Advances in Spray Drop Size and Velocity Measurement Capabilities for the Characterization of Fire Protection Systems

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Summary

The applications of sprays and mists for extinguishing fires requires further research to establish the most effective application parameters. Some of these conditions are the water flow rate directed onto the fuel, drop size and drop size distribution, velocity of the entrained air, and the drop velocity. The phase Doppler instrument is capable of providing these data in realistic environments, including measurements within the fire. Details of the local drop size, size distribution, drop size-velocity correlations, gas phase velocity, number density and volume flux can be measured. A brief description of the phase Doppler method is given along with the validations of the measurement capabilities.

1. Introduction

Fire prevention and extinguishing of fires in solid and liquid fuels remains as a very important area of research and development. One need only recall the images of the incredible disaster that occurred recently in the Berkeley hills to appreciate the destructive results of a fire out of control. The properties of water sprays as extinguishing agents have been studied for decades, if not, centuries [1,2,3,4]. The water acts as an extinguishing agent through its capacity as a cooling agent of the burning fuels. The water is normally applied in the form of a jet or a spray. The spray has the advantage of exposing a greater surface area of cooling water to the flame. In the case of the jet, the jet can penetrate into the flame even under strong convection driven air currents. Upon reaching a solid surface, the jet breaks up into a spray or film of water over the surface which enables the water to remove the heat.

Properties of the water sprays that have been found relevant to the extinction of fires include [4] mean flow rate per unit area in the region of the fire, direction of application, mean drop size and drop size distribution, velocity of the air flow due too the entrainment by the spray, and the velocity of the drops. Clearly, to be effective in cooling the fuel to its ignition point, the spray must be able to penetrate the flames to the source and be capable of removing heat effectively.

More recently water mists have been proposed as a means to extinguish fires. Although this author is not familiar with the technology, one might surmise that the use of mists would minimize the damage normally produced by the use of sprinklers and water jets. One problem with mist application may be that of delivery of the mist to the point of the flame source.

In this review paper, methods for the characterization of spray and mist drop size distributions will be described. The phase Doppler method developed by Bachalo and Houser [5] has undergone extensive development over the past 12 years [6,7,8,9] and has been thoroughly evaluated over a wide range of difficult applications. The instrument has the additional valuable capability of being able to measure the drop velocity simultaneously. This allows the determination of the drop dynamics in even the most complex flow field [10,11]. As with most turbulent two-phase flows that we have studied, it may be assumed that the interaction of the spray or mist with the turbulent air flow will serve to redistribute the spray. This information will be valuable in the analysis of the efficiencies of these methods in extinguishing fires. Other important capabilities of the method is the measurement of the local drop number density and volume flux. This information will be useful in estimating the delivery of the water to the burning surfaces.

The following sections will provide a description of the method in sufficient detail to allow the reader to appreciate its capabilities and limitations. Typical configurations of the instrument will be given to demonstrate the nonintrusive measurements can be made even in large scale facilities. An overview of the recent developments in the technology are presented to show how improvements in the instrument performance and accuracy have been made as well as simplifications to its operation. Representative test results will be provided in an effort to demonstrate the measurement accuracies of drop size and velocities, number density, and mass flux.

2.0 The Phase Doppler Particle Analyzer (PDPA)

Theoretical Description

The phase Doppler method is an extension of the well-known LDV method used for measuring the flow velocity. In addition to measuring the frequency of the scattered light, it was demonstrated by Bachalo and Houser [5] that the phase shift in the signals obtained from two or more adjacent detectors could be used to determine the size of spherical particles. A significant advantage of this approach is that the measurements depend upon the laser wavelength which is not altered by the intervening spray field as is the laser light intensity.

A helium neon or argon ion laser can be used as the light source for the instrument. The beam is split into two equal intensity beams and focused to an intersection with the transmitting lens, figure 1. In a simplified description of the method, it may be assumed that an interference fringe pattern is formed at the beam intersection as shown in figure 1. Light scattered by spherical particles passing through the beam intersection is collected by the receiver optics located at a suitable off-axis angle. A small aperture is used to limit the detection of light from only the beam intersection region. Unlike with the LDV, three detectors are used in the phase Doppler approach. Each detector receives light that passes through a segment of the receiver. The scattered light forms an interference fringe pattern at the plane of the detector that has a spacing that is inversely proportional to the particle diameter. By placing pairs of detectors or a segmented lens in the fringe pattern, two signals that have the same frequency but are shifted in phase will be measured, figure 2. Once again, in this figure, a simplified description of the approach is represented wherein a fringe pattern is assumed to be formed at the intersection of the two laser beams. The drop then acts as a magnifying element that projects the fringe pattern to the detectors. The magnification of the pattern is inversely proportional to the size of the drop. The phase shift in the time domain can be related to the spacing of the interference fringe pattern produced by the scattered light using the following simple relationship:

$$\frac{\Lambda}{s} = \frac{\phi}{360}$$

where Λ is the fringe spacing, s is the fringe spacing, and ϕ is the phase shift between the signals. It remains to accurately describe the functional relationship between the spacing of the scattered fringe pattern and the drop diameter. This has been carried out using the geometrical optics approach and the Lorenz-Mie theory. The response, as shown in figure 3, is linear which is the most desirable response for particle sizing.

Three detectors are used to extend the measurement size range while maintaining good size sensitivity. The two phase angles also serve as a redundant measurement for additional validation of the signals and allows the measurements to be carried out over phase angles greatly exceeding 360 degrees (typically, to as large as 1000 degrees). The large range in the phase measurements would allow the measurements of particles over a factor of 200 or more. However, the particles scatter light approximately as their diameter squared so the required detector amplitude response would be 10^4 for a size range of 50 to 1 if the effect of the nonuniform laser beam intensity is also taken into account. The recent development of the Fourier transform based signal processor has helped to extend this size range to a factor to 50 to 1 since the signals from small particles with a much lower SNR can be detected and processed reliably.

Theoretical Predictions of the Instrument Response

The detailed response of the phase Doppler method to the measurement of spherical particles has been described by Bachalo and Houser [5], Bachalo and Sankar [12], by Sankar et al. [13]. The original analysis, albeit correct, did not delineate all the details of the light scattering phenomena that could affect the performance of the instrument. Thus, a more detailed theoretical model of the light scattering phenomena was derived using the geometrical optics but accounting for the light scattering components. The physics of the light scattering can be better-examined and understood using the geometrical optics approach.

The details of the analyses are given in Sankar and Bachalo and only the pertinent results will be discussed here. As anticipated by Bachalo, the optimum light detection angle for most applications and especially when measuring water drops was determined to be 30 degrees from the forward direction. It is also possible to make reliable measurements at an angle of 150 degrees from the forward scatter direction. Oscillations were found to occur when measuring particles smaller than 3 µm if the light collection f# was not small enough. These oscillations were shown to be a result of the collection of light scattered by reflection, as well as the light scattered by refraction. The interference between these two light scattering components produced a secondary interference fringe pattern. The consequence of this is that the resolution for the small particles is limited to approximately 0.5 micrometer. This is not a limitation for the present application in which the measurement accuracy of particles smaller than 3 µm is not so critical. Similar resolution may be obtained in the 150 degree backscatter direction, provided that a sufficiently large aperture is used for the light collection.

