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Authors

McDonell, VG
Samuelsen, GS

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APPLICATION OF TWO-COMPONENT PHASE DOPPLER INTERFEROMETRY TO THE MEASUREMENT OF PARTICLE SIZE, MASS FLUX, AND VELOCITIES IN TWO-PHASE FLOWS

V. G. McDONELL AND G. S. SAMUELSEN
UCI Combustion Laboratory
Department of Mechanical Engineering
University of California
Irvine, CA 92717

The application of two-component interferometry is described for the spatially-resolved measurement of particle size, velocity and mass flux as well as continuous phase velocity. Such a capability is important to develop an understanding of the physical processes attendant to two-phase flow systems, especially those involving liquid atomization typical of a wide class of combustion systems. Adapted from laser anemometry, the technique (phase Doppler interferometry) measures single particle events at a point in the flow. Droplet size is deduced from the spatial phase shift of the Doppler signal. Combined with conventional laser anemometry for the resolution of velocity, the added capability of sizing allows for the discrimination of the discrete phase velocity statistics from those of the continuous phases as well as the particle mass flux. Applications are presented for four cases: an example of the discrimination of two sizes of glass beads in a jet flow, a demonstration of the discrimination of phases in a spray field, an assessment of atomizer symmetry with respect to fuel distribution, and a characterization of a droplet field in a reacting spray. In addition, the limits of applicability are discussed.

Introduction

The performance of liquid fueled combustion systems is associated, in part, with the formation, evaporation, and burnout of droplets. In particular, the atomization and evaporation of the liquid fuel, the mixing of the fuel and evaporated vapor with the air, and the burning of the resulting two-phase mixture influence the overall combustion efficiency, stability, and pollutant emission.

Insight into the behavior of two-phase liquid systems has been limited by the inability to measure the basic characteristics of the discrete phase, namely the droplet size distribution, the droplet velocity distribution, the droplet mass flux, and the dilute phase velocity at a point in the flowfield. Such data are essential not only for the physical insight, but for the development and verification as well of the models and numerical codes that are necessary to understand the physics of fuel-air mixing and reaction in this class of flows.

A relatively new technique, phase Doppler interferometry,[1] represents an opportunity to more fully explore the behavior of individual droplets in a relatively high density dispersion of droplets. The technique has the distinct advantage, as well, of differentiating the continuous phase (i.e., gas) from the discrete phase (e.g., droplets). In the two-component configuration described herein, the technique is especially powerful in delineating droplet interactions in the swirling, complex flows typical of realistic systems.

The objective of the present paper is to describe the technique, illustrate the use of the method in experiments representative of combustion problems, and to address the utility and limits of applicability of the technique.

Background

Overview:

The characterization of two-phase flows requires both spatially- and temporally-resolved measurements of: 1) mean and rms gas velocity; 2) mean droplet size and droplet size distribution; 3) mean and rms droplet velocity; 4) droplet mass flux.

Higher moments of the statistical properties, including correlations, are desirable as well. The spatial-resolution is required to establish time-averaged structure of the discrete and continuous phase. Temporal-resolution is required to identify the dynamics, both local and global, that influence and may dominate the flow structure, and thereby control the system performance.

Measurement techniques for the discrete phase are described in a number of reviews (e.g., Ref. 2 and 3). In general, the techniques can be envisioned as divided among two categories: optical visualization methods (including high speed photography, holography, TV imaging) and optical scattering methods. The focus of the present paper is on the interferometric based phase Doppler, an optical scattering method that is not covered in prior reviews as a result of its more recent introduction and evaluation. While other interferometric approaches[4,5,6,7] provide the potential of obtaining the requisite data, the phase Doppler (PD) approach shows the best promise.

The phase Doppler approach is based on the linear dependency of the Doppler burst spatial phase shift with droplet size.[8] The approach utilizes a fringe mode laser anemometry probe volume. By using two detectors, each observing a different area of the receiver lens, the spatial shift of the fringe image can be deduced. To eliminate ambiguity associated with spatial phase shifts of over 360 degrees, and to extend the dynamic range, a third detector is added. The dynamic range for droplet size is greater than 35. The technique has been evaluated in a variety of experiments.[5,8,9] In a two-component configuration, significant additional information is provided. For example, direct measurements of shear stress correlations are obtained. In addition, the second component permits trajectories to be measured, and quantifies any dependency of trajectory on particle size. Third, the second component improves the measurement of volume flux by enabling a more accurate determination of the sampling volume to be made.

The approach taken in the current work is to describe the two-component phase Doppler instrument, and present four applications of direct interest to combustion systems.

