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Authors
McDONELL, VG
SAMUELSEN, GS

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Application of Laser Interferometry to the Study of Droplet/Gas Phase Interaction and Behavior in Liquid Spray Combustion Systems

V. G. McDONELL and G. S. SAMUELSEN *UCI Combustion Laboratory, Institute for Combustion and Propulsion Science and Technology, University of California, Irvine 92717 USA*

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Abstract—The application of optical scattering techniques is described for the measurement of droplet properties in liquid sprays. Of the various approaches, phase Doppler interferometry demonstrates the highest promise for obtaining the information necessary to understand the formation and emission of toxic combustion byproducts in liquid-fueled spray reactions. The technique deduces drop size from the spatial variation in the imaged fringe pattern due to drop radius of curvature. Combined with the measurement of velocity via laser anemometry, the capability of sizing allows for the determination of continuous phase velocities as well as droplet size and velocity correlations. Such a capability is necessary to develop an understanding of the physical processes occurring within liquid combustion systems associated with incineration. Three applications are presented which are relevant to the formation of combustion by-products: the effect of swirl on the dispersion of droplets, an assessment of spray symmetry, and measurements in a reacting environment. In addition, limitations of the phase Doppler technique relative to liquid combustion systems are outlined.

INTRODUCTION

The emission of combustion byproducts from liquid-fueled hazardous waste incinerators requires an understanding of the droplet behavior in liquid sprays. Of particular interest are (1) the basic characteristics of the droplets, namely the size and velocity distributions, and the mass flux, and (2) gas phase vector properties in the presence of droplets. Both are necessary to deduce the transport, evaporation, mixing, and reactions associated with spray incineration.

The strong coupling between transport and vaporization of drops and the ensuing reaction of the vapor/oxidant mixture suggests that the most useful measurements must be *in-situ*.

At a minimum, the characterization of liquid sprays requires both spatially- and temporally-resolved measurements of: 1) gas mean and fluctuating velocities, 2) droplet velocity and size distributions obtained simultaneously, 3) droplet mass fluxes, and 4) gas scalar properties. Spatial resolution is required to adequately represent the time averaged features of the flow. Temporal resolution is required to identify dynamics, both local and global, which may influence the flow structure, and, as a result, dominate system performance. Higher order moments of the statistical properties, including correlations are also desirable. Obtaining such measurements in a non-intrusive, *in-situ* manner in relatively simple environments as well as those representative of those found in liquid combustion systems has proven to be challenging.

Laser interferometry provides the potential for obtaining these highly detailed measurements. The technique has the inherent capability of discriminating phases in the flow, and in a two-component arrangement, is especially powerful in delineating the droplet/gas behavior in complex flows typical of realistic systems.

The objective of this paper is to describe the use of laser interferometry, to illustate

the use of the method in experiments relevant to liquid combustion systems in general and the incineration of toxic liquid waste in particular, and to address the utility and limitations of the technique.

BACKGROUND

Overview

The specific measurements desired in reacting sprays should include at a minimum:

- mean and rms gas velocity
- mean droplet size and droplet size distribution
- mean and rms droplet velocity
- droplet mass flux

Measurement techniques for the discrete phase divide into two categories: optical visualization methods (including high speed photography, holography, TV imaging) and optical scattering methods. The emphasis of the present paper is on the latter.

Light scattering methods are conveniently divided into two categories, those that measure the light from a collection of droplets in a beam, and those that measure the light scattered from a highly focused laser beam by individual particles. A primary example of the former is the angular light distribution produced by droplets scattering light in the forward direction by *diffraction*. The primary example of the latter is droplets scattering light from a fringe pattern produced by *interferometry*. These two techniques represent the state-of-the-art and new frontier respectively in capability.

Diffraction Diffraction is based on the forward scattering of a parallel beam of monochromatic light which is passed through the spray. The angle through which the light intensity is scattered by the droplets can be theoretically related to the Sauter mean diameter (SMD) of the spray.* Dobbins, *et al.* (1962) described the basic theory and optical setup which is used extensively, most recently by Lefebvre and co-workers (*e.g.*, Rizkalla and Lefebvre, 1975; Lorenzetto and Lefebvre, 1977; Rizk and Lefebvre, 1983, 1984).

Swithenbank, *et al.* (1977) extended the concept of Dobbins to look, not at the distribution of intensity, but at the distribution of energy. This provides the information necessary to establish the size distribution of the spray as well as the mean drop size. A commercial instrument based on these principles has become an industry standard.

Noteworthy is that diffraction is a path measurement. Light scattered along the length of the beam is collected by the detector, thereby providing an aggregate measurement of mean droplet diameter and droplet size distribution. Creative approaches have been attempted to overcome the spatial and temporal limitation of the diffraction measurement. Tishkoff *et al.* (1982), Hammond (1981), and Dodge (1987), for example, have used a deconvolution technique to yield radial variations of droplet number density and size distribution. Another limitation of diffraction is the relatively dilute number densities in which the technique can be applied. As number density increases along the measurement path, multiple particle scattering distorts the measured size distribution towards smaller particles. Techniques have been developed which attempt to compensate for multiple scattering (*e.g.*, Dodge, 1984; Hamidi and Swithenbank, 1986).

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*$\text{SMD} = \dfrac{\Sigma D_i^3}{\Sigma D_i^2}$ where D_i is the droplet diameter.

Interferometry Interferometry is an extension of the dual-beam laser Doppler anemometer, exploiting as a measurement of droplet size the effect of droplet size on the scattered signal. Noteworthy is that interferometry is an instantaneous point measurement of an individual droplet realization. As a result, it provides detailed *spatial* as well as *temporal* resolution required to explore and document physical processes in spray reactions associated with by-product formation and emission. Four variations of interferometry have evolved: visibility, visibility/IV, visibility/IMAX, and phase Doppler.