In our more recent paper (Sankar et al.,[13]) we examined the effects of the random particle trajectories through the Gaussian beams. The particle trajectory through the Gaussian beam will affect the relative magnitudes of the light scattered by refraction versus that scattered by reflection. This could cause a measurement error as the phase shift attributable to reflection is different from that owed to refraction. The problem occurs for large particles that approach the diameter of the focused beam. When the drop passes on a trajectory that is to the side opposite the collection aperture, the peak intensity of the beam will strike the drop at a point that is reflected to the receiver. The incident intensity for the light scattered by refraction is low. Although the light scattered by refraction is approximately two orders of magnitude greater than that scattered by reflection, on these few trajectories, the scattered intensity by reflection can be significant and lead to a measurement error.

Both the theory and experiments were used to study this potential source of measurement error. We found that the error could be reduced significantly with the proper design of the optics. One approach that could be used was to increase the size of the focused beam diameter at the sample volume. However, this will create problems when attempting to size particles in relatively dense sprays. In such cases, the sample volume must be made as small as possible to insure a high probability of only a single particle existing in the sample volume at one time. Using our detailed analytical approach, it was discovered that the mutual interference between the reflection and refraction which have the same frequency not only depended upon the relative amplitude of these two scattering components but also upon the phase shift between them. In other words, the magnitude of the trajectory dependent sizing error depends upon the relative magnitudes of the reflected and refracted components and their individual phase shifts. By changing the laser beam intersection angle, it is possible to change the phase of the reflecting and refracting components, and; hence, the spatial frequency of the scattered interference fringe pattern.

The effect of changing the beam intersection angle was further investigated analytically and experimentally. A stream of monodispersed drops was directed on precise trajectories through the sample volume in these experiments. The trajectory of the drops relative to the beam radius was monitored using a video camera. These studies showed that with the proper selection of the optical parameters, the error resulting from the trajectory effect could be eliminated. Figure 4. shows the analytical and experimental results. Note that in this example, the drops used were 0.7 of the beam diameter which is a severe case. Most drops are much smaller than the focused beam diameter. However, it must be emphasized that in the accurate measurements of D30 and the volume flux, the few large drops contribute by far the largest amount to these parameters so these drops must be measured accurately. Generally, the phase Doppler method has been thoroughly researched and the recent studies have served to improve the performance of the system.

Implementation of the Method

The Aerometrics phase Doppler instrument has undergone a great deal of development and is being used effectively in numerous laboratory environments and industrial process control situations. For special applications such as monitoring drop size and number density distributions in test facilities, research and development has been conducted to produce the optimum systems for reliable and efficient data acquisition.

As stated in the previous section, the performance of the method depends heavily upon the attentive design of the optics. For example, the largest possible beam intersection angle is desirable for good resolution and accuracy when measuring small drops. Furthermore, the largest possible receiver aperture or, more accurately, the smallest f# (focal length / lens diameter) should be used. Generally, 30 degree light scatter detection will provide the best performance for the measurement of particles in the size range of 3 to 10,000 μm.

Aerometrics has built instruments both very large optical systems for measurements in large scale facilities such as used for icing studies at Boeing and for the U.S. Army helicopter rotor studies. These large Cassegrain mirror-based optical systems provide good performance while making nonintrusive measurements of particles in the size range of 1 to 500 μm. Compact systems with multiple sensor heads have also been developed for on-line quality control testing and monitoring. Systems have also been built for applications in hostile and corrosive environments.

Most appropriate for the present applications is the fiber optics based systems, figure 5. The use of single mode polarization preserving fibers allows the transmission of the laser beams to a compact probe while keeping the laser in a secure environment. In these systems, the laser beam is directed into the beam preparation module or Fiber Drive. Here, the beam is split into two and one is shifted in frequency. The laser beam wavelengths are then separated to form a four beam matrix. The four beams are steered into the fiber optics couplers. The couplers are used to precisely align the beams to the fibers which have core diameters of approximately 5 μm. At the transmitter end of the fibers, they are arranged in a four beam matrix at the design spacing and secured. A transmitter lens is used to focus the beams to an intersection to form the sample volume.

A large aperture receiver optics are used to collect the scattered light and and focus it through a small aperture. The light is then transmitted to the photodetectors using multimode fibers. This arrangement ensures good immunity from noise and allows ease of protection from moisture damage.

Signal Processing

One of the critical components of the phase Doppler method is the signal processing. The phase Doppler method has the disadvantage of requiring complex signal processing. However, this is outweighed by the advantage that the signal must be a sinusoidal wave which allows exceptional possibilities in discriminating signal from noise. Methods based on the measurement of signal amplitude, for example, do not have this possibility. Over the past decade, the signal processing technology for both LDV and PDPA applications has improved significantly. It is known that, of the methods available, the Fourier transform provides the optimum means for frequency and phase measurements. The Aerometrics Doppler Signal Analyzer (DSA) was designed to incorporate the Fourier analysis for both the frequency and phase measurements. This has significantly improved the performance of the phase Doppler method under conditions of low signal to noise ratio and high flow speed.

The DSA was developed to cover both LDV and PDPA processing tasks over a very wide range of frequencies. With the 160 MHz quadrature sampling (equivalent to 320 MHz sampling frequency), the DSA can process signals with frequencies to 150 MHz which corresponds to maximum flow speeds in the hypersonic range and a turbulence bandwidth to over 100 MHz. The system design incorporates several features that enhance the performance. The system, figure 6, consists of a master oscillator that drives the Bragg cell, the calibration laser diode, the mixers, and the analog to digital converters. Using a single frequency sources ensures that even extremely small errors are subtracted out of the system. In the electronics, the Doppler burst signal shown in the inset on the figure is high pass filtered to remove the Gaussian pedestal from the signal to leave a symmetric burst signal also shown in the inset. The signal is then mixed in quadrature with a sine wave to reduce the frequency. The high "sum" frequency is then removed by filteringwith a low pass filter and the signal is sampled with a high speed ADC. These sampled signals are then sent to the computer to be processed with the discrete Fourier transform in array processors.

Burst detection and centering is the first function of the system. This is one of the essential functions since with particle sizing, there is a very large dynamic range in signal amplitude and consequently, in the SNR between the largest and smallest particles. Failure to detect and measure the signals from the small particles reliably can seriously bias the measurements. The DSA uses both the signal power in the time domain and the SNR in the frequency domain for burst detection. Time domain burst detection is the conventional approach wherein the signal is rectified and essentially squared and then a threshold is used to detect the burst when the voltage rises above the threshold level. This approach works well when the SNR is greater than about 5 dB. The method will fail to efficiently detect the burst signals at lower SNR.

