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Symmetry Assessment of an Air-Blast Atomizer Spray

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This study represents an evaluation of the extent to which conventional and recently introduced modern diagnostics can assess the symmetry of sprays formed by three atomizers of identical design. The conventional diagnostics include sheet-lit photography, which provides a measure of the gross flowfield asymmetries; patternation, which identifies nonuniformities in the gross mass flux distribution; and laser diffraction, which reveals variations in line-of-sight measurement of Sauter mean diameter (SMD). The modern diagnostic is laser interferometry (phase Doppler), which measures local values of droplet size, two-components of droplet velocity, and droplet volume flux. Symmetry is assessed in ambient conditions for four atomizer orientations (0, 60, 120, and 180 deg), and comparisons are made between the diagnostic techniques. The results demonstrate that 1) conventional and modern diagnostics are consistent in the assessment of symmetry, 2) patternation and phase Doppler are most effective in establishing symmetry of mass flux, and 3) phase Doppler, although more tedious to employ, provides the additional information necessary to establish the sources of detected asymmetries in terms of non-uniformities in droplet velocites, size distributions, volume flux, and concentration.

Introduction

SPRAY-FUELED combustion systems are receiving increased attention with respect to design, internal flowfield structure, and mixing processes between the fuel and air. Among the principal questions is the extent to which the spray field produced by a fuel atomizer is symmetric in the spatial distribution of droplet size, droplet velocity, and droplet mass flux.

Spray-field symmetry in gas turbine combustors is of particular interest. First, the prospects of relaxed specification fuels combined with the increasing demand for improved combustor aerothermal performance is leaving less tolerance for variation in spray-field symmetry.[1] Second, the evolution of two-dimensional numerical codes for gas turbine combustors is founded on an assumption of spray-field symmetry,[2] a constraint that 1) may not be borne out in fact in model axisymmetric geometries utilized in the laboratory, and 2) may preclude consideration of combustor performance criteria likely tied to spray asymmetries (e.g., hot streaks, lean limit blowout, high-altitude ignition). Third, spray measurements of droplet size, droplet velocity, and dilute phase velocity typically assume spray symmetry, enabling data to be acquired along only a single radius at various axial distances from the atomizer.[3] The interpretation of such data is jeopardized in the absence of spray-field symmetry. Fourth, the relationship between atomizer performance in the combustor and atomizer performance in a nonreacting spray characterization chamber is not established and may be atomizer and combustor specific.[4]

Recently introduced modern diagnostics, coupled with conventional methods, portend the capability of providing the needed assessment of symmetry in both the isothermal and combustor environment. The focus of this paper is to explore the extent to which symmetry can be assessed by conventional and modern methods in the *nonreacting* environment. This report represents a first step in a study designed to address the question of spray-field symmetry and the resulting impact on combustor performance.

Assessment of Symmetry

Many techniques, some conventional and some new, are available to evaluate the symmetry of sprays produced by atomizers. Photography, for example, provides a global view of the spray field and a measurement of spray cone angle. The use of sheet-lit photography allows the interrogation of a "slice" in the spray field and greatly enhances, as a result, the utility of photography in spray field characterization. This capability notwithstanding, photography is limited to the revelation of only gross asymmetries in spray mass density and geometric alignment. In addition, photography suffers from ambiguity associated with 1) a nonlinear scattering-concentration relationship and 2) unknown size distribution influences on scattering signature.

To provide a more quantitative and detailed assessment of spray symmetry, patternation may be employed. Patternation involves the physical collection of liquid mass at specified locations within the spray field. This classic technique provides information about spray cone angle in addition to mass distribution. With a sophisticated system, patternation can provide reasonably detailed information.[5] The principal drawbacks to patternation are 1) the probable perturbation to the local dilute phase and droplet flow, 2) the absence of information regarding the spray field velocity and droplet size distribution, and 3) the inability to apply the technique to the combustion environment.