Two-Component Phase Doppler Instrument

Figure 1 shows a schematic of the two-component phase Doppler interferometric system. Figure 1a delineates details of the transmitter (Aerometrics Model 1100-3S). A 1-watt Ar^+ laser (Lexel Model 85) is used in the present application. The beam is chromatically split by a dichroic mirror into 488.0 nm and 514.5 nm wavelength beams. Each beam is then passed through a chromatic filter to ensure that no other wavelengths are present in the probe volume to be formed. In addition, the polarization of the blue beam is rotated 90-degrees from that of the green. The resulting filtered beams are each focused onto a diffraction grating which splits each beam into ordered pairs. The two first order beams of each wavelength are then recombined onto the original optical axis using a dichroic mirror, collimated, and focused by a transmitter lens to form the two-component probe volume. Various combinations of grating linepair counts and collimating and transmitting lens focal lengths are used to provide an overall sizing range of 0.8–900 microns and velocity ranges for each component of −20–130 m/s. The dynamic sizing range is 35:1 and the dynamic velocity range is 8:1. To discriminate flow direction and to broaden the velocity range, the diffraction gratings are rotated to provide frequency shift.

The layout of the receiving optics and detectors (Aerometrics Model 2100-3) is shown in Fig. 1b. The f/5 receiver lens collects the scattered light. The probe volume image collected by the front lens is focused onto a 100 micron by 1 mm slit and then collimated and split into four areas as indicated in Fig. 1b. The collection system is designed to account for misalignment due to chromatic aberration. Three of the four areas are examined by a separate photomultiplier. One component of velocity for each event is determined by the temporal frequency of the doppler burst obtained by detector 1. A polarization beam splitter separates the signals from each component, and a fourth detector is used to obtain the signal for the second velocity component.

The spatial frequency of the doppler burst is determined by a ratio of signal time shift between two detectors to the period of a single fringe crossing. Figure 1c shows an example of the time shift between signals from detector 1 and 3. The use of this ratio isolates the spatial phase shift from the temporal shift. The spatial shift is inversely proportional to the size of the scatterer.[1] Photodetector gains, signal processing, frequency shifting, and data reduction are accomplished with an IBM AT personal computer. Without the chromatic separation in the transmitter and receiver and without the fourth detector, the above system is reduced to a single component system.

The system simultaneously measures the velocity (either one or two components) and the size of individual scattering events. In addition, the instrument measures the cross sectional area of the probe volume during the measurement and uses this in conjunction with the size and collection time to determine the volume flux at each point.[10]

Direct comparison of droplet size measurement made by phase Doppler and by diffraction can be made if corrections are made for the type of measurement. The diffraction measurement is based on an average of "snapshots" taken along a path in the spray. As such, the measurement is biased towards slower moving drops.[9] This type of distribution is referred to as a "spatial" or "volume-sensitive" distribution. Since the phase Doppler makes simultaneous measurement of size and velocity, any dependency of drop velocity on size can be removed. In addition, since the variation in probe size for a

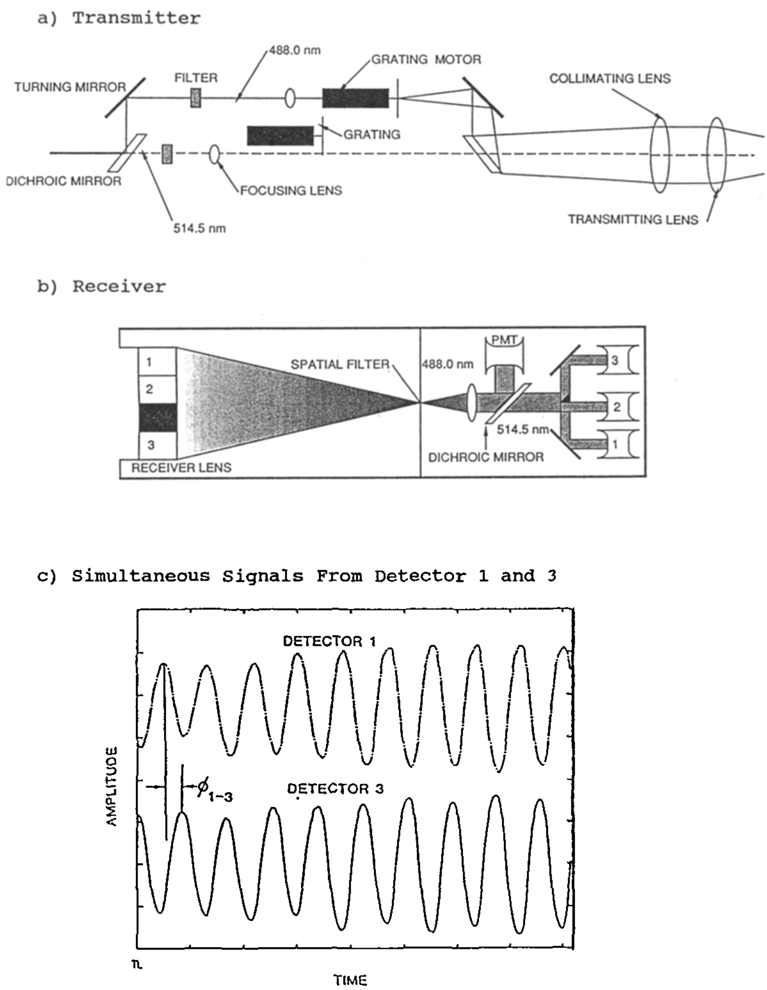

FIG. 1. Two-component phase Doppler System. a) Transmitter b) Receiver c) Simultaneous Signals from detectors 1 and 3.