When a droplet passes through the interference fringe pattern formed by two intersecting beams, not only can the droplet velocity be deduced, but from the relative amplitude modulation of the signal (*i.e.*, the "visibility" of the droplet), the droplet diameter can also be inferred (Farmer, 1973). Seeker, *et al.* (1983) report on the use of laser holography and laser diffraction in combination with visibility to measure droplet size distributions in a twin-fluid atomizer. The agreement between holography and diffraction was excellent. On the other hand, the agreement with visibility was poor. This was the first evidence of limitations that have since plagued users of commercial visibility based instruments, namely (1) limited dynamic range (less than ten in drop size and three in velocity), and (2) varying fringe contrast due to beam steering in the spray and extinction of the incident beams.

Three variations have been introduced to address the shortcomings of visibility. In the first, the peak intensity is monitored and used as an independent measurement for drop size to compare to the visibility determined value (Hess, 1984a). Known as "intensity validation" (IV), the procedure is intended to correct for beam steering. When combined with a rotating diffraction grating to increase the dynamic range of velocity, visibility/IV can be used successfully as demonstrated in comparisons against diffraction measurements of size distributions in twin-fluid atomizer sprays (Jackson and Samuelsen, 1987). The dynamic size range, however, remains an undesirable limitation.

In the second variation, one color beam of a multi-line laser is expanded to a large diameter relative to a second color beam. The second color is split into two beams, both of which are aligned to intersect at the center of the larger beam. The technique, known as IMAX (Hess, 1984b), relies on the total intensity scattered by the droplet to determine drop size, a simultaneous signal from the interferometric fringe to verify that the droplet passed through the center of the large beam, and a determination of droplet velocity from the frequency of the light scattered from the fringe. The dynamic range for drop size is reported to be greater than 30 to 1.

The third variation is based on the linear dependency of the Doppler burst spatial phase shift with droplet size (Bachalo, 1980; Durst and Zaré, 1975). Instruments resulting from application of this analysis, phase Doppler interferometers, use two detectors, each located at known distances from each other and from the probe volume. The known detector spacing allows the spatial variation of the fringe image to be deduced. To eliminate ambiguity associated with spatial phase shifts of over 360 degrees, and to extend the dynamic range, additional detectors may be added. The dynamic range for droplet size is greater than 35. The technique has been evaluated in a variety of experiments (*e.g.*, Bachalo and Houser, 1984; Dodge, *et al.*, 1987; Jackson and Samuelsen, 1987). For polydispersed sprays with a significant radial and/or swirl component, a one-component configuration is insufficient. Since practical systems generally employ sprays of this type, a second, and even a third component is required. In a two-component configuration, significant additional information is provided. For example, direct measurements of (1) shear stress, (2) trajectories, and (3) trajectory-particle size correlation are obtained. Also, the second component improves the measurement of volume flux and size distributions by enabling a more accurate determination of the sampling volume.

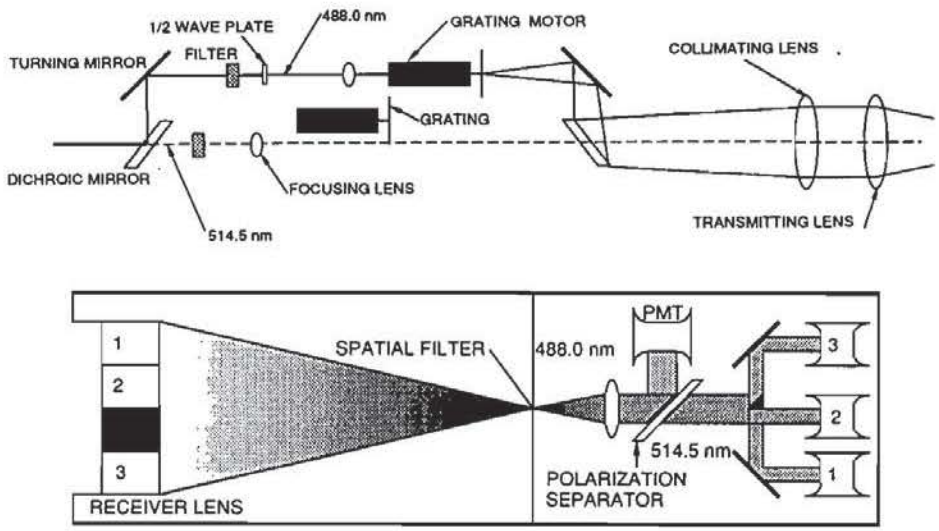

FIGURE 1 Two-Component Phase Doppler Interferometer.
a) Transmitter
b) Receiver

Compared to the other interferometric methods, phase Doppler has the following essential attributes that have proven necessary to acquire meaningful measurements in spray reactions:

- wide dynamic range in droplet size
- wide dynamic range in velocity
- relative insensitivity to variation in media refractive index

TWO-COMPONENT PHASE DOPPLER INTERFEROMETRY

Figure 1 shows a schematic of a two-component phase Doppler interferometer. Figure 1a delineates the details of the transmitter. A 1-Watt Ar^+ laser is used in the current setup to provide chromatic discrimination of the velocity components. This particular system is well suited for complex environments due to the use of polarization and line filters. As such, noise due to flame luminosity and random light scatter are minimized. The use of diffraction gratings to provide frequency shift permits a wide spectrum of shift values, enabling the user to optimize the amount of shift used.

Figure 1b presents details of the receiver. This configuration uses one receiver lens which is divided into three areas, each of which is observed by a different detector. Because the distances between the three integrated collection areas cannot be physically measured, they must be determined by calibration. Spatial resolution is inherent to the interferometric approach, while temporal resolution is achieved by tagging each event with the time of occurrence (*e.g.*, Bachalo *et al.*, 1990). Details of the theory and specifics of the instrument are available elsewhere (*e.g.*, Bachalo and Houser, 1984; Bachalo and Sankar, 1988).

Noteworthy is the inherent ability of the instrument to "discriminate" between phases. Critical to understanding behavior of droplets in sprays is knowledge of the slip velocity between phases. By seeding gaseous flows, optimizing the instrument to be most sensitive to small particles, and using scores from small droplets and seed

particles, the gaseous velocity can be determined. This approach has been successful in mono-dispersed flows (*e.g.*, Bulzan, 1988; Mostafa *et al.*, 1989) as well as poly-dispersed flows (*e.g.*, McDonell and Samuelsen, 1988a; Breña de la Rosa, *et al.*, 1990). Such measurements can, in principle, lead to determination of local drag coefficients (*e.g.*, Rudoff *et al.*, 1988), although knowledge of the gaseous physical properties must also be known.