Laser diffraction is a widely used method for the nonintrusive measurement of a spray and has been described in detail elsewhere.[6,7] In the common application of this technique, a line-of-sight measurement of the Sauter mean diameter (D_{32}) is obtained. Using sophisticated deconvolution techniques, the local drop-size distributions may be obtained, from which local volume-sensitive D_{32} values can be obtained.[8] (Note that to avoid significant added complexity to the deconvolution approach, the assumption of axisymmetry is often made.) Still, droplet velocities are not deduced.

A relatively new diagnostic, phase Doppler interferometry, provides the capability of measuring droplet size and droplet velocity at a point.[9] Recent comparisons between single-component phase Doppler and laser diffraction are encouragind with respect to correspondence relative capability, and operation of both methods.[3,4,8]

The present work utilizes all of the above techniques in a complementary and comparative manner in an effort to establish the utility of each technique in assessing the spray-field symmetry of atomizer in the absence of reaction.

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Approach

The approach is to adopt three test articles (atomizers) of the same model and apply the following spray-characterization techniques to assess the extent to which each is effective in delineating spray-field symmetry: 1) sheet-lit photography, 2) patternation, 3) laser diffraction (Malvern), 4) laser interferometry (Aerometrics Phase Doppler). Each atomizer is characterized at four orientations (0, 60, 120, and 180 deg) and the various axial locations shown in Fig. 1. At each orientation, 1) a sheet-lit sequence of photographs is secured for the full spray field; 2) three replicate sets of patternation are obtained at one axial location; 3) Malvern laser-diffraction measurements of Sauter mean diameter (SMD) are obtained for the full axial extent of the spray, from 25 mm to 300 mm (including stations at 50, 85, and 150 mm); and 4) phase Doppler particle analyzer (PDPA) measurements of droplet size, droplet velocity, and droplet flow rate are acquired at axial locations of 50, 85, and 150 mm. At each axial location, phase Doppler (PD) data were obtained at up to 40 radial points on a full-diameter traverse.

Experiment

Atomizer

The atomizer design utilized in this study is shown in Fig. 2.[10] It is a production air-blast atomizer for use in a helicopter gas turbine engine. The atomizer features swirled, centrally injected air and, via an outer shroud, swirling external air. The fuel is filmed onto a circular surface (via six ports which inject the fuel tangentially) and sheared between the two air passages.

Methanol is adopted as the liquid fuel due to the suitability of the resultant data for modeling. In particular, the vapor of methanol has nearly the same mass density as air (1.33 vs 1.2 kg/m^3) and, when injected into ambient conditions at $-10°C$, liquid methanol evaporates isothermally and thereby minimizes both density gradients in the gaseous environment and temperature gradients within the droplets. The atomizer is operated at an air-to-fuel ratio of 1.0 and a mass flow of 0.0021 kg/s for each phase. (These flow rates correspond to the "cruise" operation of the atomizer.) For this study, several atomizers of the same model number were evaluated. The paper reports on the detailed assessment of three such nozzles, denoted here as nozzles A, B, and C.

Spray Characterization Facility

A schematic of the test facility is shown in Fig. 3. The diagnostics remain fixed, oriented about a square cutout in the table which measures 900 × 900 mm. The test article is directed downward from the end of a 28-mm tube which supplies fuel and atomizing air to the atomizer. This tube is connected to a vertical traverse; the full tube traverse is attached to a support structure that is, in turn, attached to the table via a two-dimensional horizontal traverse system. Hence, 3 degrees of freedom are available to the test article. In addition, the tube in which the test article is secured is free to rotate about the centerline, permitting measurements at any degree of orientation.

Rigid plastic walls and a plastic sheet form an enclosure that surrounds the entire traversing/support system and insures a stagnant environment by isolating the spray field from room perturbations. Air introduced into the structure to meet entrainment requirements is removed via an exhaust system located in the fuel collection plenum. A stainless steel mesh separates the exhaust entrance from the structure to preclude local suction and insure that the exhaust suction is distributed over the large area of the plenum.

