Summary

The velocity, size, and related statistical parameters of the selected conditions studied in this research program are presented in this section. They are given in entirety in the Comprehensive Data Report.

(1) **Air Velocity Uniformity Check:** 13 points taken along both centerlines of test section at 30 cm plane.

Series: VELOCITY

---

**Figure 27.** Probe Numbering When Viewed from Top of the Rig
### Table 4

Vaporization Data Via Spillover Technique

<table>
<thead>
<tr>
<th>ORIFICE</th>
<th>ORIFICE</th>
<th>ORIFICE</th>
<th>ORIFICE</th>
<th>RIG</th>
<th>RIG</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEMP</td>
<td>TEMP</td>
<td>TEMP</td>
<td>TEMP</td>
<td>RATIO</td>
<td>RATIO</td>
</tr>
<tr>
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<td>F</td>
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</tr>
<tr>
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<td>100</td>
<td>100</td>
<td>100</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

FUEL FLOW: 69.34  
FUEL AIR: 636.4  
RATIO: 0.02903  
MEAN ISOQINETIC VELOCITY: 123.0

### Sampling Location

<table>
<thead>
<tr>
<th>ORIFICE</th>
<th>ORIFICE</th>
<th>ORIFICE</th>
<th>ORIFICE</th>
<th>RIG</th>
<th>RIG</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEMP</td>
<td>TEMP</td>
<td>TEMP</td>
<td>TEMP</td>
<td>RATIO</td>
<td>RATIO</td>
</tr>
<tr>
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<td>F</td>
<td>F</td>
<td>F</td>
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<td></td>
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<tr>
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<td>700</td>
<td>700</td>
<td>700</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

FUEL FLOW: 6910.3  
FUEL AIR: 632.5  
RATIO: 0.02903  
MEAN ISOQINETIC VELOCITY: 123.4

### Sampling Location

<table>
<thead>
<tr>
<th>ORIFICE</th>
<th>ORIFICE</th>
<th>ORIFICE</th>
<th>ORIFICE</th>
<th>RIG</th>
<th>RIG</th>
</tr>
</thead>
<tbody>
<tr>
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<td>TEMP</td>
<td>TEMP</td>
<td>TEMP</td>
<td>RATIO</td>
<td>RATIO</td>
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<td>700</td>
<td>700</td>
<td>700</td>
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<td></td>
</tr>
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</table>

FUEL FLOW: 6910.3  
FUEL AIR: 632.5  
RATIO: 0.02903  
MEAN ISOQINETIC VELOCITY: 123.4

### Sampling Location

<table>
<thead>
<tr>
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<th>ORIFICE</th>
<th>ORIFICE</th>
<th>RIG</th>
<th>RIG</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEMP</td>
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<td>TEMP</td>
<td>TEMP</td>
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<td>RATIO</td>
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FUEL FLOW: 6910.3  
FUEL AIR: 632.5  
RATIO: 0.02903  
MEAN ISOQINETIC VELOCITY: 123.4

### Sampling Location

<table>
<thead>
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<th>ORIFICE</th>
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<th>RIG</th>
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</thead>
<tbody>
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<td>TEMP</td>
<td>TEMP</td>
<td>TEMP</td>
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FUEL FLOW: 6910.3  
FUEL AIR: 632.5  
RATIO: 0.02903  
MEAN ISOQINETIC VELOCITY: 123.4

### Sampling Location

<table>
<thead>
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<th>RIG</th>
<th>RIG</th>
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</thead>
<tbody>
<tr>
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<td>RATIO</td>
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FUEL FLOW: 6910.3  
FUEL AIR: 632.5  
RATIO: 0.02903  
MEAN ISOQINETIC VELOCITY: 123.4
Table 4 (Continued)

<table>
<thead>
<tr>
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<td>ORIFICE TEMP</td>
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<tr>
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<table>
<thead>
<tr>
<th>FUEL FLOW</th>
<th>AIR FLOW</th>
<th>FUEL/AIR</th>
<th>MEAN ISOKINETIC VELOCITY, FT/SEC</th>
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<tr>
<td>187.8</td>
<td>1800</td>
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### SAMPLING LOCATION B-5

<table>
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<th>GAS VELOCITY AT PROBE TIP</th>
<th>CO2</th>
<th>CO</th>
<th>UHC</th>
<th>F/A</th>
<th>EQUIVALENCIE</th>
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<td>PPM</td>
<td>PPM</td>
<td>RATIO</td>
<td>RATIO</td>
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<tr>
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<tr>
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PERCENT OF FUEL VAPORIZED 89.57%