The instrument used for the present applications is an Aerometrics Model 1100 Phase Doppler Particle Analyzer (PDPA).

RESULTS AND DISCUSSION

For studies of by-product formation in liquid spray systems, the spatial distribution and transport of droplets, the symmetry of the mass flux of the fuel, and the effect of reaction on droplet transport are among the important questions to be resolved. Two-component phase Doppler interferometry has the potential to provide this information and, as examples of this potential, three applications of the instrument are presented: (1) the dispersion of droplets due to aerodynamic swirl, (2) an assessment of spray symmetry, and (3) droplet behavior in reacting flows.

Effect of Swirl on Droplet Dispersion

Understanding the role of swirl in the dispersion of droplets is important in the design and operational procedures of burners for liquid combustion systems. Figure 2 depicts the geometry used in a study conducted which examines the effect of swirling and non-swirling co-flow on the dispersion of drops in a non-reacting spray. Such information is useful in the design of burners for liquid combustion system. Questions about swirler design and atomizer design may be addressed with knowledge of the interaction between the aerodynamics and the droplets. An example of such a study follows.

Figure 3 presents radial profiles of the droplet size distribution D_{32} (SMD) at 3 axial positions from the atomizer. With no swirl, small drops remain at the centerline of the flow, and large drops remain away from the centerline. With the addition of swirl, the droplet size becomes uniform across the spray. Even 75 mm downstream of the atomizer, the case without swirl shows strong segregation of droplets, with large drops present at the outside of the spray, and small drops present at the center. Such phenomena are important to understand, because local clustering of large drops can lead to locally rich pockets of fuel, which may result in unburned fuel escaping as combustion byproducts.

Figure 4 presents vector plots of the axial/radial velocity of two different drops size classes. With the addition of swirl, 11–20 μm drops at the edge of the spray are moving away from centerline with much greater velocity than are the drops with non-swirling co-flow. In contrast, the 61–75 μm drops exhibit similar behavior for either the swirling or non-swirling case. A modest increase in the radial spread is observed for the larger drops, but the difference between the swirling and non-swirling cases is markedly greater for the smaller drops. Note that the larger drops are travelling significantly faster at the edge of the spray in the case with swirl.

The results indicate that the addition of swirl concentric to the atomizer results in a more uniform distribution of drop sizes, which is caused by variation in the trajectories of the drops. The addition of swirl, although reducing the axial/radial velocities of drops at the centerline, increases these velocity components of drops at

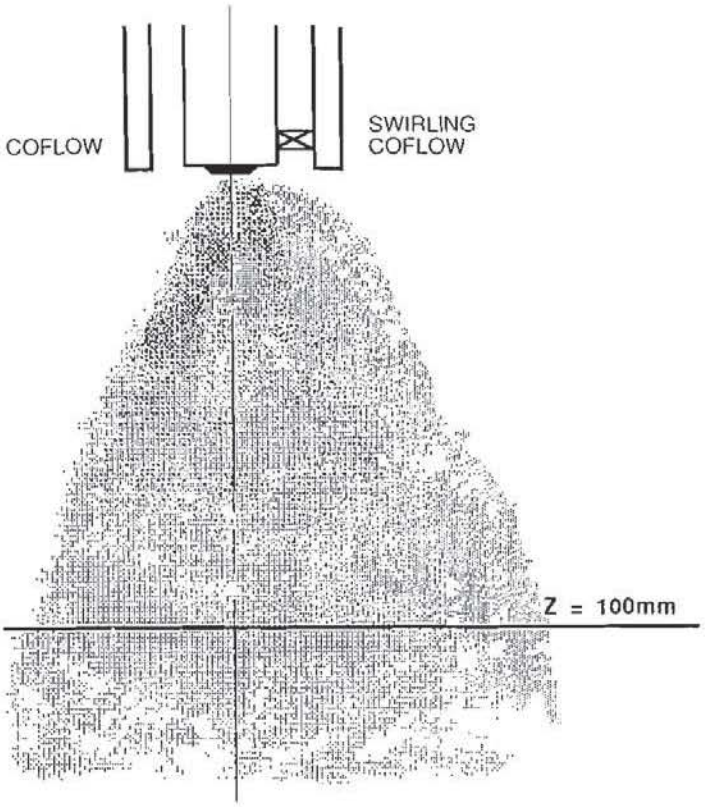

FIGURE 2 Geometry of Swirling/Non-swirling Coflow Study.

the outer edge. One implication of the measurements is that small drops and large drops will be more likely to collide in the swirling case. Such behavior may or may not be desirable in the combustion of liquid fuels. These measurements demonstrate the value in applying the technique to (1) understanding how swirl interacts with the droplets, and (2) to developing a methodology to ensure adequate combustion related residence times for a given type of fuel.

Assessment of Spray Symmetry

Careful introduction of liquid fuel into the combustion system is required to achieve efficient combustion. It is likely that non-uniform dispersion of the fuel leads to local peaks in emissions. Classically, studies of fuel dispersion have been carried out using patternation which leads to considerable information about the local flux in the spray (*e.g.*, Ortman and Lefebvre, 1985; McVey, Russell and Kennedy, 1989). Detailed characterization of the atomizer using the PDPA can lead to increased understanding such behavior with no physical perturbation, but with greater effort (McDonell, Cameron, and Samuelsen, 1990).