given radial profile is deduced, the spatially resolved flux-sensitive measurement made by the phase Doppler can be compared to the volume-sensitive measurement made by diffraction.

Figure 2 shows an example of the comparison between the distributions made at 3 axial stations in a spray field from an air-assist atomizer.[11] Note that the comparison is most favorable at a distance far from the atomizer. This is attributed to the high number density of the spray near the atomizer and subsequent multiple scattering causing a reduction in the size measured by diffraction.[12]

Results and Discussion

Four applications of the instrument are presented, ranging from examples of fundamental interest to examples of practical interest in combustion: 1) discrimination of two different sized glass beads, 2) a demonstration of the discrimination of phases in a spray field, 3) an assessment of atomizer symmetry with respect to fuel distribution, and 4) a characterization of a droplet field in a reacting spray.

Discrimination of Two Different Sized Beads in a Gas Jet:

As a first step in the understanding of the processes occurring in two-phase flows, the development of flows laden with monodispersed, nonevaporating particles is studied. The provision of the flowfield of interest places restraints on the particles used. Glass beads are utilized in the present study due to their availability in narrow size ranges

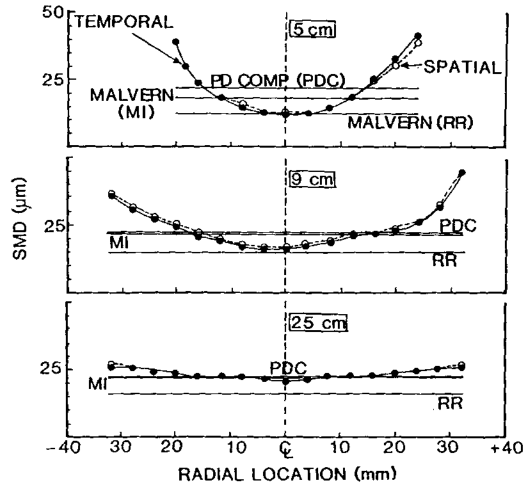

FIG. 2. Comparison of Phase Doppler and Diffraction based Drop Size Measurements.[11]

at relatively low cost. Figure 3a shows an example of one size range of beads obtained from the manufacturer. The shards and small satellite beads were removed via air classification to produce the product used in the study as shown in Fig. 3b. This optimization procedure was conducted for two different size groups (20–30 and 100–110 microns).

The two sized beads are then injected in equal number into an axisymmetric turbulent jet ($D_{inlet} = 24.9$ mm). Figure 3c shows an example of the histogram obtained using phase Doppler. This size range indicated by phase Doppler is broader than that indicated by microscopic examination. This is due to several factors which are delineated in the next section. Figure 3d presents the associated size-axial velocity correlation. By separating each group by size, the velocities of each particle size is deduced at points throughout the flow.

Figure 3e presents radial profiles of mean axial velocities for each size group at three axial distances from the pipe injector. In addition to the bead velocities, the velocity of the gas phase is also presented to establish the extent and direction of momentum transfer between the phases. The gas phase velocities are deduced in the same manner which is outlined in the next application. The profiles demonstrate that momentum is transferred between phases. The direction and magnitude of the transfer is a function of the particle size. In general, the smaller particles follow the gas phase more closely than do the larger particles. Note that at 2 and 50 mm (in the developing region of the jet) the direction of momentum transfer relative to the two phases changes at a certain radial position. At 150 mm (in the fully developed region), momentum is transferred only from the beads to the gas, and the slip velocity of the larger particles is uniformly greater than it is for the small particles.

Discrimination of Phases in a Spray Field:

As diagnostic and numerical analysis tools become more sophisticated, there is an increased need to not only characterize the spray field, but the gas phase as well. In this manner, the effect of interphase transport may be evaluated. Various approaches have been used to electronically discriminate between phases with varying degrees of success when applied to monodispersed particle laden flows similar to that described above.[13,14,15,16]

Using the phase Doppler technique, it is possible to physically discriminate between phases, and therefore provide discrimination not only in mono or bi-dispersed flows as demonstrated above and elsewhere,[17,18] but in polydispersed flows as well. The approach utilizes the ability of the phase Doppler technique to size all scatterers. In the current flow, particles which are less than 3 microns in diameter are used to represent the gas phase. Hence, velocities of particles which size as less than 3 microns (seed particles and very small drops) are extracted from the rest of the data and used to generate the statistics for the gas phase.