Diagnostics

The sheet-lit photography is produced by expanding a collimated 5-mm Ar$^+$ laser beam (Spectra Physics Model 165 operating at 5 W in the multiline mode) through a cylindrical lens. Photographs are obtained using a 35-mm camera (Olympus II) and TRI-X (Kodak) film.

The patternator is a necklace-type design that provides 25 collection tubes space 4 deg apart on an arc with a radius of 100 mm. The tip of the central collector tube is positioned precisely at this radial distance (100 mm) from the atomizer. The centroid of the patternator is located 85 mm from the tip of the test article. This 85-mm station, along with the 150-mm station, are two of the axial locations at which both Malvern and phase Doppler data were collected (Fig. 1).

Laser-diffraction data were obtained using a Malvern Model 2200. Care was taken to ensure that the full extent of the spray was within the range of the instrument (300-mm

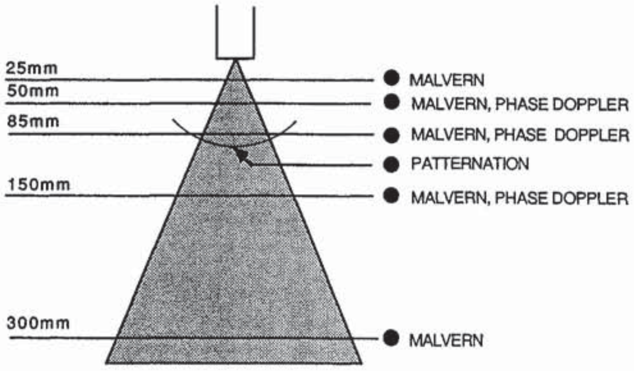

Fig. 1 Measurement locations.

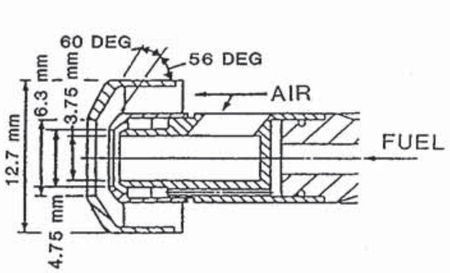

Fig. 2 Atomizer.[10]

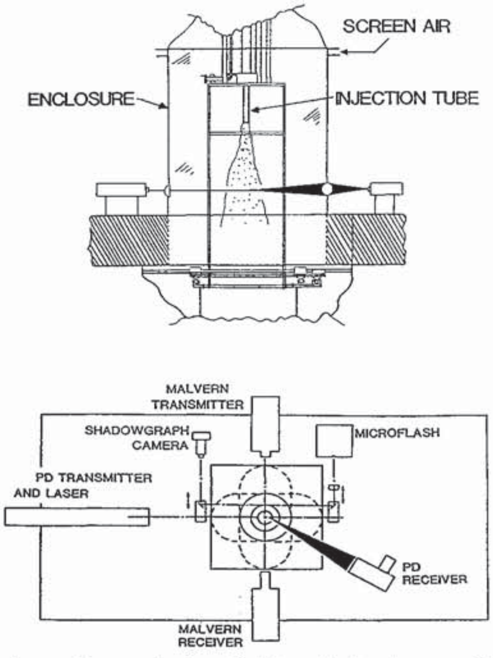

Fig. 3 Spray-characterization facility: a) chamber; and b) optics configuration.