### SAMPLING LOCATION B-6

<table>
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<th>CO2</th>
<th>CO</th>
<th>UHC</th>
<th>F/A</th>
<th>EQUIVALENCIE</th>
</tr>
</thead>
<tbody>
<tr>
<td>FT/SEC</td>
<td>PPM</td>
<td>PPM</td>
<td>PPM</td>
<td>RATIO</td>
<td>RATIO</td>
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<td>0.022</td>
</tr>
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<td>112.45</td>
<td>0.43</td>
<td>0.0</td>
<td>5</td>
<td>0.00207</td>
<td>0.030</td>
</tr>
<tr>
<td>43.75</td>
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<td>5</td>
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<td>0.027</td>
</tr>
<tr>
<td>78.97</td>
<td>0.27</td>
<td>0.0</td>
<td>6</td>
<td>0.00130</td>
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</table>

PERCENT OF FUEL VAPORIZED 87.53%

### SAMPLING LOCATION B-1

<table>
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<th>CO2</th>
<th>CO</th>
<th>UHC</th>
<th>F/A</th>
<th>EQUIVALENCIE</th>
</tr>
</thead>
<tbody>
<tr>
<td>FT/SEC</td>
<td>PPM</td>
<td>PPM</td>
<td>PPM</td>
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Table 5

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<th>Date</th>
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<th>Probe Location</th>
<th>Flow Meter Reading</th>
<th>Temperature (°F)</th>
<th>Pressure in. Hg</th>
<th>CO₂ (%)</th>
<th>CO (ppm)</th>
<th>UHC (ppm)</th>
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</thead>
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<td>2/14/80</td>
<td>1216</td>
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<td>70</td>
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<td>0</td>
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</tr>
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</tr>
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<td>1030</td>
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<td>45</td>
<td>70</td>
<td>+1.3</td>
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<td></td>
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Recalibrated with 0-5% CO₂

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Spillover Test Rig Data

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<td></td>
<td>°F</td>
<td>°F</td>
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32
(2) **Air Velocity**: 16-point rectangular matrix

Series:
- AXAIR 1 - 30 cm plane
- AXAIR 2 - 15 cm plane
- AXAIR 3 - 7.5 cm plane

(3) **Radial Air Velocity**: 16-point matrix.

Series:
- RADAIR 1 - 39 cm plane
- RADAIR 2 - 15 cm plane
- RADAIR 3 - 7.5 cm plane

(4) **Droplet Velocity/Size**: 16-point matrix.

Series:
- SPRAY 1 - 30 cm plane
- SPRAY 2 - 15 cm plane
- SPRAY 3 - 7.5 cm plane

(5) **Radial Droplet Velocity**: 16-point matrix

Series:
- RADVEL 1 - 30 cm plane
- RADVEL 2 - 15 cm plane
- RADVEL 3 - 7.5 cm plane
4

CONCLUSIONS

A new method of measuring fuel droplet size and velocity was developed during the mid 1970's. The significant factors in this method are the (1) simultaneous measurement of size and velocity and (2) the capability to measure the droplets in situ with no flow disturbing probes. The measuring instrument is based on the laser doppler velocimeter (LDV) principles.

While applications of this instrument can be found in many technical areas, the area of particular interest to gas turbine engines is the study of fuel sprays during fuel/air preparation and combustion in liquid fueled gas turbine engines. Once the fuel size and velocity characteristics are measured in an engine environment, combustion engineers will gain a more basic understanding of the fuel atomization process. The desired goal of this understanding is the production of low emission gas turbine combustors. The results could be applied to gas turbine combustors burning various types of heavy oils or synfuels.

Fuel spray characterization data was needed to calibrate and test an analytical model of lean premixed, prevaporized (LPP) combustors. To obtain data useful in the model development, a new measurement technique was developed.

In order to obtain the data, it was necessary to design and build a test rig with well-defined and controlled conditions. The rig was successfully completed and run for extended periods of time.