Radial profiles of the axial turbulence intensity are presented in Fig. 4a. The presence of the spray reduces the gas phase turbulence intensity. The consequences of this are shown in Fig. 4b, where isopleths of the mean axial velocity are presented. The gas phase flowfield is narrowed, and the radial velocity gradients are steeper when the spray is present. In addition, asymmetry in the continuous phase radial spread is dampened by the presence of the spray.

Detailed information such as this is critical to understanding the fundamental processes occurring in spray fields produced by practical atomizers. The improvement of codes to solve two-phase flowfield requires information of the type displayed in Fig. 4. The ability to measure both phases also leads to the assessment of droplet drag coefficients.[19]

Assessment of Symmetry using Volume Flux Measurements:

The assessment of spray symmetry, like the measurement of both phases in the spray field, is increasing in importance. Higher performance requirements, coupled with the need for lower weight to thrust ratios, create the need for high tolerance atomization performance and the generation of a highly uniform spray field. Hot streaks tied to an asymmetry in the distribution of fuel in current practical injectors cannot, in the future, be tolerated.

Assessment of fuel distribution is typically per-

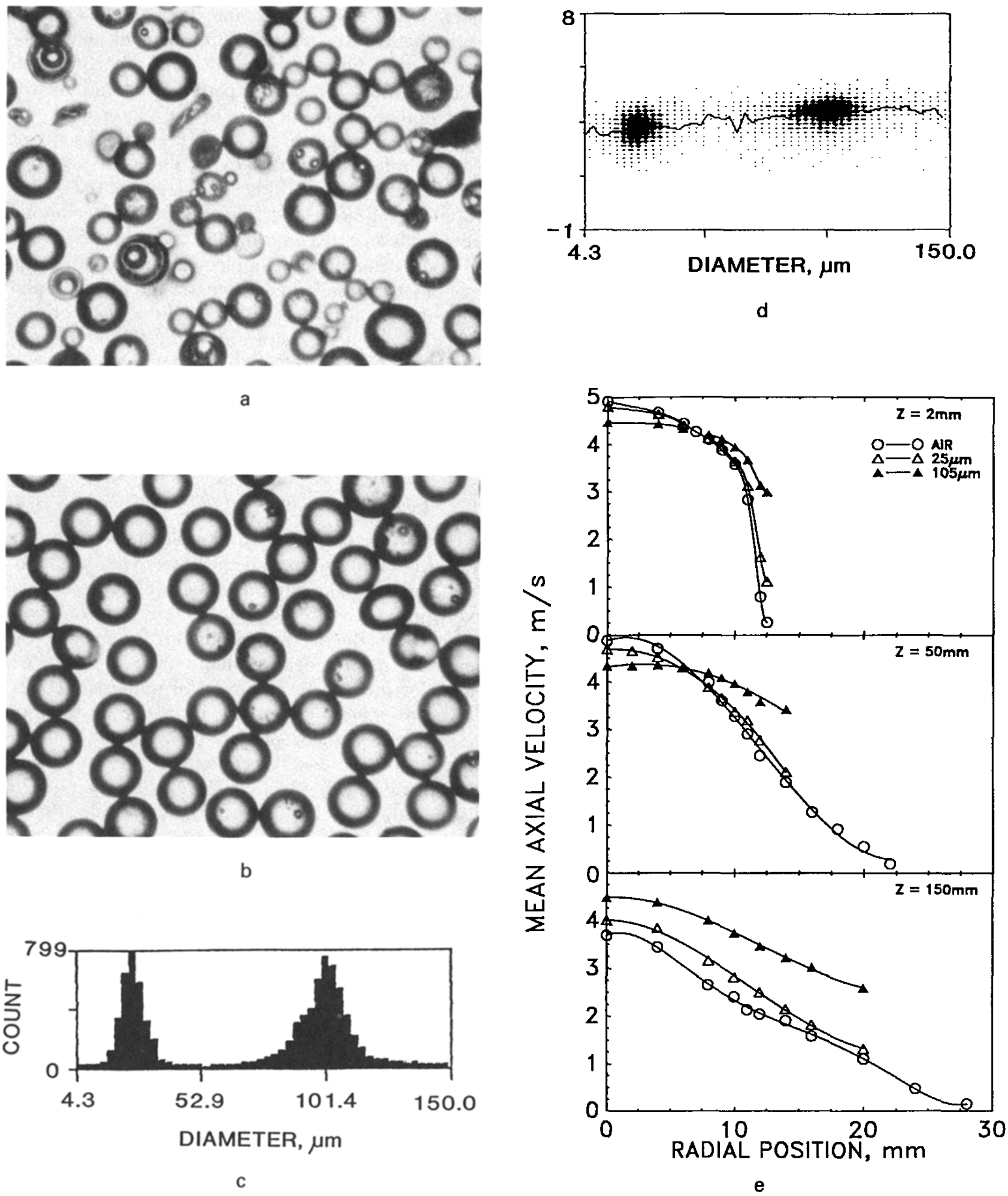

FIG. 3. Discrimination of 25 and 105 micron Glass Beads a) Single Size Range Before Classification b) Single Size Range After Classification c) Size Histogram d) Size-Axial Velocity Correlation e) Radial Profiles of Axial Velocities in Free Jet

formed using patternation, which is relatively quick and simple to operate. Patternations can be conducted for several injector orientations and then analyzed to establish the extent to which symmetry exists in the resulting fuel distribution. Depending upon the type of patternator used, information can be obtained which is highly quantitative.[20] A "necklace type" patternator is used in the current study, as it typifies the current "industry standard" for assessing symmetry. This type of patternator can