Recently, we have developed an innovative approach to burst detection using the Fourier transform (patent pending). The incoming signal is continuously sampled with this method irrespective of whether a Doppler burst signal is present or not. A 16 point discrete Fourier transform (DFT) is performed on the record at a maximum rate of 20 million DFT's per second. Thus, no part of the incoming record is missed. The SNR values of these DFT's are compared to a preset level in real time to determine if a coherent signal was present. Burst detection occurs based on the SNR exceeding this level. The method has the significant advantage of being independent of the background noise amplitude that may result from flare light and it is also independent of the signal amplitude. This is important in particle sizing where the signal amplitude varies with the particle size. The method can reliably detect Doppler burst signals even when the SNR is below 0 dB. Furthermore, the signal frequency is determined to sufficient resolution with the burst detector, so that signal frequencies corresponding to velocities outside the selected range can be ignored. Hence the burst detector can perform a filtering function. The burst detector does not require adjustment as the measurement conditions change as in the case of the time domain burst detector which helps to simplify the operation of the instrument.

Evaluations were made using simulated and real Doppler burst signals. In these studies, the SNR (recorded after filtering the signal) was decreased in steps and the data rate measured. The frequency measurements remained accurate to within 0.2 % throughout the range of SNR. Note that in figure 7, the time domain burst detector validation rate drops rapidly for SNR below 5 dB. On the other hand, the FTBD validation does not begin to fall until the SNR drops below -5 dB. This shows the remarkable improvement in detecting the Doppler burst signals with the FTBD.

Volume Flux and Number Density Measurements

Perhaps the most difficult task has been to achieve acceptable accuracy in the measurement of the volume flux and the drop number density. Both quantities depend upon the accurate definition of the sample volume. For example, the volume flux is given by

$$F = \frac{\pi}{6} D_{30}^{3} \frac{N}{At}$$

where N is the number of drops measured and A is the probe area. Previously, the sample volume was determined using the measured diameter of the beam waist and the length along the beam delineated by the receiver aperture. Because of the Gaussian beam profile, the effective diameter of the sample volume will change with the particle size. That is, small particles must pass closer to the high intensity center of the beam than larger particles to produce a detectable signal. This behavior can also be predicted using the fact that the beam intensity profile is Gaussian. Because of this behavior, the measured variation in the sample volume size must be used to correct the size distribution. The problem of determining the sample volume size accurately is further exacerbated by attenuations of the beam and scattered light resulting from the intervening drop field and windows, if any. For this reason, Aerometrics has developed an in situ means for measuring the probe volume size.

The diameter of the sample volume can be measured by measuring the transit times for particles in each size class. Reliable measurement of the transit time requires reliable burst and burst length detection which has been achieved with the FTBD. A statistical distribution of particle trajectory lengths through the probe volume are computed by taking the particle velocity times its transit time and these results are accumulated for each drop size class. The maximum measured lengths in each distribution indicates particles that passed through the diameter of the probe volume and; hence, can be used as a measure of the diameter. These results are then fit with the theoretical curve and used to estimate the probe volume size and the correction needed to make the sampling probability the same for all size classes.

The probe length is also a significant parameter in defining the sample volume size. This length is delineated by the aperture in the receiver, the magnification of the receiver and the off-axis light detection angle. Although high quality air-spaced triplet lenses are used in the receiver, there is a degree of blur in the image of the drops formed on the aperture. Clearly, the cutoff of the particles by the aperture will also depend on the size of the drop. A larger drop passing just outside the slit image across the beam may still produce a detectable signal. Smaller particles passing on the same trajectory will not be detected. This bias has not been addressed previously and may be the cause of the variance observed in the number density and flux data. Analysis of this effect is currently being carried out.

3.0 Validation of the Results

Evaluations of the Particle and Velocity Measurements

Over the past decade, the Aerometrics Phase Doppler Particle Analyzer has undergone very extensive tests to prove its reliability and accuracy while performing measurements under a wide range of conditions. The most basic approach used in the calibration and testing of the instrument is the monodispersed drop generator. This device produces a laminar jet of water at a precisely set flow rate. A sinusoidal disturbance at the Rayleigh frequency is imparted to the jet to cause the jet to break up at the excitation frequency to form drops of uniform size. These drops are formed to monodispersed sizes that can be determined to within a fraction of a percent error. Measurements of these drops represents an ideal situation for the instrument and calibration and repeatability of the measurements are most often to within a 1% error bound.

Other means have also been devised for evaluating the measurement accuracy under more realistic conditions. A mixture of classified polystyrene particles (PSL) was used to simulate a particle size distribution that would be representative of a mist has been used. In this case, 4 different sizes were mixed together in proportions by counts that would simulate a particle size distribution. The measurements were made with a standard phase Doppler instrument configured to have a minimum size resolution of +/-0.5 μm. As can be seen from the results, figure 8, the data agree with the expected sizes. The spread in the measurements for each size class is due, in part, to the spread in the PSL samples.

Comparative measurements have also been made to other established techniques. Figure 9 shows a comparison of data obtained in the NASA Lewis Icing Research (IRT) wind tunnel [14]. In this facility, aircraft icing clouds are simulated. A great deal of care has been devoted to the cloud drop simulations and measurements since this facility is a national resource used in the FAA certification process for aircraft. The "calibration" data shown on the plot were obtained with the PMS probes (Particle Measuring Systems). This was the preferred approach until the development of the Aerometrics PDPA instrument. Note that the agreement in the measurements is good except that the PDPA data show smaller median volume diameters at the highest operating pressure. This may be due to the fact that the PDPA is more sensitive to the smaller drops.

In figure 10, comparisons were made to the Malvern instrument that use Fraunhofer diffraction as a means for sizing the drops. This instrument performs a line-of-sight measurement. In order to make comparisons to the point measurements across the spray made with the PDPA, Dodge [15] performed a deconvolution on the measurements using the Abel inversion scheme. As can be seen in the figure, the agreement is excellent providing confidence in the measurement capabilities of both methods.

Evaluations of the measurements in realistic spray environments were conducted using a less direct approach. There is a very high level of confidence in the measurements of the drop velocities. In this capacity, the instrument is simply a laser Doppler velocimeter and as such, is a highly developed technology. The approach used to evaluate the sizing capability was to generate a spray in our two-phase flow wind tunnel and allow it to impinge on a cylinder [16]. The flow along the stagnation streamline can be easily calculated or measured based on particles of less than 5 μm in diameter. Measurements of the drop size and velocity were obtained at stations well upstream of the cylinder and at stations up to the cylinder surface. The drop lag (difference between the local drop velocity and the air flow) will be proportional to the drop mass, figure 11. With the assumption of a suitable drag law, the particle size can be calculated from the velocity lag. These results were compared to the measured drop sizes and found to be in excellent agreement.

This approach is useful in evaluating the instrument under a range of conditions including different drop size distribution, flow turbulence levels, and drop number densities.

Evaluations of the Particle Number Density and Volume Flux Measurements

Significant effort has been devoted to the verification of the number density and volume flux measurements. Experiments that involved measuring the radial distributions of sprays and comparing the integrated volume flux to the flow rate into the nozzle have been used. When these tests were conducted carefully and the atomizer produced a uniform axisymmetric spray, good agreement was achieved. We have also used sampling probes positioned under the measurement point of the PDPA to collect a sample for determining the actual volume flow rate. These results were compared to the PDPA data and sample results are shown in figure 12. In this case, where the direction of the drops was known to be nearly unidirectional, the agreement was excellent. If the drops are in a highly turbulent swirling environment, the results are not always as reliable.