Optical measurements were successfully performed using a rig described above. The optical measurements included drop size and velocity distributions made at 30 points in three planes. The data were plotted and are consistent with expectations. This is the first known application of this technique to combustor fuel preparation investigations.
APPENDIX A

DETAILS OF SIZE DETERMINATION BY LDV
METHODS OF LDV CALIBRATION
LDV MEASUREMENT CAPABILITIES

Spectron Development Laboratories (SDL) in close collaboration with John C. Meier of Solar, has developed an instrument for combustion research in gas turbine combustion system. The LDV instrument is unique in its capabilities of measurement of droplet size and two component velocities in the severe environment of an operating gas turbine combustor system. The instrument incorporates the following capabilities:

- Measurement of a two-dimensional velocity vector with a range of ±(0.01-200 m/sec)
- Measurement of particle size when the particles are in the velocity range of 5-30 m
- Specification of probe volume position coordinates with a high degree of accuracy (±0.5 mm)
- Immediate on-line data checks
- Rapid computer storage of acquired data

The optical system of the LDV was constructed based on proven designs. The optical system is designed so the instrument can be used in the backscatter observation mode or 90 degrees off axis. The electronic system was built around an existing design which is capable of:

- Measuring signal visibility (proportional to particle size) for each velocity component
- Measuring signal time period (proportional to particle speed and velocity) for each velocity component
- Sorting data pertinent to particle size or velocity for each velocity component
- Producing the particle size and velocity data in a format compatible with digital computer recording systems

The optical system is mounted on a moveable platform which provides environmental protection and allows the operator to specify the position of the sample space with high accuracy. The system is designed for remote operation. Table A-1 shows the general capabilities and system advantages.

Signal Analysis for Determination of Particle Size

A brief review of the basic principles which must be used to determine particle size from a measurement of signal shape in the LDV.
Table A-1
LDV General Description

1. The LDV determines particle size over a 10:1 size range via the relative magnitude of light scattered from particles passing through crossed laser beams interference fringes, and determines particle velocity over a 10^5:1 range (not simultaneously).

2. The system is capable of measuring particle size, number density and velocity at a rate of 20,000 particles/sec for particles from 5 μm to 300 μm in diameter and ±1 cm/sec to ±200 m/sec.

3. Requires no material probes and therefore performs perturbation-less measurements.

4. Calibration for particle composition not required since size determination is not dependent on absolute measurement of radiation intensity.

5. High quality receiving optics not required.

6. With calibration LDV can be used to directly determine particle mass concentration.

Two equal-intensity, well-collimated, coherent light beams intersect at a common origin (geometric center) with an included angle, (Fig. A-1). Huygen's diagram of the wavefronts shows that planar interference fringes are generated which are perpendicular to the plane defined by the beam centerlines and are parallel to the bisector between the beams. The distance between the periodic fringes, δ, is given by:

\[
δ = \frac{λ(2 \sin (α/2))}{2}
\]

where λ is the wavelength of the coherent light. When a particle (assumed spherical) much less than δ in diameter crosses the fringe pattern, it can be assumed to be uniformly illuminated at all points along its path through the fringe pattern, and the light which is scattered by the particle is proportional to the observable flux illuminating it. Thus, measurement of the time period, T, of the scattered light is related to the velocity, v, of the particle through the relationship:

\[
v = \frac{δ}{T}
\]

As the size of the scattering particle increases relative to δ, the illumination of the particle is no longer uniform and must be averaged over the cross-sectional area of the particle. The nonuniform illumination of the particle results in a reduction in the contrast or visibility of the scattered

---

[Table A-1]

<table>
<thead>
<tr>
<th>LDV General Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. The LDV determines particle size over a 10:1 size range via the relative magnitude of light scattered from particles passing through crossed laser beams interference fringes, and determines particle velocity over a 10^5:1 range (not simultaneously).</td>
</tr>
<tr>
<td>2. The system is capable of measuring particle size, number density and velocity at a rate of 20,000 particles/sec for particles from 5 μm to 300 μm in diameter and ±1 cm/sec to ±200 m/sec.</td>
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<td>3. Requires no material probes and therefore performs perturbation-less measurements.</td>
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<tr>
<td>4. Calibration for particle composition not required since size determination is not dependent on absolute measurement of radiation intensity.</td>
</tr>
<tr>
<td>5. High quality receiving optics not required.</td>
</tr>
<tr>
<td>6. With calibration LDV can be used to directly determine particle mass concentration.</td>
</tr>
</tbody>
</table>
light signal. Let \( I_{\text{max}} \) by the maximum value in intensity in a period of the scattered light from a particle and \( I_{\text{min}} \) the next successive minimum. The visibility, \( V \), and then be defined as:

\[
V = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}}
\]