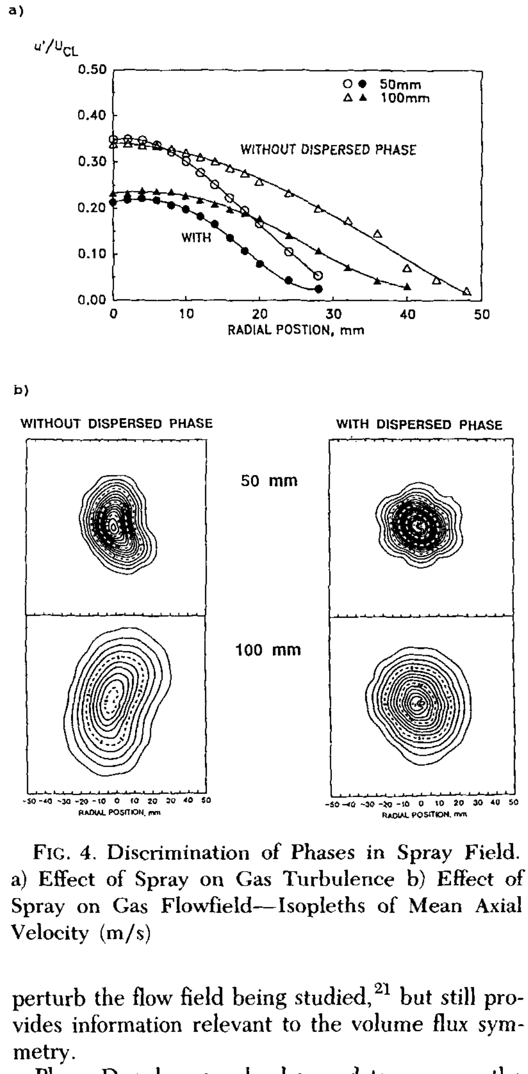

FIG. 4. Discrimination of Phases in Spray Field. a) Effect of Spray on Gas Turbulence b) Effect of Spray on Gas Flowfield—Isopleths of Mean Axial Velocity (m/s)

perturb the flow field being studied,[21] but still provides information relevant to the volume flux symmetry.

Phase Doppler can also be used to measure the volume flux of the fuel as a function of injector orientation. The accuracy of the optical technique is dependent upon several factors. The instrument measures the cross section of the measurement volume and then utilizes the measurement of the drop size and velocity to obtain the local volume flux. Like the patternator measurement of volume flux, the local measurement made by the phase Doppler can be integrated over the area represented by the measurement and give a measurement of volume flow rate.

Figure 5 shows contour plots of the normalized volume flow rate measured by the phase Doppler and the patternator. Summation of the volume flow rate over the sampling sectors (60-degree segments) provides a check of the ability of each technique to deduce the total flow. The total volume flow rate measured by the phase Doppler is 79% of the injected flow. The total volume flow rate measured by the patternator is 54% of the injected flow. Reasons for this difference are due to the perturbation effects in the case of the patternator, and instrument limitations in the case of the phase Doppler, the latter of which are discussed in a subsequent section and are amenable to resolution.

The above results indicate that both the phase Doppler technique and the patternation technique provide descriptive information regarding fuel distribution. The phase Doppler technique however, provides the simultaneous measurement of droplet size and velocity distributions, yielding far more information about the nature of any asymmetry present, if any.[22] In addition, phase Doppler possesses the potential to accurately deduce the volume flow rate, and thus provide quantitative information regarding evaporation.