More recent work has been devoted to the further development of the methodologies required for measuring the number density and volume flux in highly turbulent flows [17]. Number density measurements were obtained in various swirling and non-swirling sprays. Comparative measurements of the number density were made using beam extinction and the Beer-Lambert Law along with the size distribution measurement. An example of these results are shown in figure 13.

Liquid water content (LWC) data were obtained at NASA Lewis and compared to their data obtained with other methods. These data are shown in figure 14. Although there is some scatter in the results, the greatest portion of the results falls within a +/-10% error band. It should be acknowledged that the methods used for comparison will also have some variance in their results. Thus, we have further confidence in the potential measurement accuracy for the mass flux.

Summary

The phase Doppler method has evolved as a very useful research tool for spray characterizations. The drop size distributions are measured directly with this instrument without a need for distribution functions or elaborate and unreliable inversion schemes. Since the measurements are based on the wavelength of the light, the results are not affected by the intervening spray environment. Another significant advantage of the system is that it does not need calibration after leaving the factory. The optical systems have been designed to cover a wide range of applications from small compact probes to large systems for long range measurements. Signal processing based on the Fourier transform has led to a significant improvement in the instrument performance especially when conducting measurements in difficult environments.

The theoretical analysis of the technique has been thoroughly researched over the past ten years and the parameters affecting the measurements are well understood. There remain some special cases such as the measurement of slurries and other multi-phase drops that require additional study.

The measurement accuracy of the method has been evaluated by a number of researchers and found to be better than required for most research applications and for other quality control tasks. The size and velocity measurements have been shown to be exceptionally reliable. Measurements of the number density and volume flux have not always been as satisfactory. However, a combination of developments in both the signal processing electronics and the software algorithms have led to some significant improvements in this area.

Acknowledgements

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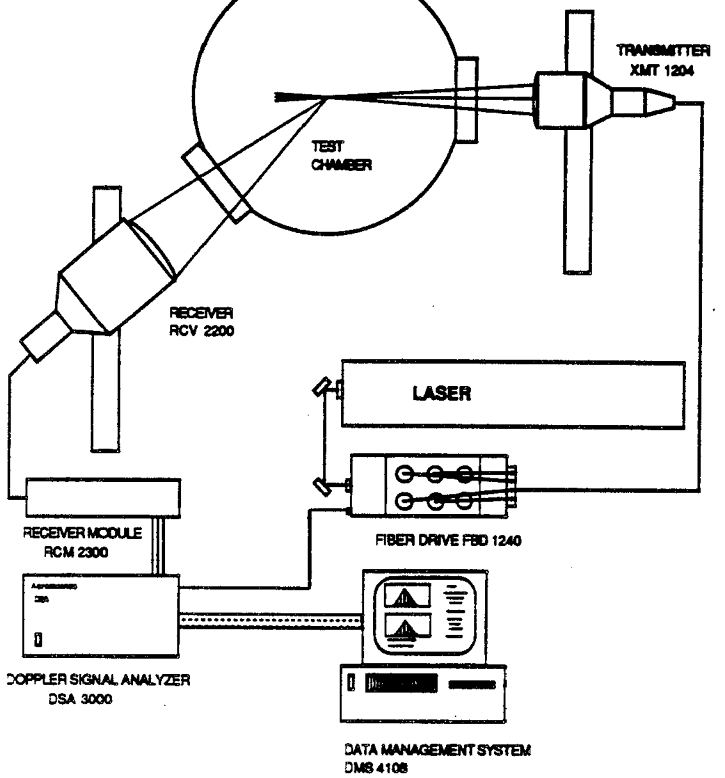

Figure 5. Schematic of the Two-Component Phase Doppler Particle Analyzer Using Single Mode Polarization Preserving Fibers on the Transmitter, Multimode Fibers For the Receiver, and the Advanced Fourier Transform Signal Processor, DSA.

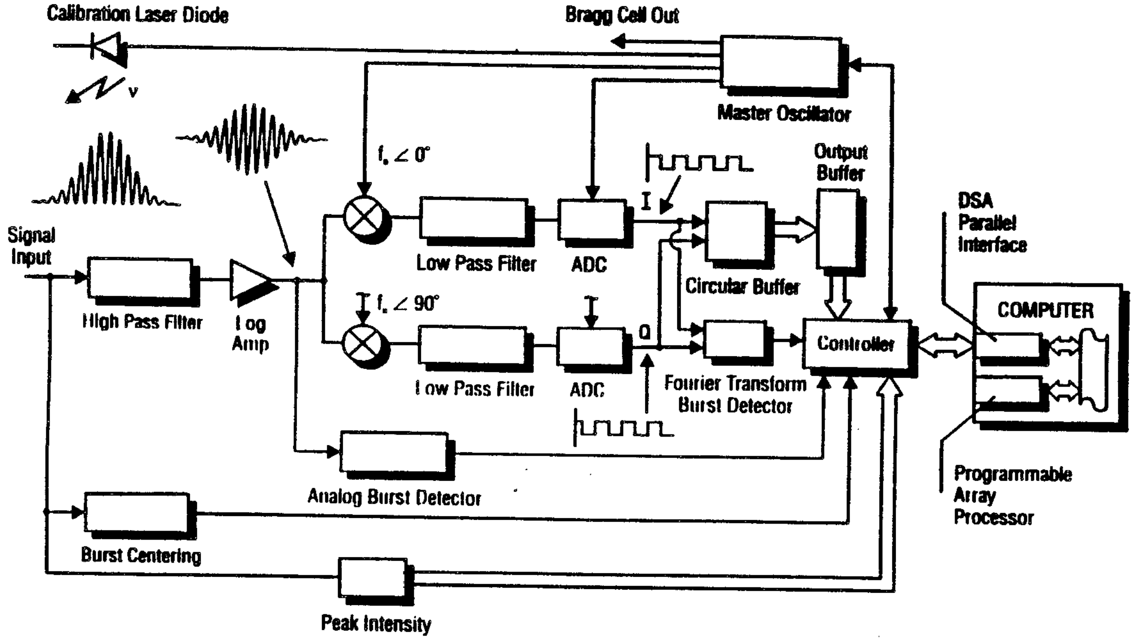

Figure 6. Block Diagram of the DSA Fourier Transform Signal Analyzer (DSA) Showing the Signal Filtering, Down Mixers, Analog-to-Digital Converters, and the Burst Detection System.