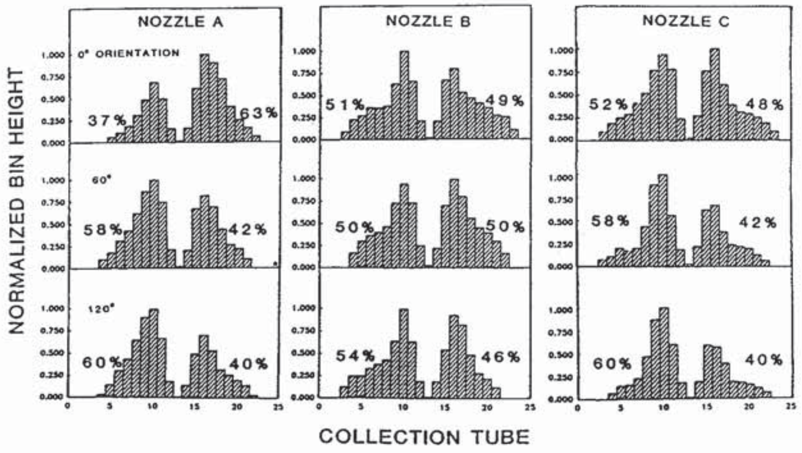

Fig. 4 Patternation results.

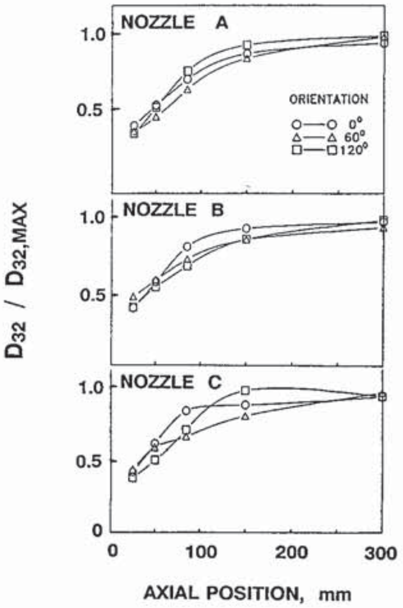

Fig. 5 Laser-diffraction (Malvern) results.

receiving lens was used). Phase Doppler data were obtained using a first generation prototype Aerometrics two-component instrument. Additional details are provided elsewhere.[4] The Aerometrics instrument, in contrast to the Malvern, provides detailed droplet velocity (two components) and droplet size information. The instrument is capable of providing satisfactory size measurements as evidenced by the extensive verifications conducted in comparison with visibility and the Malvern.[3,4,8] Mass flux can also be obtained and thus direct comparisons to patternator data can be made. The instrument has demonstrated encouraging performance with respect to mass flux in a droplet stream with a dominant axial velocity component.[8] In droplet streams, such as that found in the present case where three significant velocity components can be present, the precise determination of the probe volume has not been firmly established. Hence, an accurate determination of mass flux cannot be measured with complete confidence For the assessment of symmetry, absolute values of the mass flux are not necessary and, in the present case, the data are normalized to focus attention on the uniformity of the radial profiles.

Symmetry Assessment by Independent Instruments

Photography

Still photographs using both a vertical and horizontal sheet of laser light were obtained to provide a global, time-averaged view of the full spray. Sheet-lit photography provides a means to study a persistent asymmetry in the spray flowfield. Streaks (high-spray density regions) and holes (dilute regions), for example, can be readily detected. In the present case, the still photographs did not reveal asymmetries in the spray fields associated with any one of the three nozzles selected for characterization.

Patternator

The patternator provides qualitative and quantitative information about the mass flux distribution in an atomizer spray field. In Fig. 4, for example, the patternation results are presented for the three atomizers at three orientations: 0, 60, and 120 deg. (Data obtained at 10-deg increments revealed no additional insight into symmetry of the atomizer spray field. As a result, only data obtained at 60-deg increments are presented.) The "*y*-axis" label is the normalized bin height (i.e., volume) obtained by weighting the mass collected in a given tube per unit time by the area of the annular sector generated by a revolution of the tube about the centerline (vertical axis) of the patternator. This weighted mass flux is normalized by the maximum bin height measured in a given patternation.