Figure 5 presents a surface plot of the volume flow measured by two-component phase Doppler interferometry and patternation for a twin-fluid atomizer. It is observed that the results from each technique are qualitatively similar, and reveal a local peak in the volume flow on one side of the flow. This peak can be attributed to several factors. For example, (1) bigger droplets, (2) reduced radial spread of drops at that

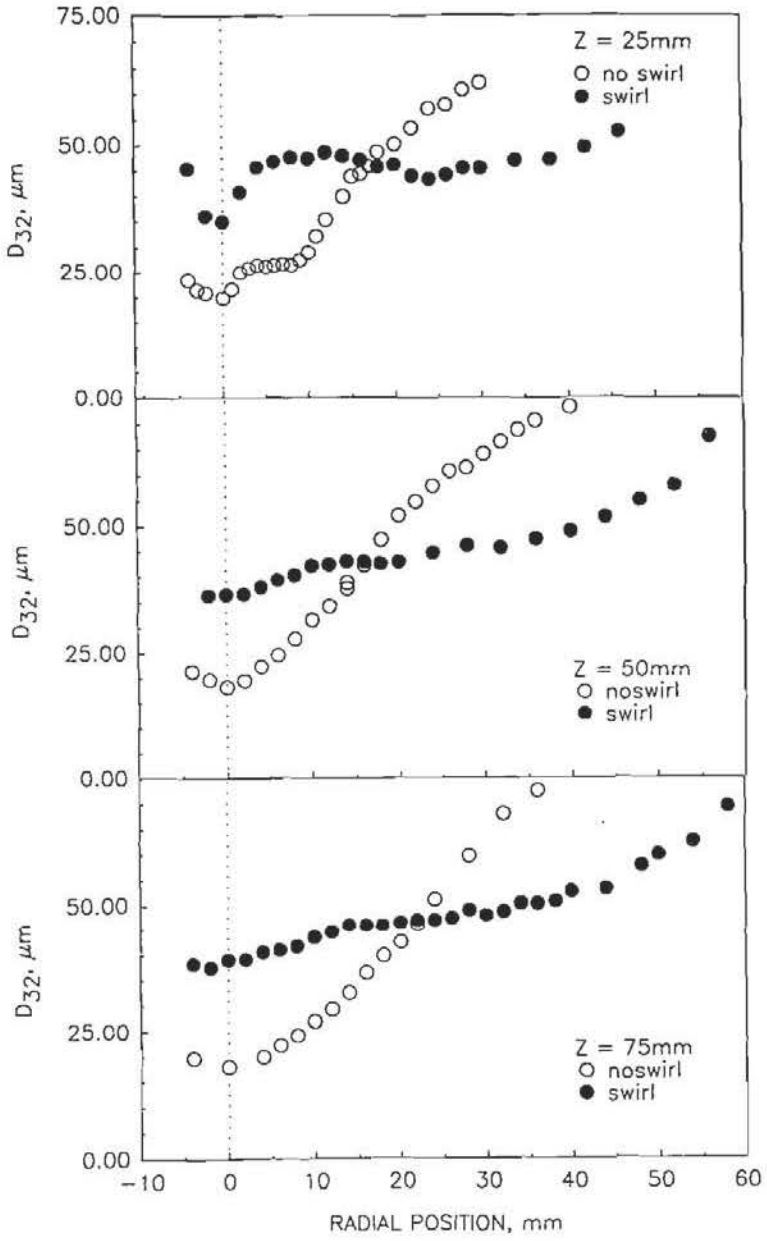

FIGURE 3 Radial Profiles of Size Distribution D_{32}.

location, or (3) more droplets regardless of their size, could all contribute to the local peak.

Utilizing the additional information available from the interferometric technique, insight into the exact cause of the inconsistency can be gained. Figure 6 shows a contour plot of the surface plot shown in Figure 5. The two lines with points on them

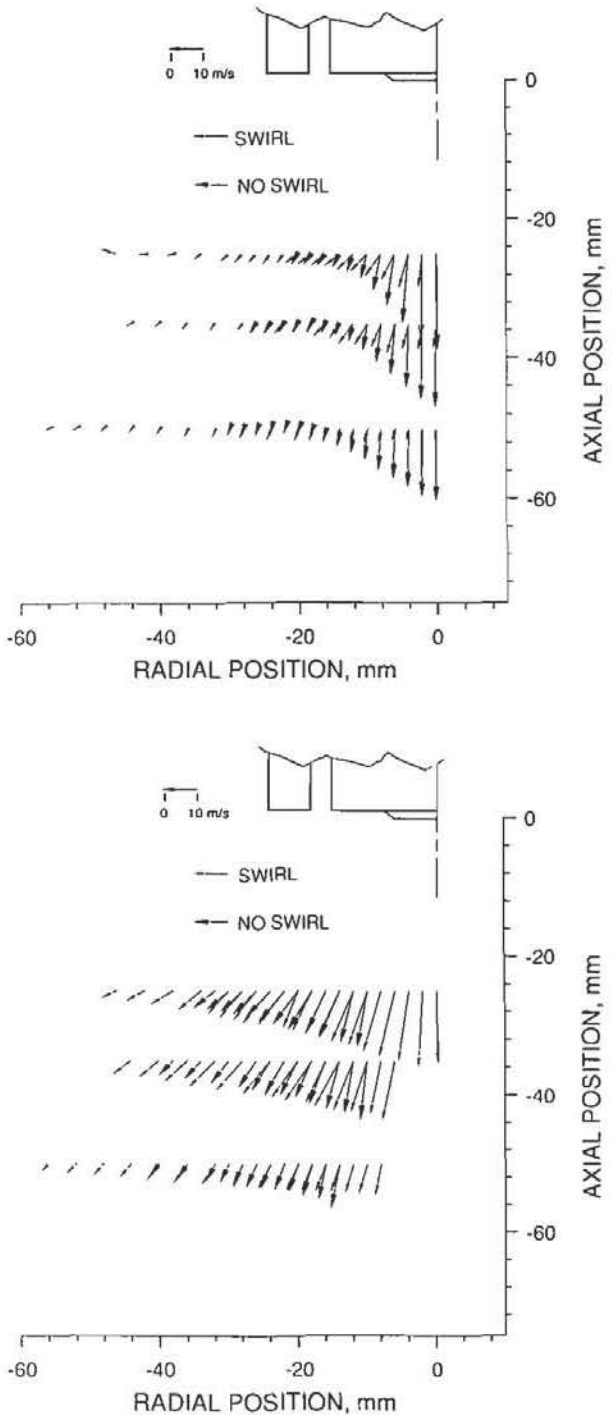

FIGURE 4 Vector Representation of Droplet Velocities. a) 11–20μm, b) 61–75μm.