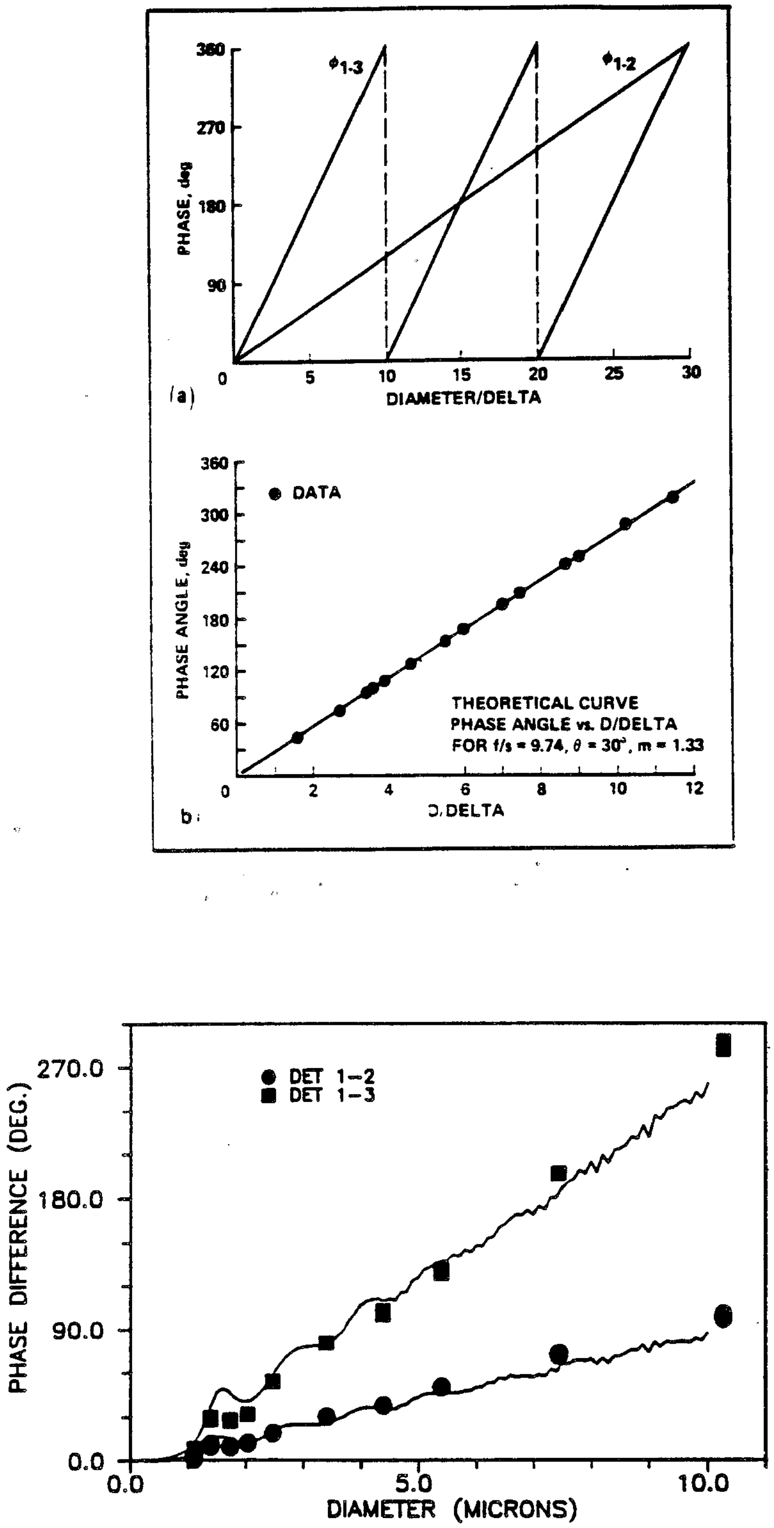

Figure 3. Theoretical Prediction Showing the Phase Variation With the Dimensionless Drop Size: (a) Relationship for Three Detectors and (b) Comparisons With Experiment for Very Small Particles, (c) Comparisons Using a Dimensionless Size Format.

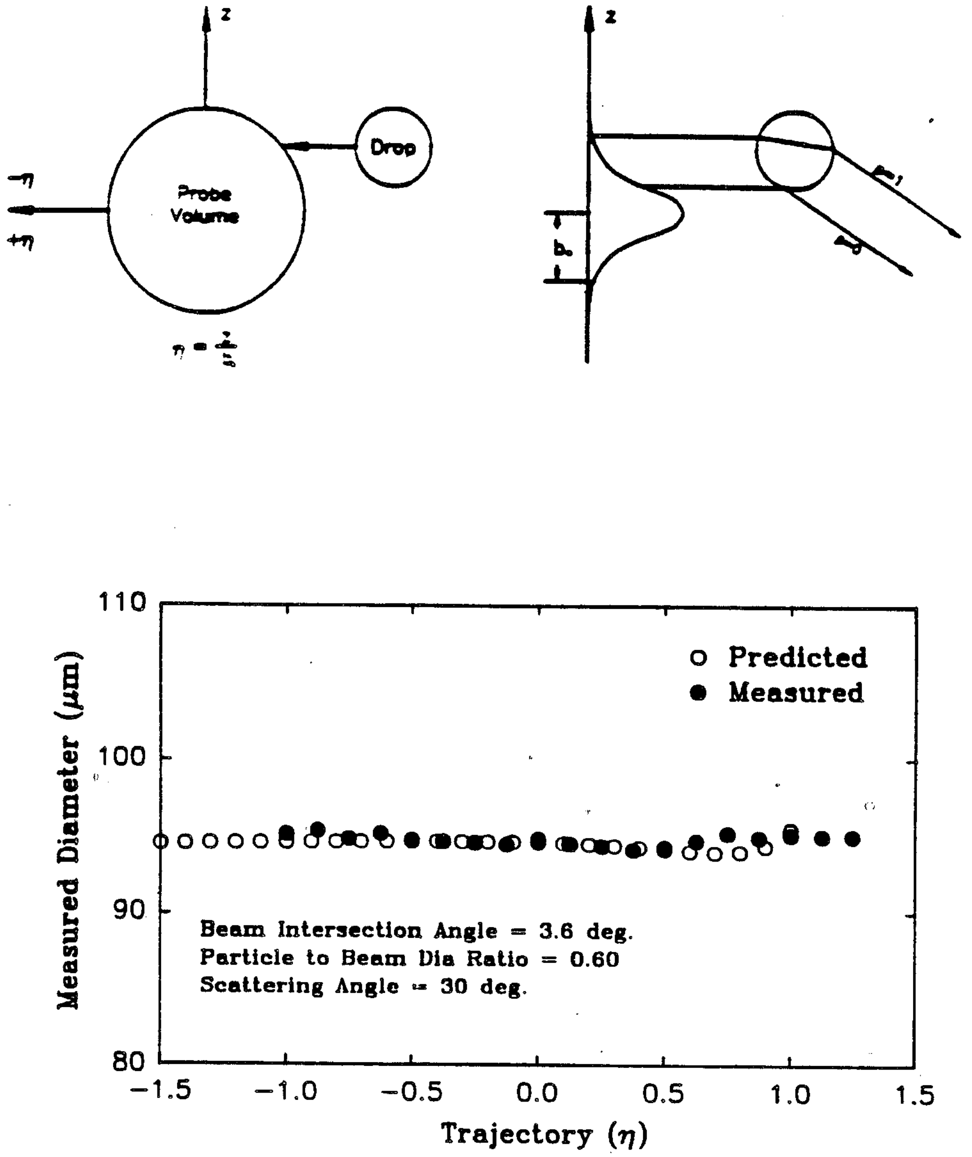

Figure 4. Analysis of the Trajectory Dependent Light Scattering Showing a Schematic of the Particle Trajectory Through a Gaussian Beam, the Light Scattering Mechanisms of Reflection and Refraction Involved, and the Improvement Using a Larger Beam Intersection Angle.