It is straightforward to show that \( V \) is fully equivalent to the ratio of AC amplitude divided by the DC amplitude of the scattered light signal. Henceforth, the high frequency "Doppler" portion of the signal will be referred to as the "AC". It usually has many cycles of information relative to that of the DC component, which refers to the Gaussian shaped low frequency terms describing the signal. Analytically, the visibility may be written as:

\[
V = \frac{\int_{A_p} I_o \cos (2\pi t/\delta) dA_p}{\int_{A_p} I_o dA_p}
\]

where \( A_p \) is the cross-sectional area of the particle; \( I_o \) is the intensity distribution across one of the illuminating beams; and \( \gamma \) is the coordinate normal to the fringe planes. When \( I_o \) is a Gaussian function (TEM\(_{00}\) laser beam), it can be shown that Equation (4) is an accurate approximation over a depth of field, \( \delta \), given by:

\[
\delta = 0.8 b/\lambda
\]

where \( b \) is the radius of the \( e^{-2} \) intensity point in the illumination beam. For depths of field greater than \( \delta \), the signal visibility is a function of particle size and position in the illumination. To simplify Equation (4) for Gaussian beams and still maintain accuracy, it is required that the particle diameter, \( D \), satisfy the relationship:

\[
D < 0.8 b/\lambda
\]
\[ D \leq 0.2 \, b \]  \hspace{1cm} (6)

and for \( \delta \) to satisfy:
\[ \delta \leq 0.2 \, b \]  \hspace{1cm} (7)

Under these conditions, \( V \) for a sphere can be written as:
\[ V \approx 2J_1\left(\pi D/\delta\right)/\left(\pi D/\delta\right), \]  \hspace{1cm} (8)

where \( J_1 \) is a Bessel function of the first kind. For a cylinder, \( V \) can be written as
\[ V \approx \sin(\pi FL/\delta)/(\pi FL/\delta). \]  \hspace{1cm} (9)

Equations (8) and (9) are plotted in Figure A-2 to illustrate the salient features of the visibility in particle size measurement.

Determination of particle size using a visibility measurement has a number of advantages over other optical techniques. Among the more important is the fact that:

- High quality, scattered-light-collecting systems are not required.
- A visibility measurement can determine particle size to, at least, 10 times better than the resolution limit of the transmitting lens.
- True particle flux rate, i.e., mass concentration, may be determined with the LDV system.
- Size measurements may be made from backscattered light.

On the other hand, disadvantages in using this technique are also apparent. For example, application of the LDV system must account for the fact that:

- Size measurement is particle shape dependent.
- High quality, transmitting optical systems are required.
- Particle size measurement of spheres is limited to approximately a 15:1 size variation range for a given fringe period.
- High quality spatially coherent light is required for good interference fringe quality.
- The particle size measuring ability is limited by the frequency response of the signal process in electronics.

The last item results from the fact that the signal frequency is velocity dependent. Hence, an instrument which measures signal visibility is limited to the measurement of particle with velocities which are less than those which produce a signal frequency greater than the frequency response limit of the instrument.
Signal Processing Considerations

To minimize error in the estimate of particle size, it is of utmost importance that signal visibility be measured with high accuracy and precision. This is due to the fact that signal visibility error and particle size error are not linearly related. For spherical particles, Figure A-3 illustrates the particle diameter uncertainty for several different values of visibility. As the figure shows, where the ratio of particle diameter $D$ to fringe period $d$ is near 1, the particle diameter uncertainty is the same as the visibility uncertainty.

A summary of the principles of operation of the LDV is provided in Table A-2. A schematic representation and interpretation is summarized in Table A-3 and Figure A-2.
### Principle of LDV Operation

1. Two equal intensity, coherent light beams are mixed at an angle.
2. A well-defined set of equally spaced interference fringes is formed by interference of the two beams.
3. Light scattered by a particle traversing the fringe set is modulated according to size and position of the particle.
4. Particle size is determined from the ratio of the amplitudes of (1) the modulated scattered intensity to (2) the average scattered intensity.
5. Particle velocity is determined by measurement of the signal time period.