The data reveal that nozzle B gives the most symmetric spray for the three orientations selected. Both nozzles A and C give asymmetries depending on the orientation: for example, although nozzle C appears to produce a symmetric spray at the 0-deg orientation, asymmetries are evident at 60 and 120 deg. Another measure of asymmetry is the distribution of mass on either side of the patternator centerline. The mass is distributed almost equally on the two sides for nozzle B. For nozzles A and C, the difference between the two sides is as much as 20%, depending on the orientation.

Laser Diffraction

The Malvern instrument was used to obtain line-of-sight measurements of D_{32} along the centerline of the spray field (maximum D_{32} valves were less than 50 μ). The results presented are for a Rosin-Rammler size distribution. Although this is a qualitative measurement in terms of symmetry assessment, the Malvern results do reveal repeatable differences in the axial profiles of D_{32} at different orientations of the test articles (Fig. 5). Nozzles A and B show a relatively modest spread in D_{32} due to orientation. By comparison, significant differences are apparent for nozzle C.

Although the relative symmetry of the three atomizer spray fields is identical based on the Malvern and the patternator measurements, a direct comparison between the patternator and Malvern is not possible since both measure different quantities. If fortuitously the mass flux variations deduced by the patternator were due to a variation in D_{32} (rather than droplet velocity, size distribution, or D_{30}), the two should be related. However, questions would still remain since 1) the patternator tubes in the necklace design are not all at the same axial location, and 2) the patternator is vulnerable to perturbing the local two-phase flowfield.

Phase Doppler

Full radial profiles of normalized droplet axial and azimuthal velocity (maximum mean axial velocity and azimuthal are less than 20 and 2.5 m/s, respectively) for each of the test articles are presented in Fig. 6a. The velocity field of both nozzles A and B are relatively symmetric in contrast to nozzle C. The aerodynamic center of nozzle C is clearly shifted to the right of the geometric center (approximately 4 mm). Thus, these data provide insight to a possible source of the previously deduced asymmetry in nozzle C, namely, a distortion in the actual centerline of the spray from the geometrical centerline.

Full radial profiles of the normalized phase Doppler flux sensitive (maximum valves are between 80–100 μ) D_{32} are shown in Fig. 6b. As with the velocity, clear evidence of a geometrical asymmetry in nozzle C is observed. These data also reveal a probable source for the asymmetry in nozzle A, namely, a significant variability in droplet size at the edge of the spray.

Summary of Symmetry Assessment

The above results show that a reasonable correspondence exists between the techniques used in determining asymmetry in the flowfield of the test articles considered here. The results also demonstrate that asymmetries in the flowfield are most clearly delineated by phase Doppler and patternation. In the next section, emphasis is directed to a comparative study between these two techniques and the use of both for *quantifying*, as well as identifing, spray asymmetry for one of the atomizers examined above.

Comparative Results

Mass Flux: Patternator vs Phase Doppler

In addition to the droplet velocity and size information provided above, the phase Doppler instrument also determines mass flux through the interferometric probe volume by 1) combining the measurement of drop size with a measurement of the probe volume cross section, and 2) correction for the Gaussian intensity profile of the beam. For direct comparison to the patternation data, spatially resolved measurement of mass flux can be integrated over the annular areas associated with each measurement point to provide an area-weighted mass flux. The comparative results for area-weighted mass flux, normalized to the peak mass flux in each data set, are shown in Fig. 7 for nozzle A. The comparison reveals consistency between the two methods.