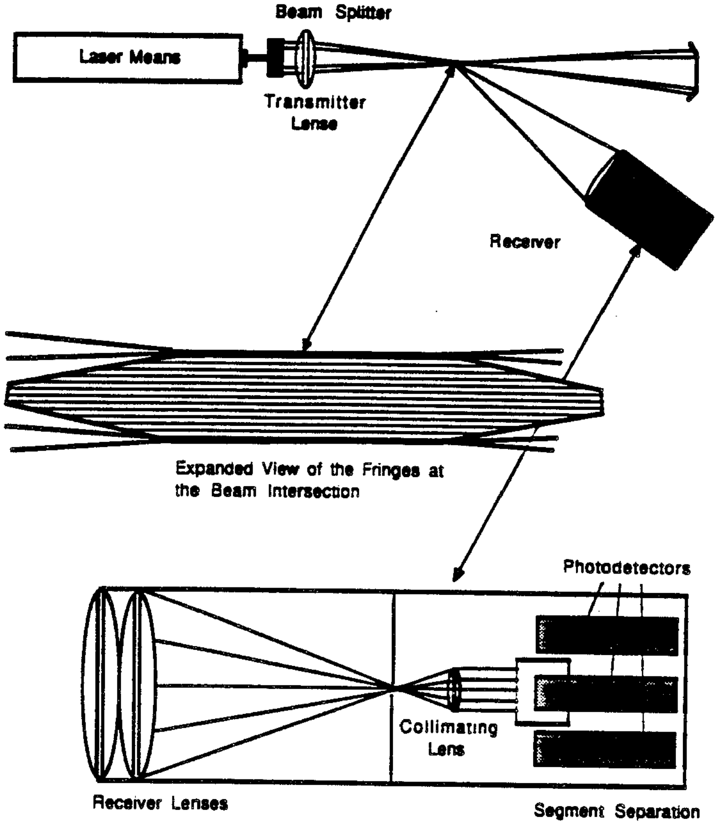

Figure 1. Schematic of a Basic Phase Doppler Optical System showing the Transmitting and Receiving Optics, the Fringe Pattern Formed at the Beam Intersection, and the Construction of the Receiver with the Segmented Lens and the Three Detectors.

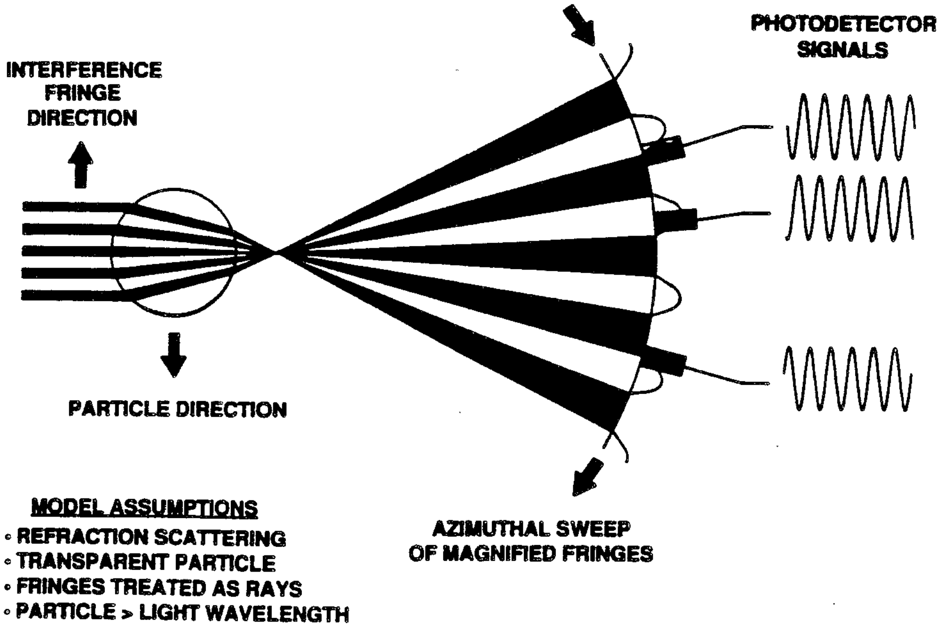

Figure 2. Diagram Illustrating the Method With the Fringe Model Where a Fringe Pattern is Formed at the Sample Volume and the Drop Projects the Pattern to the Receiver.

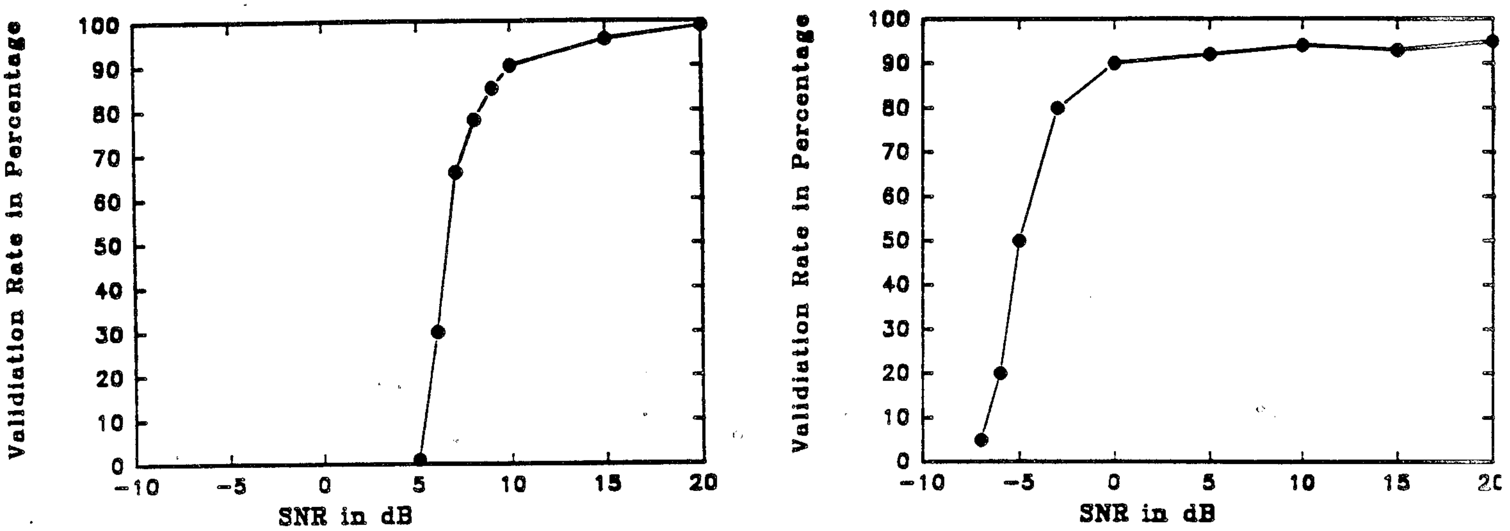

Figure 7. Plots Showing the Performance Comparison Between the Conventional Analog Burst Detector and the New Fourier Transform Burst Detector Indicating How Reliable the Method Is Even at Low Signal To Noise Ratios.