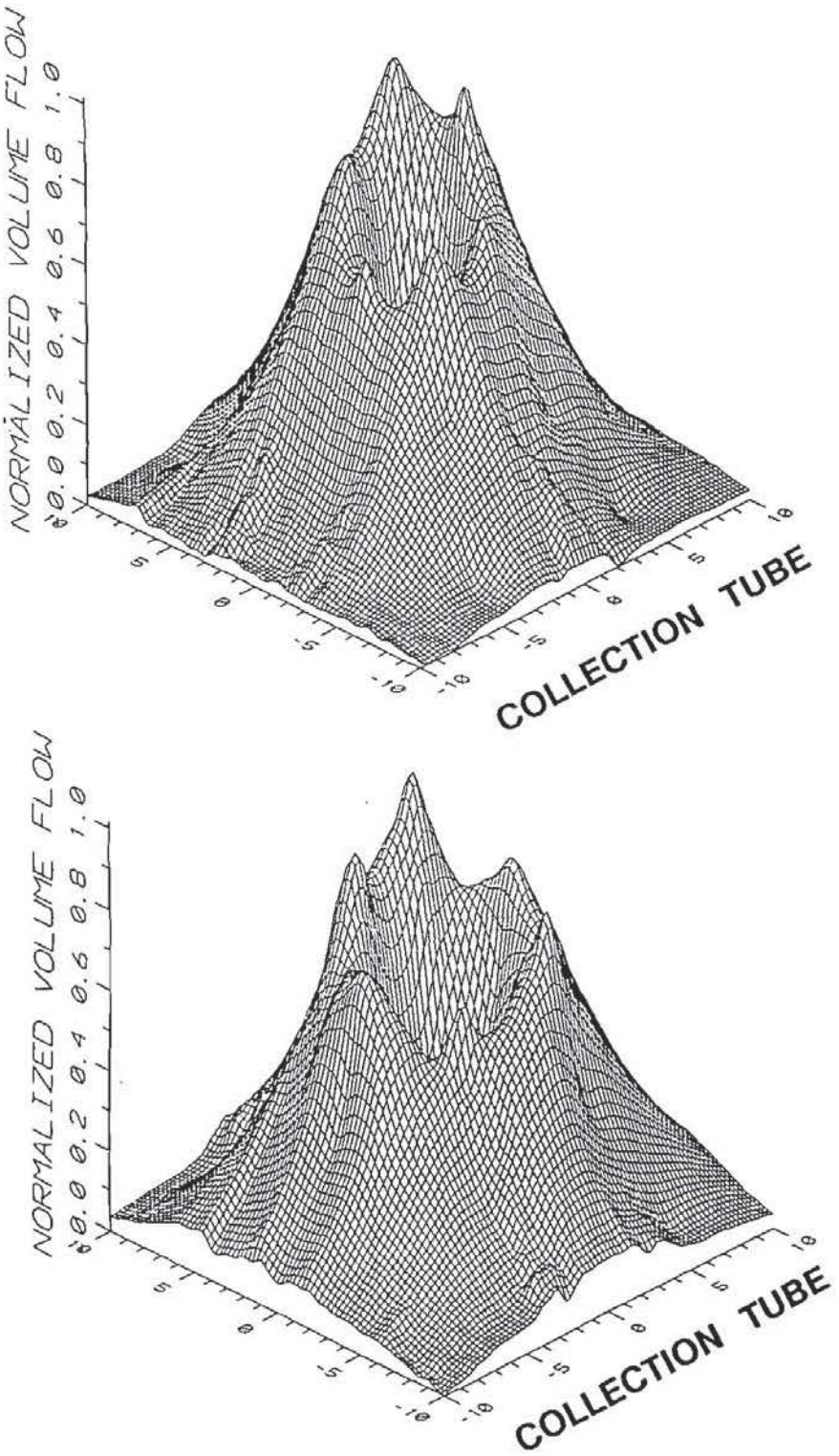

FIGURE 5 Surface Plot of Volume Flow (McDonell and Samuelsen, 1988b). a) Patternator b) PDPA.

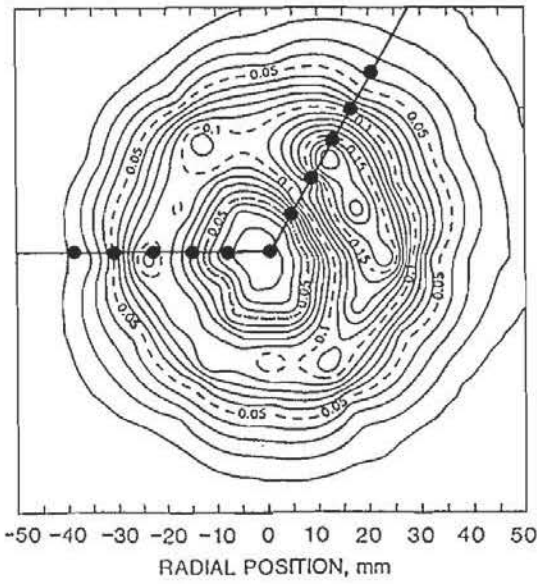

FIGURE 6 Contour Plot of Volume Flow (PDPA).

represent locations at which detailed comparison was conducted. The data revealed that (1) more drops were present on the side of the spray with less volume flux, (2) more large drops were present on the side with the most flux, and (3) the velocities of the drops on either traverse were similar. Thus, the data reveal that, despite the intuitive result that larger drops were responsible for the local peak in volume flux, higher concentrations of drops were present in the regions of lower flux. This type of information is important if correlations between atomizer performance and the emission of combustion by-products are to be generated.

Measurements in Reacting Environments

Extrapolation of measurements of droplet behavior obtained in a non-reacting environment to practical environments has not been satisfactorily demonstrated. The ability to correlate non-reacting characterization to reacting environments representative of actual burners has been limited at best (*e.g.*, McDonell, Wood, and Samuelsen, 1986; Cameron, *et al.*, 1988). At a minimum, *in-situ* measurements of droplet behavior in reacting environments are required if any postulated correlation is to be verified.