An integration of the mass-flux profile for each method yields a total flow rate of 1.66 g/s for the phase Doppler and 1.13 g/s for the patternator. This compares to an injected flow rate of 2.1 g/s. Evaporation alone cannot account for the missing mass. Other factors play a significant role. The testing protocol selected for the present study, for example, terminates the collection of phase Doppler data at the radial position for which the droplet data rate drops below 5% of the

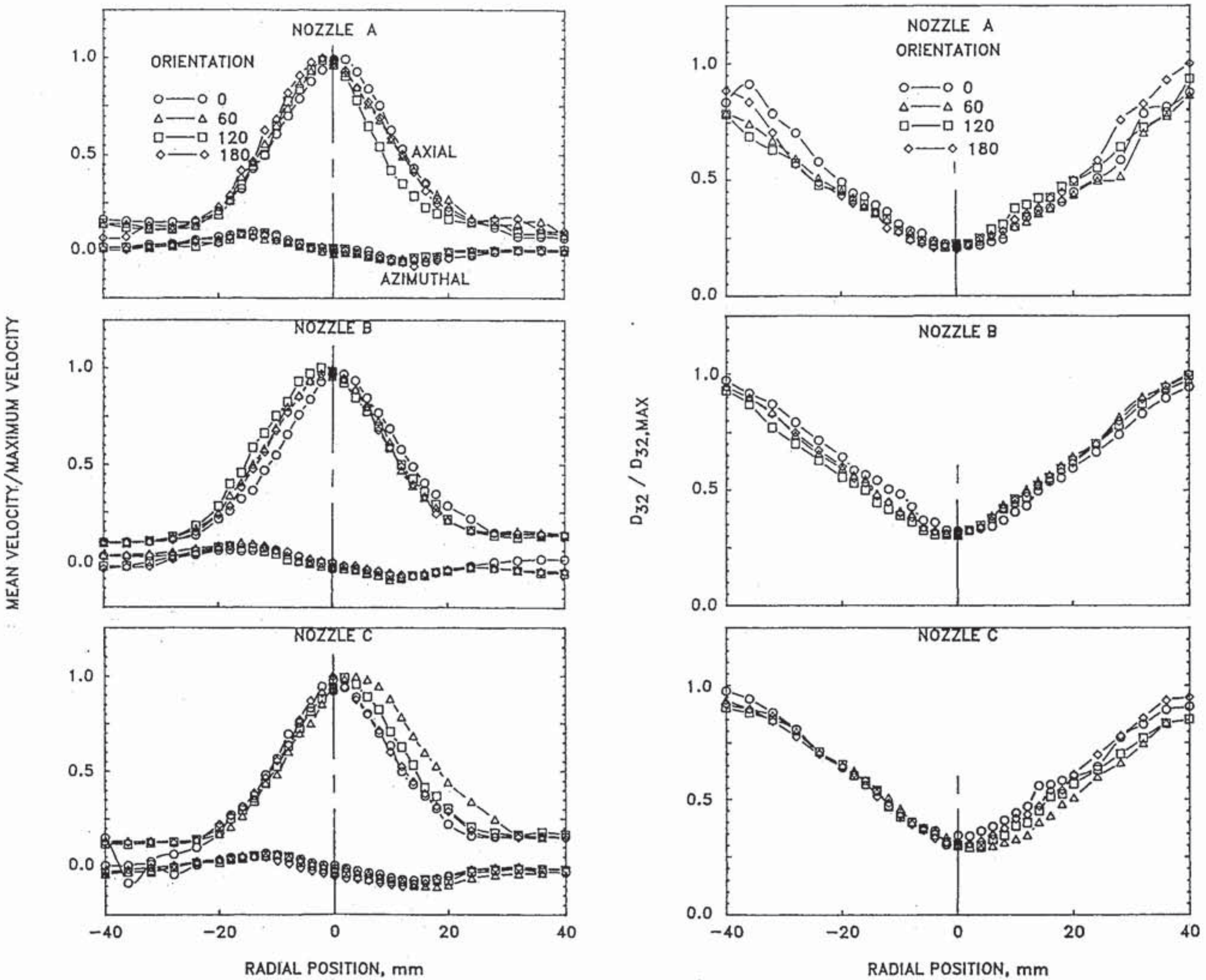

Fig. 6 Phase Doppler (Aerometrics) results (85-m axial station): a) mean velocity; and b) Sauter mean diameter D_{32}.