Measurements in Reacting Environments:

The nature of the phase Doppler technique provides the ability to extend the above measurements to reacting flow conditions. The technique is relatively insensitive to the hostile environment, and presently is the leading candidate for making the necessary in-situ measurements of droplet and gas phase for further development of numerical codes. There are potential limitations involving variation in refractive indices of the environment and the droplet itself due to reaction. A previous study demonstrated the effectiveness of the technique in distinguishing mechanisms for flame stabilization in a model spray fired axisymmetric can combustor.[11] The results demonstrated the necessity of making the measurements of drop size, velocity, and density within the environment that the injector is performing. Work conducted recently in a model axisymmetric can combustor (80 mm in diameter) with wall jets (two sets of four jets located at 80 and 160 mm from the injector plane), described in the present proceedings again shows the applicability of the technique for making in-situ measurements.[23] Important issues are raised, however, with respect to the extent of applicability in such systems.

In applications to less imposing experimental configurations, more confidence may be placed on the instruments accuracy in measuring within reacting environments. Figure 6a presents a comparison of volume flux profiles obtained in reacting and non-reacting methanol sprays produced by an airblast atomizer. Note that in the reacting case, the flame stands between 35 and 45 mm off the face of the injector. Hence, the flame has little influence on the spray at which 50 mm which is just inside the flame front. At 75 and 100 mm, significant differences are observed, with substantial reduction in volume flux associated with droplet evaporation and burnout occurring in the reacting case.

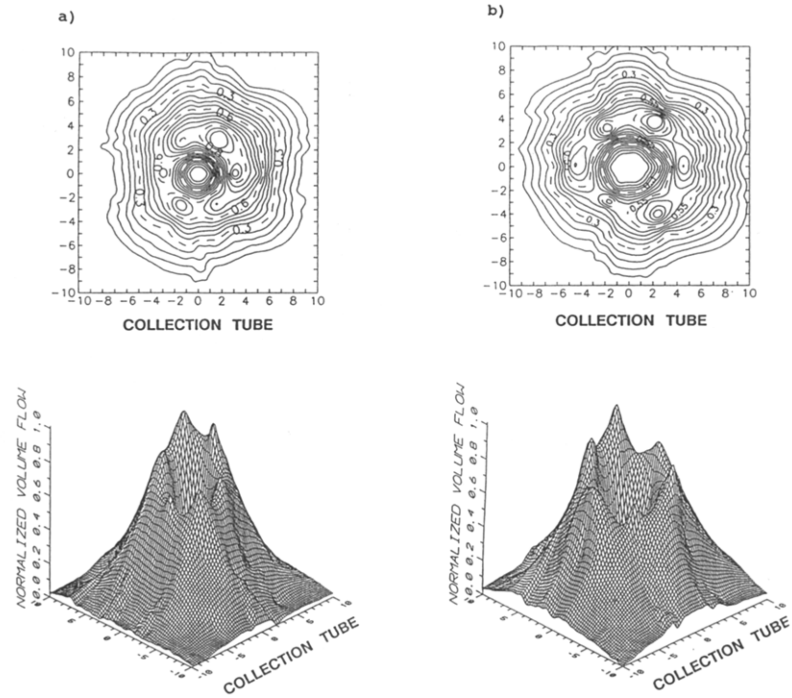

FIG. 5. Contour and Surface Plots of Volume Flow. a) Patternation b) Phase Doppler

To better estimate the performance of the instrument in the reacting environment, the radial profiles of volume flux may be integrated in the azimuthal direction and provide, as a result, a measurement of volume flow rate which can then be compared to the injected flow rate. These results are presented in Figure 6b. Considering that the measurement of volume flux requires: 1) accurate measurement of drop size, 2) proper handling of the sampling bias due to the gaussian intensity profile of the laser beams, and 3) proper determination of the cross sectional area of the probe volume, the results are quite encouraging. Considering that the integration of a single profile assumes axisymmetry from an atomizer which is not, the results are even more encouraging. The low value at 50 mm for the non-reacting case is probably low in spite of assumptions made. This is attributed to the high data rates (>3000 Hz) which could be reduced using a smaller spatial filter and narrower waist (but not smaller than the largest drops).

Limitations in Applicability of Two-Component Phase Doppler Interferometry:

Although applicable to a wide variety of problems associated with combustion systems, the technique itself and the particular instrument utilized are not without limitation. With regard to the technique itself, several restrictions are required of the flows being studied. First, to properly size, the technique requires the scatterer to be spherical, regardless of whether reflected or refracted light is used to deduce the size. Deviations from spherical shapes lead to errors in the size measured, or rejection of the sample. As such, it is imperative that time is taken to evaluate the locations at which measurements are to be made to ensure that droplets, not ligaments, are present. In addition to sphericity requirements, variation in refractive index within the particle can lead to errors. Figure 3b, despite showing a uniform size distribution, also reveals imperfections in the surface of some beads, and bubbles in others, causing local variation in refractive index. (This influence, in conjunction with slight asphericity, is the source of the broadening observed in Fig. 3c of the measured glass bead size.) In evaporating multicomponent fuel sprays, this effect must also be considered, though the influence is less severe (the refractive index of most hydrocarbons only varies from 1.4 to 1.46). In reacting flow, variation in the flowfield refractive index must also be considered, as beam steering will change the fringe spacing and hence affect the velocity and size measured.