**Figure A-3.** Interferometric Measurement of Velocity and Particle Size
Table A-3
Signal Description

1. The signal contains two components in amplitude
   - the modulated scattered intensity of ac component
   - the average scattered intensity of dc component

2. The time period, $T$, of the modulated scattered intensity is a function of particle velocity.

Table A-4
Signal Parameters and Particle Characteristics

1. Particle velocity $v$ is computed from
   \[ v = \delta/T \]

2. Particle size is computed from signal visibility
   \[ U = \text{ac}/\text{dc} \]

3. For spherical particles of diameter $D$
   \[ U = 2J_1(\pi D/\delta)/(\pi D/\delta) \]
   \[ J_1(\cdot) \text{ is a first order Bessel function of first kind} \]
Figure A-4. Uncertainty in Spherical Particle Diameters for Various Values of Uncertainty in the Visibility

Uncertainty is the same as the visibility uncertainty. However, as $D/\delta$ decreases, particle diameter uncertainty rapidly increases. Thus, when $D/\delta$ is small, the error in particle size will be much greater than that in the visibility. An instrument which measures signal visibility must seek to minimize errors in the visibility measurements if an accurate particle size measurement is to be obtained.

Potential Sources of Error in a Signal Visibility Measurement

In examining the LDV signal, a number of potential error sources are evident which could produce considerable error in a visibility measurement. Among the most important error sources are:

- Signal noise
- Asymmetric signal shapes
- Variations in the signal visibility
- Signals resulting from more than one particle.
Signal noise may result from any number of sources but is usually either broad
band, Gaussian-distributed noise occurring during the entire duration of the
signal; single, very-high-frequency spikes which occur randomly in the signal;
or periodic amplitude variations which mix with the signal. The first two
forms of noise are usually evident when signal magnitudes are low. The third
form usually results from a radiative pickup from high-power consuming or gen-
erating instruments operating across the entire frequency spectrum. Asymme-
tric signal shapes result from particles with trajectories that do not pass
through the optical axis of the probe volume. Such signals can also arise
through turbulence induced distortions in the signal (Fig. A-5). Variations
in signal visibility occur when D/δ is near 1, and the AC component of the
signal has only a few cycles of information relative to that of the DC com-
ponent. Signals resulting from more than one particle usually generate
aperiodic signals of skewed shapes. The LDV optical designs account for the
possibility of multiple particle signals by generating a probe volume which is
small enough to produce a low probability of observing more than one particle.
Certain types of error logic may also be used in the signal processing elec-
tronics to reject such signals.

Visibility From Signal Integration. To minimize the errors which may result
from "real world" LDV signals, it is most desirable to observe and measure as
much of the signal as possible. One method of satisfying this requirement is
through integration of the entire signal (within preset limits). Consider a
particle whose trajectory passes through or near the geometric center of the
probe volume. It can be shown that the visibility obtained by computing the
integral of the DC component, and the integral of the full-wave rectified
value of the AC component, and by dividing the integrated DC into the inte-
grated AC is (to within a known numerical factor) identical to that measured
for a single cycle measured at the center of the signal. Integration of the
signal is most desirable because the noise components previously listed will
contribute very little to an integral value of the signal. For example,
Gaussian-distributed white noise and periodic noise have zero or nearly zero
values for an integration, and high-frequency-noise spikes contribute very
little to the overall integral value. Furthermore, integration of asymmetric
signals tends to reduce the effects of the asymmetry by producing an overall
signal average. The primary difficulty in using a signal integration to
determine the signal visibility resides in the fact that the dynamic response
of an integrator will be affected by large frequency variations in the signal
input. Thus, without design precautions, an integrator could produce consid-
erable error in attempting to measure particle size in turbulent flows where
there are considerable velocity variations.

Signal Amplitude Constraints. While a visibility measurement is independent
of signal magnitude, detailed considerations must be given to relative signal
amplitude in order for a visibility measuring instrument to have a sufficient
dynamic range in amplitude response.

For particles of identical index of refraction and of a size greater than
about 5 μm, i.e., for particles with scattering gain coefficients independent
of particle size, the signal amplitude can be expected to vary by a factor of
100 over the measurable size range. Probable volume intensity variations can
be expected to range over factors of 10 in each of two orthogonal probe volume dimensions. Thus, an instrument must be capable of responding to relative signal amplitude variations of at least 10³:1 and, more reasonably, 10⁴:1. Linear amplifiers can cover a linear dynamic range of approximately 10² for a single-range setting. The designer is thus faced with the difficulty of producing an instrument which at one range setting can cover sufficient dynamic range to eliminate instrumental bias in particle size measurements.