maximum data rate measured at that axial station. As a result, the phase Doppler data do not include droplets at the far edge of the spray field. Since drops at the edge of the spray are large, and possess a relatively large amount of mass, the integrated phase Doppler mass flow rate is lower than the injected flow rate. In other studies where more complete traversing has been conducted, measured mass flows in the spray correspond closely to that injected at axial locations away from the injector.[11] The loss of mass from the patternator, which collects over the entire realm of the spray field, is attributed to local perturbation and the unidimensional character of the patternator design. The swirling component of the spray (see Fig. 6a) contributes to the underprediction of mass. The skewed angle of impact at the opening of the collection tube causes the effective collection area of the tubes to be less than for normal impact, which is assumed in the tube area calculation.

In Fig. 7, both techniques indicate the presence of an asymmetry in the distribution of droplet mass flux. An advantage of the phase Doppler technique is the ability to *simultaneously* measure the various statistics. Hence, in principle, the phase Doppler data can identify the source and explain the evolution of the asymmetry. In the following, the data obtained by the phase Doppler are examined to assess the cause of the volume flow asymmetry.

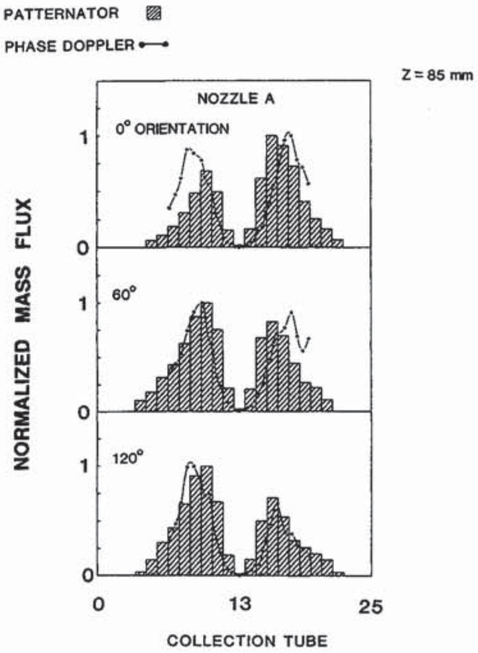

Fig. 7 Comparison of phase Doppler and patternator mass flux.

To establish the nature of the asymmetry, the distribution of droplet size in the spray must first be established. Consider, for example, the 120-deg orientation of nozzle A. Presented in Fig. 8 are normalized phase Doppler size distributions obtained at radial locations of 12, 16, and 20 mm on either side of the centerline. A high number of small drops are present at 12 mm, and relatively few small drops are present at 20 mm. For the present atomizer and operating conditions, small drops are entrained towards the centerline, whereas larger drops possess enough momentum to be transported to the outer edge of the spray field.

Returning to Fig. 7, both the patternation and phase Doppler data reveal an asymmetry in the peaks of the distribution at collection tubes 10 and 16. These tubes correspond to radial displacements of ±16 mm from the centerline. The phase Doppler mass flux at -16 mm is 65% of the value at $+16$ mm. The volume mean diameter D_{30} at -16 mm is 84% of the value at $+16$ mm (30.3 μ for the positive side, 25.5 μ for the negative side) which corresponds to 60% less volume for the -16-mm side.

The difference in volume mean diameter indicates that the drops at -16 mm are smaller than those at $+16$ mm. Since the difference in mass flux is less than the difference associated with volume mean, one conclusion drawn might be that less droplets must pass through the probe volume at $+16$ mm per unit time than at -16 mm. Examination of the normalized count vs size distributions at 16 mm on either side of centerline (Fig. 8) indicates that there are actually *fewer* total drops passing through the probe volume on the $+16$-mm side.