Another restriction placed on the flowfield is that only one particle may be present in the probe volume during a measurement. This limits the density of the flows to be studied. In some applications, realistic particle concentrations may preclude the

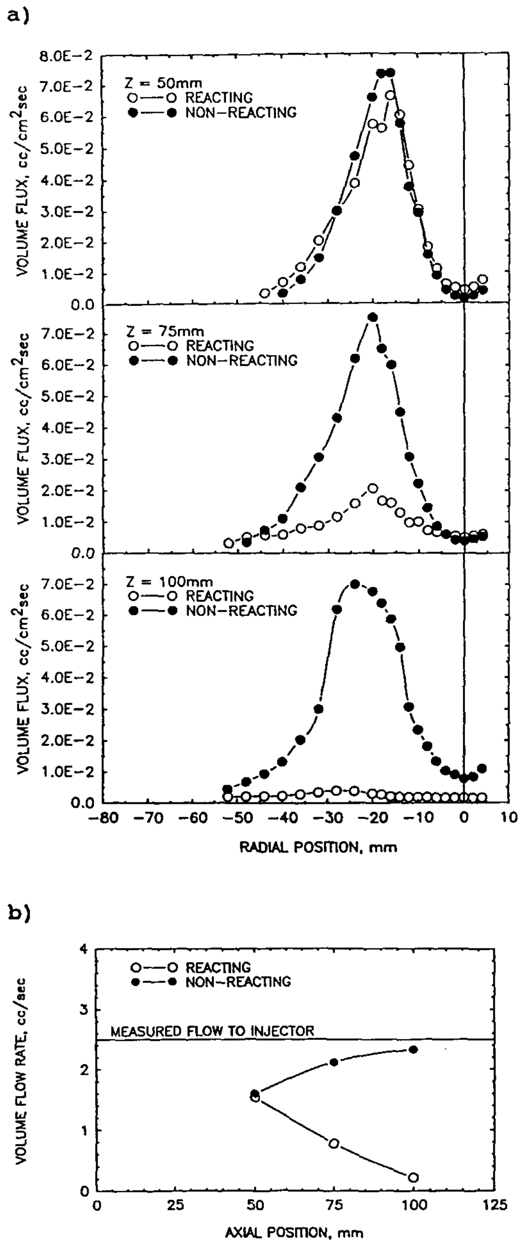

FIG. 6. Comparison of Phase Doppler Measurements in Reacting and Non-Reacting Methanol Spray.[24] a) Radial Profiles of Volume Flux b) Axial Variation in Integrated Volume Flux

use of phase Doppler, or other single particle counters.

With respect to the instrument itself, several factors must be considered. With a wide range of user controlled parameters (e.g., PMT voltage, size ranges, velocity ranges, filter selections, spatial filter sizes, frequency shift, threshold), experience in using the instrument becomes important. This is especially true if volume flux is being measured. In conjunction with the above flowfield restrictions, care must also be taken to optimize the instrument sensitivity to encompass the entire size range present. In addition, to make volume flux measurements, correction of the counts to account for variation in sample volume with particle size must be done properly. This can only be done if the total velocity of the particles is measured. If the velocity of the particles is not normal to the fringes, or if there is any dependency of trajectory on particle size, errors will result in the measurement of the sampling area, and an error in volume flux will result.

The two-component instrument has the potential to partially correct for the trajectory effect, as two components of velocity are obtained for each size. However, the extension to two-components also introduces another possible source of error. Due to the stringent coincidence requirement for accurate shear stress measurement, small misalignment of the probe volumes can result in missed particles. This can reduce the volume flux measured.

Conclusions

The current study demonstrates that phase Doppler interferometry is capable of providing a significant amount of information about spray fields that was previously unavailable and is necessary for development of advanced numerical tools. The technique has been applied in the study of particle size influence, discrimination of continuous and discrete phases, the detailed characterization and assessment of symmetry in fuel distribution from a typical gas turbine atomizer, and in the characterization of sprays under reacting conditions.