One technique to overcome the dynamic range limitation is the use of logarithmic amplifiers. For example, if an integration technique is used to determine
the signal visibility from a logarithmically amplified signal, it can be shown
that the visibility is given by:

\[ V = \text{sech} \left( \int \ln(i_{AC}) - \int \ln(i_{DC}) \right), \]  

(10)

where \( \int \ln(i_{AC}) \) is the integrated logarithmically amplified AC component of the
signal and \( \int \ln(i_{DC}) \) is the integrated DC component. Logarithmic amplifiers can
easily cover a dynamic range of \( 10^4:1 \) for low frequency signals, making an
instrument much more sensitive to small particle signals. The primary diffi-
culty with such amplifiers is that their sensitivity is a strong function of
signal frequency and quickly decreases as the frequency increases, making
their effectiveness questionable at the carrier frequencies involved with the
laser flame analyzer.

Another solution to this limitation is obtained in using the integration
approach to visibility measurement. An integrator can be designed to cover a
10:1 dynamic range visibility processor designed by SDL personnel utilizes
four parallel integration circuits each overlapping the other in range so
that for a given signal frequency a dynamic amplitude range of \( 10^4:1 \) with
three-digit accuracy can be covered. Such accuracy gives an acceptable error
in particle size determined by a visibility measurement even when the particle
size is small.

LDV CALIBRATIONS

The LDV is a recently developed instrument and as such requires attention to
the methodology of calibration. Four separate experimental procedures were
developed to achieve a high confidence level in the calibration and therefore
in the data from the instrument. The experiments are the monodispersed
droplet generator, the spinning disc velocity calibrator, the nitrogen tunnel
for simultaneous particle size and velocity measurements and comparison with
data from a calibrated spray nozzle. (A second method would be used to
calibrate the spray nozzle.)

Monodispersed Droplet Generator

A droplet generator was successfully designed, built and tested on non-program
funds. The generator produces a stream of liquid droplets (water) of uniform
diameter in the range 20-300 microns. A built-in deflection circuit allows
the experimenter to divert one droplet (minimum diameter 40 micron) at regular
intervals. The diversion of a single droplet is critical to calibration since
the LDV probe volume can only contain that one droplet without signal dropout.
Optical verification techniques (photomicrographs) of the same drop being
measured by the LDV will give the LDV user confidence in the size data. A
photograph of the stream of droplets produced by the Solar monodispersed
generator is in Figure A-6. The deflection of one droplet can be seen in
that photo.
An overall view of the equipment used to make the droplets is shown in Figure A-7. Basically, the droplets are formed by the passage of the liquid through a vibrating orifice plate. Pulsed deflection plates downstream of the orifice deflect the chosen droplet if the liquid has been lightly doped with an electrolyte. The entire droplet generating head is mounted on the XYZ micro-positioning translator.

Spinning Disc

The spinning disc calibration consists of a motor driven disc with one wire protruding radially from its circumference. The circumference of the wheel is known. The rotational speed of the wheel is accurately measured by a frequency counter. Thus the wire passes through the probe volume at a precisely known translational velocity. Velocities can be controlled up to 100 m/s. The equipment is pictured in Figure A-8. A scope trace taken after the passage of the wire through probe volume is shown in Figure A-9. The characteristic LDV signal trace is seen there.

The LDV was successfully calibrated for velocity accuracy using this technique. The calibrations were performed for four fringe periods at one transmitter focus, 40 inches, and one scan distance, 20 inches. Two channels of the LDV were calibrated at the four fringe periods and the entire calibration was performed a second time in reverse order to check for systematic errors. At each fringe period, the instrument was checked at six different velocities. Five separate sets of one hundred measurements were made at each velocity. In total, 48,000 measurements were made during the fringe period (velocity) calibration. The data from the fringe period calibration exists on several pages. A typical data sheet is reproduced in Figure A-10. A statistical analysis of that data is shown near the bottom of that figure.
Figure A-7. Monodispersed Droplet Generator Mounted on XYZ Positioner

Figure A-8. LDV Spinning Disc With Target for Velocity Calibration
A summary of all data points is shown in Figure A-11. The standard deviations are less than one percent and most are less than 0.5 percent of the fringe period.

Nitrogen Tunnel

The nitrogen tunnel experiment was designed, built, calibrated and tested on non-program funds (Solar). The purpose of this device is to calibrate the LDV for size and velocity simultaneously. Particles or beads of a known size are injected into an airstream of known and controlled velocity. The LDV measures the size and velocity of the group of particle as they exit the tunnel. A catch basin is provided to remove the spent particles from the atmosphere. The gas used is pure, high pressure nitrogen, boiled from an LN\textsubscript{2} supply. That uniform gas enters the test tunnel from the top (see Fig. A-12), passes through flow straighteners, and encounters a throttle. Gas pressure and temperature are measured just above the throttle. Three throttle plates were built. Each was calibrated in the tunnel by the Colorado Experimental Station in Boulder, Colorado. The gas passing the plate enters a venturi section in which the particles are injected. To insure uniform distribution of the particles in the air stream, they are fed from a fluidized bed into six ports placed symmetrically around the tunnel just above the Venturi. For small particles the six injectors are perpendicular to the gas stream. For heavier particles a second set of injectors pointing 15 degrees upstream is used. The calibrator is totally operational.
### STATISTICAL ANALYSIS