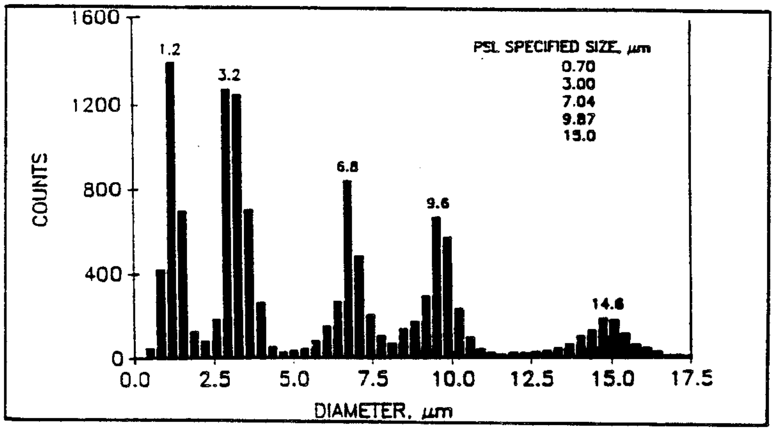

Figure 8. Validation of the PDPA Particle Size Measurements Using a Mixture of Polystyrene Particles of Five Known Sizes and In a Proportion to Simulate a Size Distribution.

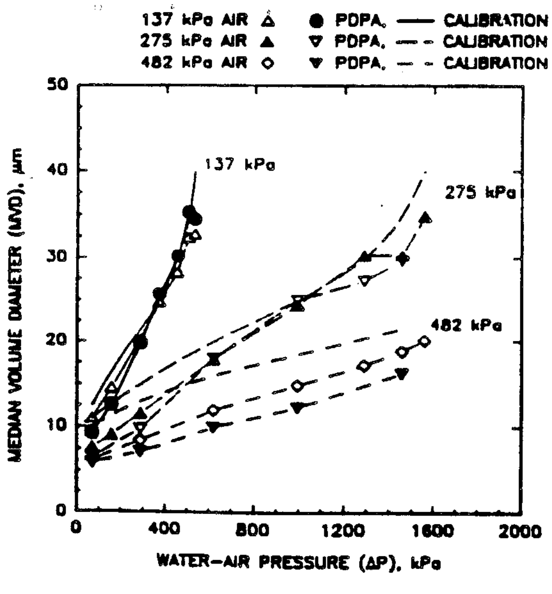

Figure 9. Validation of the PDPA By Way of Comparison to Measurements Obtained With a PMS Instrument For Data Obtained in the NASA Lewis Icing Research Wind Tunnel.

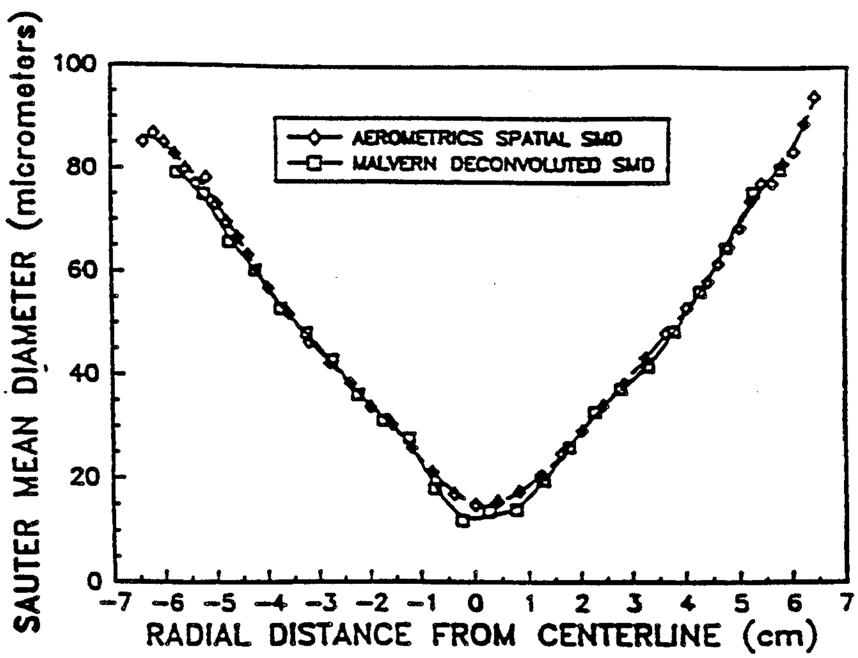

Figure 10. Comparisons of a the Radial Spray Distribution of the Spray Sauter Mean Diameter With the Malvern Fraunhofer Diffraction Method and Using an Abel Deconvolution on the Malvern Data.