The conclusions from this study are:

1) Phase Doppler interferometry is capable of providing needed information (spatially resolved simultaneous measurement of droplet size, droplet velocity, droplet mass flux, and dilute phase velocity) in two-phase flows under reacting as well as non-reacting conditions.
2) The technique offers a new approach in the discrimination of phases by using physical differentiation of each phase.
3) The method has the potential, as a result, of providing the information necessary to 1) advance the understanding of the physical processes (e.g., evaporation, mixing) in two-phase flows, and 2) advance existing numerical tools for two-phase and evaporation modeling.
4) The technique is capable of providing detailed information about sprays in reacting flows and can thereby add to the understanding of com-

plex turbulent phenomena in practical combustion systems.

5) Important questions remain with respect to the limits of applicability, but future software and hardware development has the potential to resolve many of the outstanding issues.

Acknowledgments

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COMMENTS

S. Starner, Univ. of Sydney, Australia. You mentioned that the instrument requires that the refractive indexes of both phases be constant: to what extent would the results in a combusting flow be affected by the obviously large refractive index changes in the gas phase?

Author's Reply. The instrument relies upon a difference in the refractive index across the droplet surface. The ratio of the droplet index of refraction to the gas index of refraction then gives the appropriate function relation between phase shift and size. The relationship, however, is not linear. For the present case, the refractive index of the gas may be taken in the worst case as 1.01.[1] This leads to errors from the case where the refractive index is 1.0 (for air) of 1.5% in measured size. Errors associated with formation of products are second order.[1] Clearly, the dominating factor in the refractive index difference detected by the instrument is the droplet refractive index. Errors due to beam steering may also arise, but are minor in the present case since the flame is small.

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W. Waesche, Atlantic Research Corp., USA. It would be helpful to compare data from this technique from those acquired through other techniques throughout the sampling volume.

Author's Reply. This is an important observation in that new techniques must undergo substantial verification before they may be used reliably. One way to do this is via comparsion to data acquired by other instruments. Malvern, considered an industry standard, may be compared to the phase Doppler measurements by either 1) averaging the phase Doppler data into a line-of-sight measurement or 2) deconvolute the diffraction based data into spatially resolved measurements. Such comparisons have been done (e.g., Ref. 9, 11 in text). Additional comparisons have been made with Visibility (e.g., Ref. 5). In each of the above cases, reasonable agreement was achieved. Additionally, the data may be analyzed in such a way as to validate the measurement (e.g., integration of volume flux profiles to obtain volume flow rate to compare).

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J. K. Martin, Univ. of Wisconsin, USA. What procedures were used to produce data from a single environment with drop sizes from 1 to 135 μm?

At what point in the spray do you conclude that the quantities measured, such as volume flux, are no longer valid?

Author's Reply. Although the instrument is specified by the manufacturer to have a dynamic range of 35:1 for sizing, the actual response characteristics make this a conservative figure. To address this, and to specifically provide a feature to implement the discrimination of phases, the manufacturer provides the capability of extending the lower size limit. A user-enabled feature places size scores in a selected number of bins which would contain scores smaller than the lower limit (the 35:1 range) into the first bin.

Another alternative is the normalization and splicing of two overlapping size windows, taking into consideration the response characteristics to particles within each range, the collection time, and the variation in bin width.

The ultimate limit is dictated by the point within the spray where ligaments and non-spherical drops still exist. In this region, many events can be rejected, resulting in a measured volume flux which is too low. High magnification shadowgraphs and cinematography are required to determine the regions in the spray where ligaments and non-spherical drops persist.

In regions where spherical drops exist, the discussion in the paper applies. Namely, the single particle requirement and proper determination of the probe cross section are the dominant phenomena in the accurate measurement of volume flux.

At least two approaches can be taken in dense sprays. One is the tailoring of the probe volume via a smaller waist and smaller spatial filter. As long as the waist is larger than the largest drops, an accurate measurement may be derived. If the waist is smaller than the largest drops, situations arise where the reflected and refracted portions of the scattered light become equal in magnitude. This leads to large drops being sized as small drops and visa versa.

The use of frequency domain processing may provide an answer to multiple particles in the probe volume by deducing the fundamental phase shifts from each particle. This approach is still in the developmental stages at this time.

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H. G. Semerjian, National Bureau of Standards, USA. Your initial measurements with "nominally" monodispersed glass beads (D ≈ 105 μm) indicated a fairly wide size distribution extending from 45 to 135 μm. Is this because the beads are not really monodispersed or due to non-uniformity in optical properties of the particles, or due to instrumentation problems?

Author's Reply. The broadened size measurement is attributed to at least two factors. First, the classification procedure used to produce the size range desired at a reasonable cost yields a size range of

100–110 μm with 90% of the beads within this range. The second factor, the optical quality of the beads, is the principal reason for spread in the measured size. Under microscope inspection, the beads show various defects, including internal cracks, bubbles, and asphericities, which all lead to broadening of the measured size distribution (Figure 3c in the text). The calibration of the instrument is regularly checked against a monodispersed droplet generator and rarely changes.