Number of data points: \( n = 30 \) runs of 100 replications each

\[ \overline{x} = 70.78, \quad 68.59 \leq \overline{x} \leq 72.92 \]

Standard deviation: \( S_x = 0.73, \quad \sigma_x = \pm 0.13 \)

True value of \( x = 70.78 \pm 0.13 \)

### OPERATING PARAMETERS

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<th>Setting</th>
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</tr>
<tr>
<td>L-4</td>
<td>3070</td>
</tr>
<tr>
<td>L-5</td>
<td>6.0</td>
</tr>
<tr>
<td>Transmit</td>
<td>60.11</td>
</tr>
<tr>
<td>Receiver</td>
<td>3.420</td>
</tr>
<tr>
<td>Power</td>
<td>750 mV</td>
</tr>
<tr>
<td>CRT</td>
<td>300 V</td>
</tr>
<tr>
<td>Line #</td>
<td>7</td>
</tr>
</tbody>
</table>

Figure A-10. Typical Fringe Period Calibration Data Sheet
### Figure A-11. Summary of Fringe Period Calibration Data

<table>
<thead>
<tr>
<th>Channel A Fringe Period Horizontal Velocity Compression</th>
<th>Standard Deviation</th>
<th>Channel B Fringe Period Vertical Velocity Compression</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>82</td>
<td>0.1</td>
<td>56</td>
<td>0.6</td>
</tr>
<tr>
<td>105</td>
<td>0.4</td>
<td>70</td>
<td>0.3</td>
</tr>
<tr>
<td>160</td>
<td>0.4</td>
<td>105</td>
<td>0.1</td>
</tr>
<tr>
<td>278</td>
<td>1.4</td>
<td>179</td>
<td>0.4</td>
</tr>
</tbody>
</table>

### Figure A-12.

Nitrogen Tunnel Experiment
Calibrated Spray Nozzle

The intent of this experiment is to measure the droplet size and velocity distributions from a pressure atomizing spray nozzle calibrated by another method and compare the data from the two methods. This was not accomplished during the period of the reported effort.
APPENDIX B