Recently, detailed measurements using phase Doppler interferometry in spray flames have been obtained which demonstrate the applicability of the technique to characterizing droplet behavior in such environments (*e.g.*, Mao *et al.*, 1986; McDonell *et al.*, 1986; Cameron, *et al.*, 1988; McDonell and Samuelsen, 1988a; Bachalo *et al.*, 1990). Several comments about the application of technique to such environments are warranted.

Since the instrument relies upon the difference between the index of refraction between the liquid drop and gaseous media *at the droplet surface*, accurate size measurements can still be realized despite variation in the gaseous refractive index. Intuitively, one would expect large variation in the gaseous index of refraction in a

spray flame, however, local variations are relatively small (< 1.01 times that of room air (Weinberg, 1963)). The relation between refractive index and size is not linear, and the error decreases as the index of refraction of the scatter becomes greater. Perhaps more important is the change in liquid refractive index due to temperature. This effect can be reduced with proper collection angles, and may not cause serious errors depending on the liquid considered.

Along a significant path length, the variation in refractive index of the gas can cause changes in the optical path, an effect known as beam steering. McDonell (1990) shows that in a spray flame of less than approximately 50 mm in diameter, beam steering does not cause significant error in the measurement of mono-dispersed droplets. Of course, probe volume waist sizes, flame thickness, ambient pressure, and other factors make generalization difficult, but the results give confidence to measurements made in small spray flames.

Figures 7–9 present measurements obtained in reacting and non-reacting methanol sprays produced by an air-assist atomizer. For methanol, the size error due to variation in refractive index from room temperature to its boiling point is less than 3.5% with the 30° collection angle used. Figure 7 presents radial profiles of the gas phase velocities for the (1) single phase atomizing air only flow, (2) non-reacting spray, and (3) the reacting spray. The results demonstrate that the presence of the droplets has a significant influence on the gas velocities. The differences are attributed to momentum exchange between the drops and the gas. The results also reveal that, at an axial distance (Z) from the atomizer of 15 mm, little difference is observed between the reacting and non-reacting spray. This is expected since the flame stabilizes approximately 15–20 mm from the face of the atomizer. At locations farther downstream, the profiles again indicate the momentum exchange. For example, at $Z = 75$ mm, the presence of the droplets in the non-reacting case has narrowed the gas flow. Also, the presence of reaction causes significant expansion of the gases which is observed in the measurements.

Figure 8 presents radial profiles of the droplet volume flux. The results indicate that, near the injector, little difference exists between reacting and non-reacting cases, which is not surprising since the location of flame stabilization is 15–20 mm, from the injector face. At $Z = 35$ mm, some decrease in volume flux is observed in the reacting case. At $Z = 75$ mm, significant burnout has occurred in the reacting case. It is noted that despite the large burnout of drops, the distribution D_{32} remains on the same order for either case.

Figure 9 presents radial profiles of the droplet axial velocity as a function of droplet size. These results indicate that significant differences are observed between the two cases. In fact, for the present case, the sign of the size velocity correlation at $Z = 75$ mm reverses for the reacting spray. This behavior is attributed to several factors such as (1) variation in droplet drag coefficient (*e.g.*, Dukowicz, 1984), (2) differences in history of the droplets (*e.g.*, a 50 micron drop at $Z = 75$ mm in the reacting case may have been a 100 micron drop at $Z = 15$ mm), or (3) variation in the interaction of the atomizing air with the surrounding air flows between the two cases.

To illustrate the impact of droplet life history, Figure 10 shows a comparison of droplet mean "flight" paths for a non-swirling, air-assisted spray running under reacting and non-reacting conditions. Because of the relatively simple non-swirling conditions, the measurements obtained *in-situ* can be used to determine the mean trajectory and magnitude of velocity of a given drop size at each axial station. This information can be used to "track" the given size drop to the next axial location where the procedure can be repeated. Although representative of the droplet behavior, the

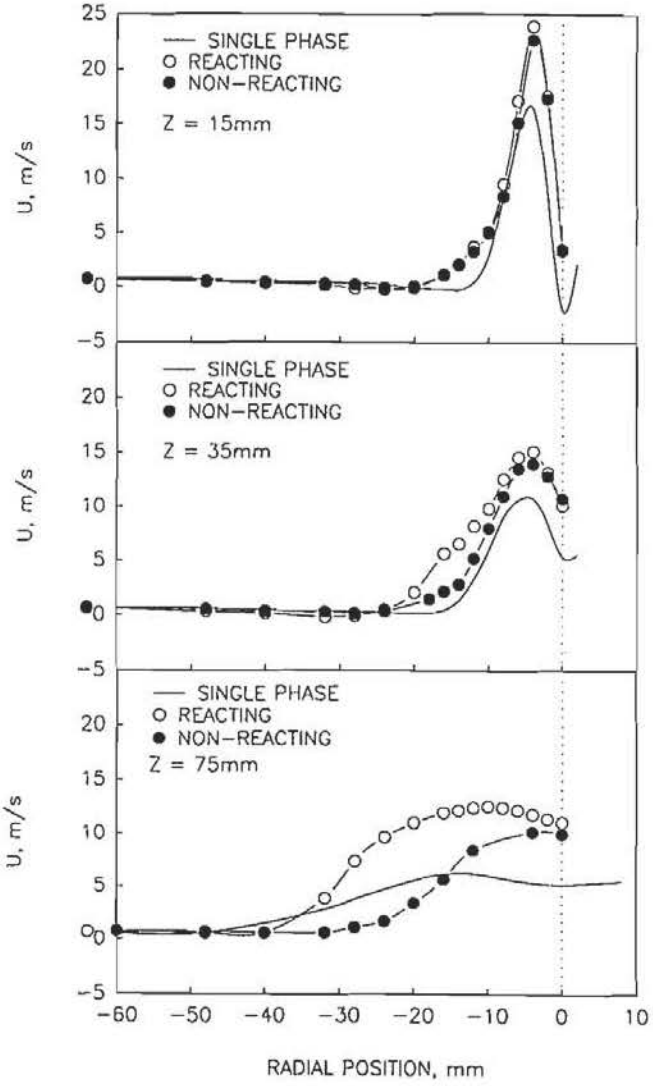

FIGURE 7 Radial Profiles of Gas Phase Mean Axial Velocity.