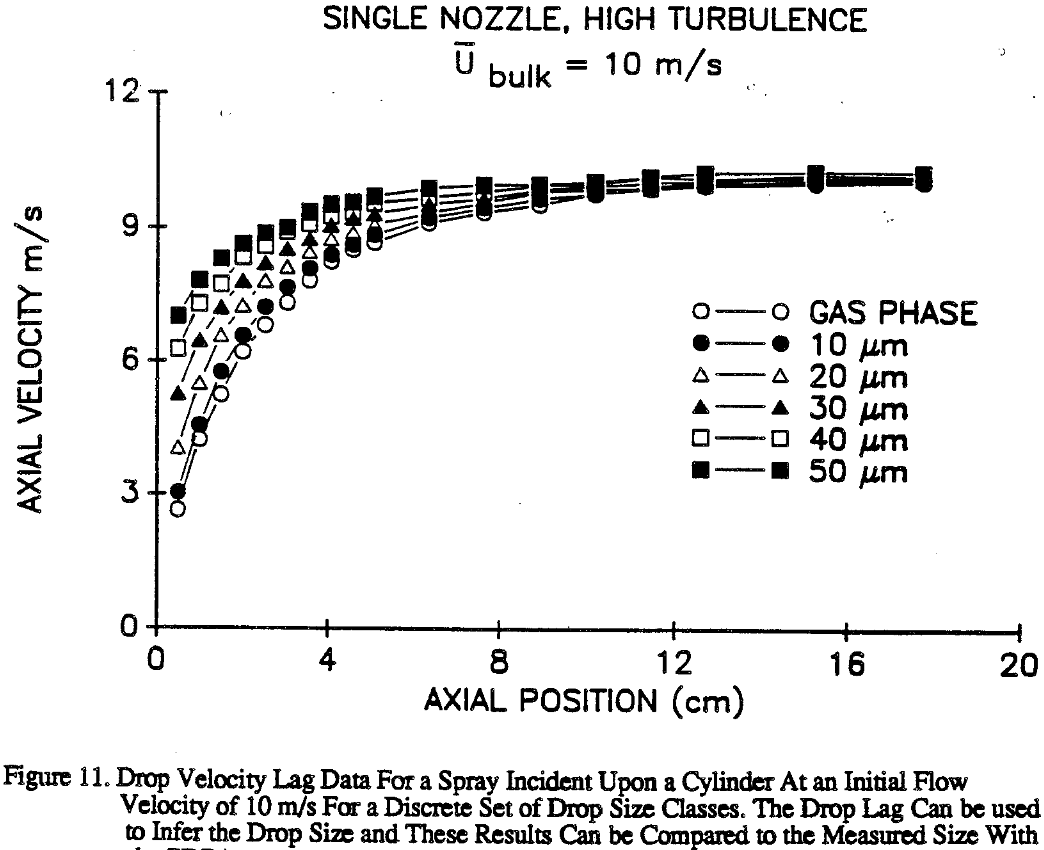

Figure 11. Drop Velocity Lag Data For a Spray Incident Upon a Cylinder At an Initial Flow Velocity of 10 m/s For a Discrete Set of Drop Size Classes. The Drop Lag Can be used to Infer the Drop Size and These Results Can be Compared to the Measured Size With the PDPA.

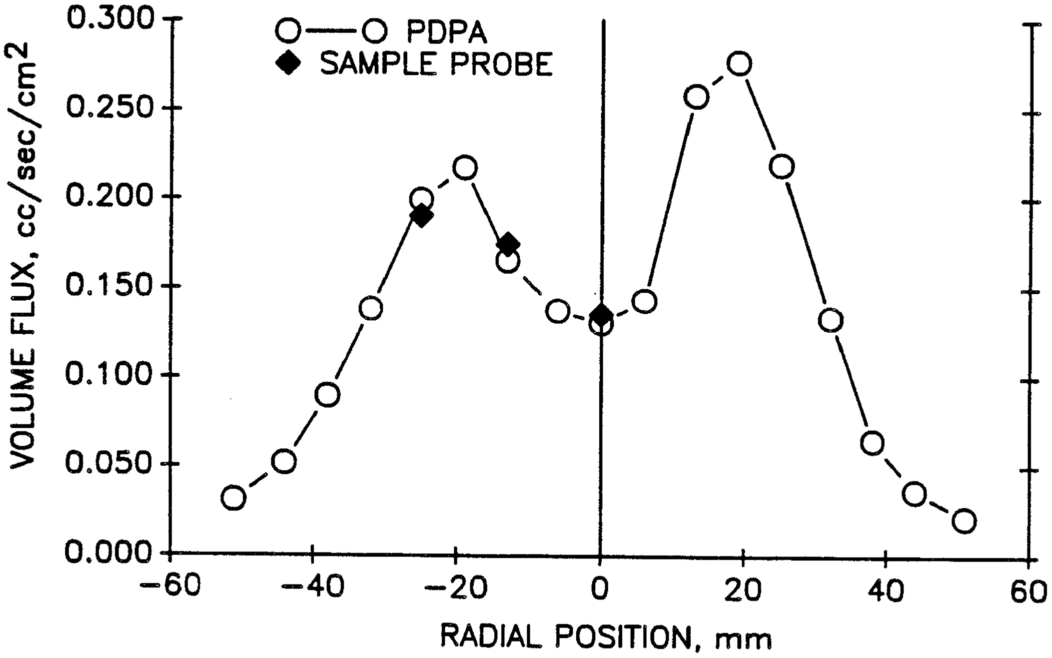

Figure 12. Volume Flux Measurements of a Spray With Measurements Compared to Sampling Probe Data.

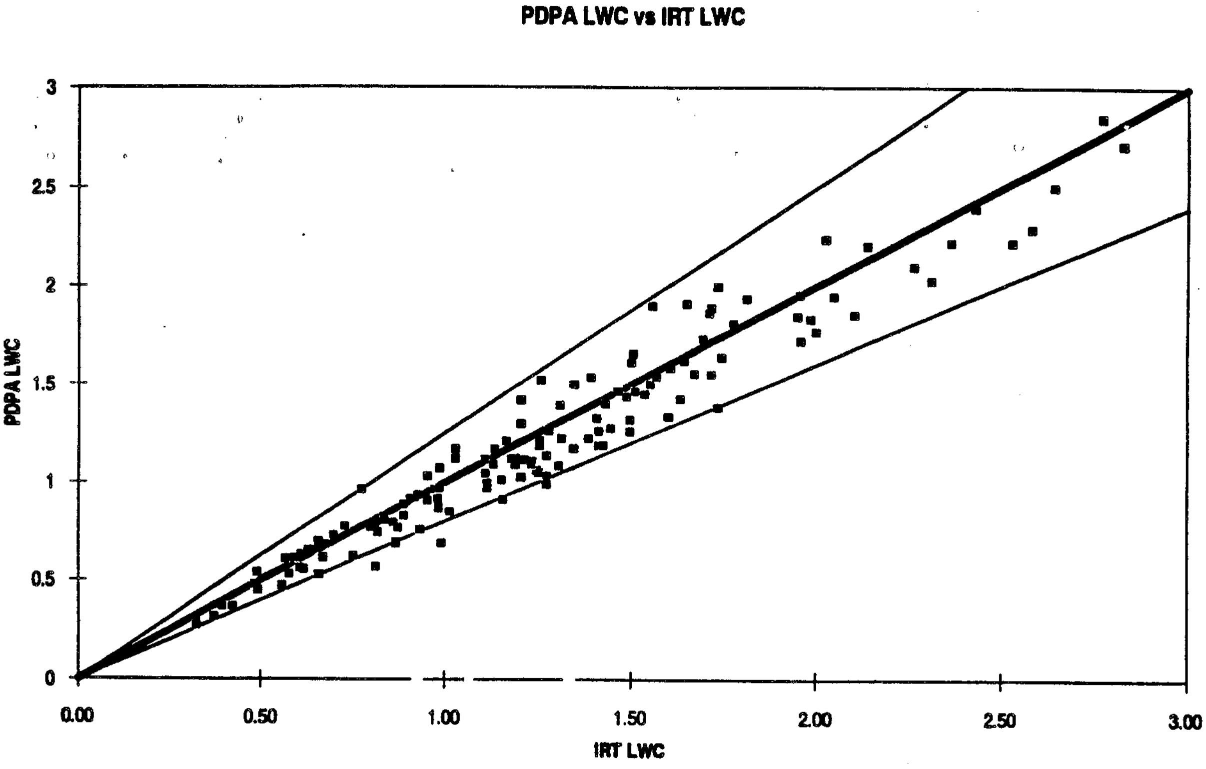

Figure 13. Liquid Water Content (LWC) Data Obtained in the NASA Lewis Icing Research Tunnel With the PDPA and Compared With Other Methods For Obtaining These Data.