VAPORIZATION COMPUTER CODE
REM CALCULATION OF DEGREE OF VAPORIZATION
REM NASA-SOLAR LASER RIG
REM SPILL-OVER TECHNIQUE
DIM R$[2,5], BS[2,5], CS[2,5], MS[2,5], HS[2,5], A$[8], B$[8]
DIM BS[5,5], CS[5,5], C$[6]
PRINT TAB2:"NASA-LEWIS/SOLAR LASER RIG"
PRINT TAB14:"VAPORIZATION DATA VIA SPILL-OVER TECHNIQUE"
PRINT "INPUT DATE AND FUEL:"
INPUT A$, B$
PRINT TAB20:"DATE:" A$ TAB 40: "FUEL:" B$
PRINT TABS:"INPUT RIG DATA:";
PRINT TAB1010:"ORIFICE TEMP: # DEG F"
PRINT TAB1040:"ORIFICE PRESS.: PSIG"
PRINT TAB1070:"ORIFICE PRESS. DROP. IN HG"
PRINT TAB1100:"RIG TEMP: # DEG F"
PRINT TAB1130:"RIG PRESS.: PSIG"
PRINT TAB1160:"CYCLES/SEC FUEL FLOW"
PRINT TAB1190:"ORIFICE TEMP: ORIFICE PRESS.: RIG TEMP: RIG PRESS.";
PRINT TAB1220:"TEMP: PRESS: DELTA P: TEMP: PRESS:";
PRINT TAB1250:"F: PSIG: IN HG: F: PSIG:";
WRITE (15, 1260) T1, P1, D1, T2, P2
PRINT TAB1290:"ORIFICE PRESS:";
PRINT TAB1340:"ORIFICE ORIFICE RIG RIG"
PRINT TAB1390:"TEMP TEMP GLUE FUEL/AIR"
PRINT TAB1390:"AIR FLOW AIR FLOW FUEL/AIR MEAN ISOKINETIC VELOCITY, FT/SEC"
PRINT TAB1390:"FUEL FLOW FUEL FLOW RATIO MEAN ISOKINETIC VELOCITY, FT/SEC"
PRINT TAB1390:"LB/HR LB/HR RATIO MEAN ISOKINETIC VELOCITY, FT/SEC"
PRINT TAB1390:"WRITE (15, 1320) F1, P1, D1, T2, P2"
PRINT TAB1390:"WRITE (15, 1260) T1, P1, D1, T2, P2"
PRINT TAB1390:"INPUT DATA FOR EACH SAMPLING POINT"
PRINT TAB1390:"INPUT NO. OF PTS AND LOCATION:";
INPUT P$, C$
PRINT TAB1390:"PRINT TAB14"SAMPLING"
PRINT TAB1390:"PRINT TAB14"LOCATION"
1367 PRINT TAB(5,C$)
1369 DISP "INPUT ROTAMETER AND GAS ANALYSIS DATA";
1370 FOR J=1 TO P
1371 INPUT M1[J],H1[J],B1[J],B4[J],B5[J]
1372 REM N(1,J)= ROTAMETER READING; DIVISIONS 605 TUBE, SS FLOAT
1373 REM H(1,J)= ROTAMETER PRESSURE; IN HG
1374 NEXT J
1375 GOTO 125
1376 REM M(J)= ROTAMETER READING
1377 REM H(J)= ROTAMETER PRESSURE
1378 REM M(J)= PERCENT CO2
1379 REM H(J)= PERCENT CO
1380 REM H(J)= UHC
1381 REM H(J)= FUEL RATIO H/C
1382 REM H(J)= A8= FUEL RATIO H/C
1383 REM H(J)= F/A RATIO EMISSIONS
1384 REM H(J)= EQUIVALENCE RATIO EMISSIONS
1385 S1=34.3791636-274.219526/(12.01*A8)
1386 NEXT J
1387 RETURN
1388 END
1389 STOP
1390 REM SUBROUTINE FOR CALC OF FUEL/AIR RATIOS
1391 B(1,J)= PERCENT CO2
1392 B(4,J)= PERCENT CO
1393 B(5,J)= PERCENT UHC
1394 A8= FUEL RATIO H/C
1395 N1=(M(J)-B4[J]*0.68+B5[J]*1.9)/(1+88/2*10t(-S)*B5[J])
1396 NEXT J
1397 RETURN
1398 END
1399 STOP
1400 REM SUBROUTINE FOR CALC OF V(1,J) SAMPLING VEL AT PROBE TIP
1401 FOR J=1 TO P
1402 C(J,J)=(0.2903*M(J)-M(1,J)+0.0871)*SQR(C(29.92+H(J))*29.92)*0.0005865
1403 NEXT J
1404 RETURN
1405 END
1406 STOP
1407 REM SUBROUTINE FOR CALC OF DEGREE OF VAPORIZATION
1408 FOR J=1 TO P
1409 W1=0
1410 N1=0
1411 Y1=0
1412 Z1=0
1413 END
6070 W1=W1+(V0/V1,JJ)*2
6080 X1=X1+(V0/V1,JJ)
6090 Y1=Y1+(R1,JJ/R0)
6100 Z1=Z1+(V0/V1,JJ)*(R1,JJ/R0)
6110 NEXT J
6120 REM SOLVE OF DEGREE OF VAP
6130 B=(Z1-(Y1*W1)/X1)/(X1-(P*W1)/X1)
6140 M=(Y1-B*P)/X1
6141 E=B*(B+M)*100
6142 PRINT
6150 PRINT TAB24:"PERCENT OF FUEL VAPORIZED"
6152 FORMAT 30X,F8.3
6153 WRITE (15,6152)E
6160 RETURN
6170 END
7000 STOP
7001 REM SUBROUTINE FOR DATA PRINTING
7120 PRINT
7122 PRINT TAB5:"GAS VELOCITY"
7123 PRINT TAB5:"AT PROBE TIP CO2 CO UHC F/A EQUIVALENCE"
7124 PRINT TAB8:"FT/SEC % PPM PPM RATIO RATIO"
7133 FOR J=1 TO P
7134 FORMAT 7X,F7.2,6X,F5.2,2X,F5.1,2X,F6.0,4X,F8.5,6X,F6.3
7135 WRITE (15,7134)VL1,JJ,BL1,JJ,BL4,JJ,BL5,JJ,BL1,JJ,BL2,JJ