"flight paths", like time averaged streamlines in a turbulent flow, cannot be used to ascertain the actual flight path of a given drop.

Further, using the measured value of velocity at each point, the average time of flight can be determined. Finally, using this time, an empirical vaporization law can be applied to estimate the size of the given drop as it travels through the spray. Since the velocities of both phases are measured, relative velocities can be utilized in the analysis.

Figure 10 illustrates the estimated "flight path" of drops 55 μm in diameter starting at an axial distance of 7.5 mm from the atomizer and at a radial location of 5 mm from the centerline. Variation in the estimated flight path based on the size velocity

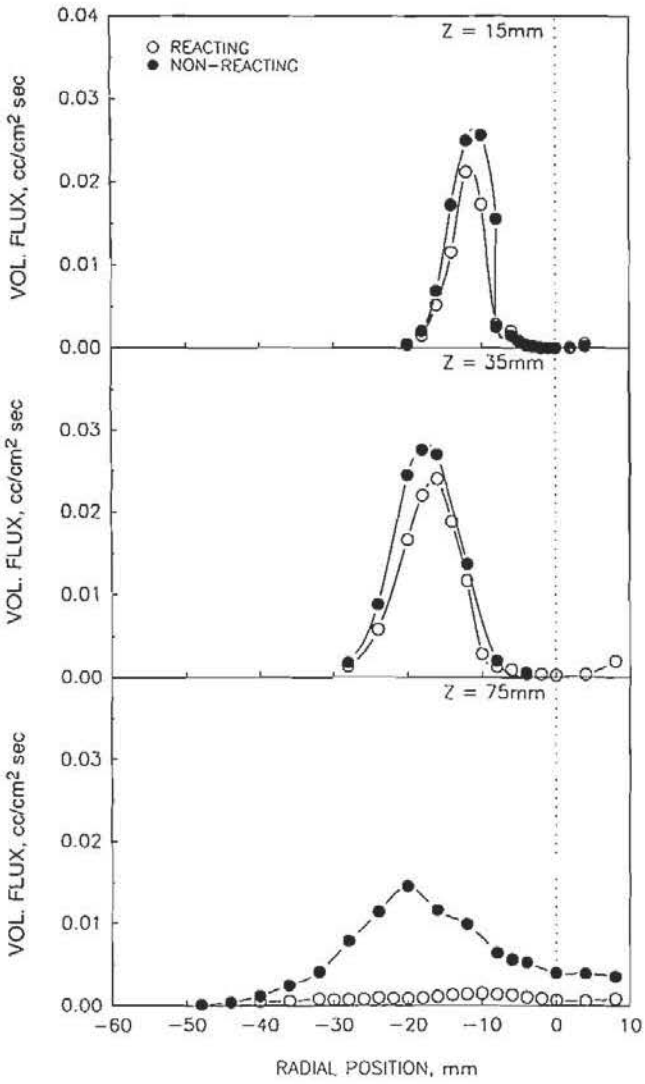

FIGURE 8 Radial Profiles of Volume Flux.

correlation are presented as lines on either side of the mean path. For reference, the gas velocity vectors are presented as well.

For this spray, the results indicate that the presence of reaction does not significantly alter the flight path of the 55 μm drops. It does, however, provide an idea of the mean lifetime of drops of this size, which is clearly an important parameter to consider in the emission of toxic byproducts.

The example demonstrates how the *in-situ* measurements can be combined with empirical relations to estimate the behavior of drops within the spray. Although significantly more challenging, the extension of this approach to complex sprays could be made. Clearly, measurements of all three components of velocity obtained at many, closely spaced axial stations would be necessary.

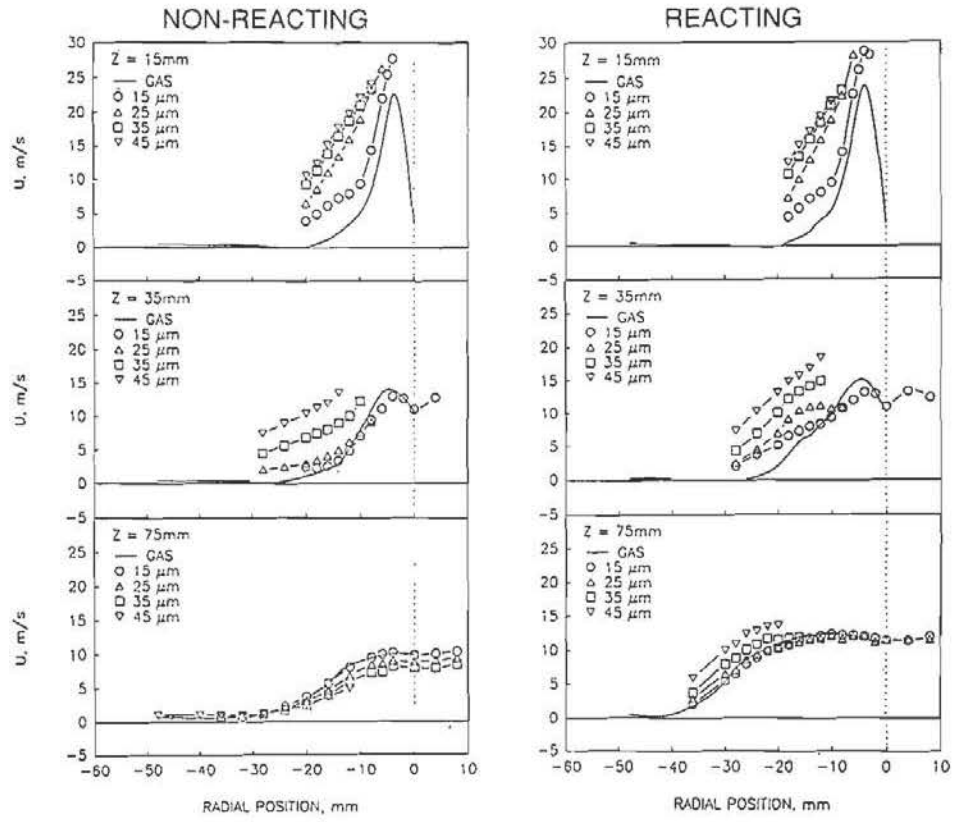

FIGURE 9 Radial Profiles of Mean Axial Velocity.

LIMITATIONS

Although phase Doppler interferometry has been successfully applied to many flows of interest, the technique is not without limitation. Several studies have been undertaken to assess the accuracy of the PDPA instrument (*e.g.*, Jackson, *et al.*, 1988; McDonell and Samuelsen, 1990) which, although are useful, cannot be used to judge the technique itself. Instrument comparison is extremely valuable in the assessment of accuracy. Without such luxury, other steps can be taken to assess the accuracy, such as comparison of integration of volume flux profiles with the injected amount (*e.g.*, McDonell and Samuelsen, 1988b; Dodge and Schwalb, 1989). Unfortunately, integration schemes such as these are somewhat misleading because (1) they assume axisymmetry, and (2) they cannot provide independent verification of each term in the volume flux determination. The second point is illustrated by considering that a serious error in size measurement, coupled with miscounting of drops, can still lead to correct integrated values. The following summarizes some of the issues regarding limitations.

Since the instrument is a single particle counter, dense sprays pose difficulties, although steps can be taken to reduce errors (*e.g.*, Bachalo, *et al.*, 1988) in these situations, such as reducing the effective sampling volume. The physical limit of the

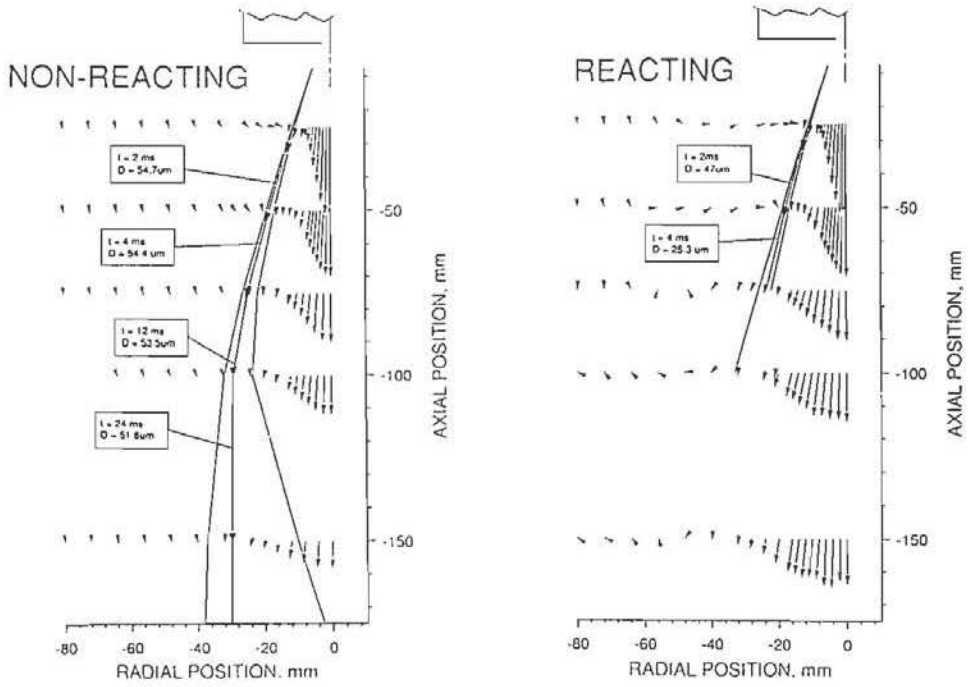

FIGURE 10 Estimated "Flight Paths" of 55μm Drops in Reacting and Non-Reacting, Non-Swirling Air-Assisted Sprays with Associated Gas Phase Velocity Vectors.

measurement is the requirement that only one droplet may be present in the sampling volume during the measurement of that droplet. Imperfections in optics and electronics further limit the density of the sprays. In such cases, alternative signal interpretation schemes such as frequency domain processing have shown promise in recovering data in dense sprays (*e.g.*, Bachalo, *et al.*, 1989).

As previously mentioned, beam steering and variation in refractive indices can lead to errors. These effects are non-linear, and assessment of such errors in each particular case is required. If a high boiling point fuel is used, the temperature induced variation in refractive index can become significant. In cases where selective evaporation of fuel components occurs, the effect of variation in refractive indices of the droplets may also be important. For typical hydrocarbon mixtures, the refractive indices of the various components are similar, although it is unclear what the effect of combining the components is. In cases such as this, backscattered light or other collection angles could be used to avoid ambiguities associated with refractive indices.

Also, errors can arise due to physical restrictions on the geometry of the droplets (*i.e.*, the theory applies to spheres). Studies conducted to assess the influence of non-sphericity (*e.g.*, Alexander, *et al.*, 1985) demonstrate that asphericities can lead to significant error in the measurement of drop size.

CONCLUSIONS

The current paper describes the role of optical scattering techniques in providing detailed information that is important to understanding the formation and emission

of combustion byproducts in spray combustion. The conclusions are as follows:

- Two-component phase Doppler interferometry is capable of providing spatially and temporally resolved measurements of gas and droplet velocity statistics, and droplet mass flux in two-phase flows under reacting the non-reacting conditions. Such information is necessary to advance the understanding of the physical processes (*e.g.*, transport, evaporation, mixing) associated with by-product formation in combustion systems.
- The method can provide insight to the behavior of spray fields in relatively hostile environments (turbulent, reacting, two-phase flows with recirculation) typical of practical environments.
- Major uncertainties regarding the limits of the method are yet to be resolved.

ACKNOWLEDGEMENTS

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