This conclusion is verified by presenting the data of Fig. 8 in a different manner. Figure 9 presents the same distributions in the form of volume vs size. Note that, although there are significantly more small drops on the -16-mm side, the volume associated with these drops is relatively small. Also, the slightly greater number of larger drops on the $+16$-mm side causes a large discrepancy in volume. Figure 9 demonstrates that the reduction in mass flux associated with the reduction in the overall number of drops is offset by the increase in the number of large drops. Note that simply because the drops are large does not necessarily mean that a large volume flux will exist. The number of drops per unit time, as well as size, influence the flux.

In summary, the patternator and the phase Doppler measurements of mass flux are consistent. The measurement of

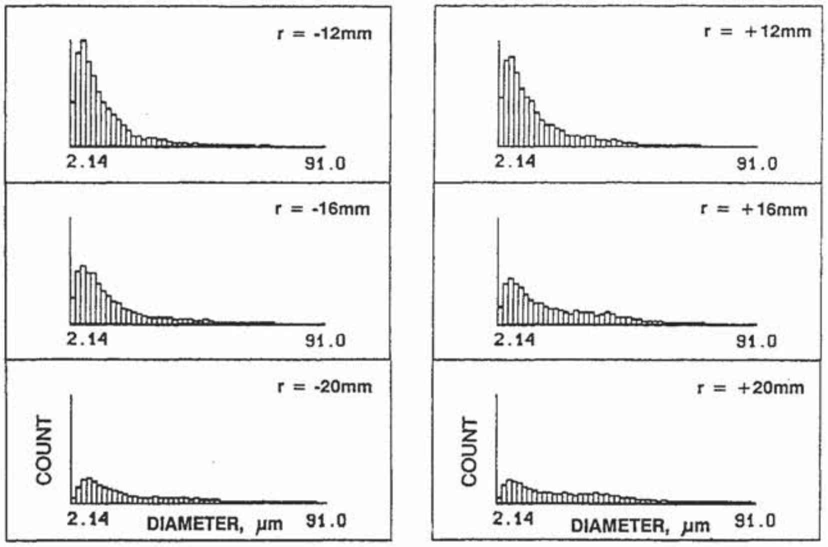

Fig. 8 Normalized count vs size (nozzle A: 120-deg orientation).

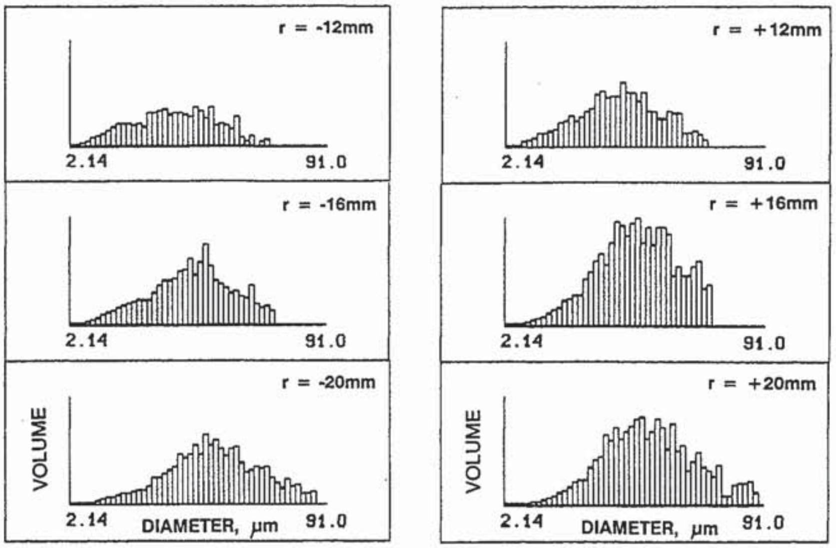

Fig. 9 Normalized volume vs size (nozzle A: 120-deg orientation).

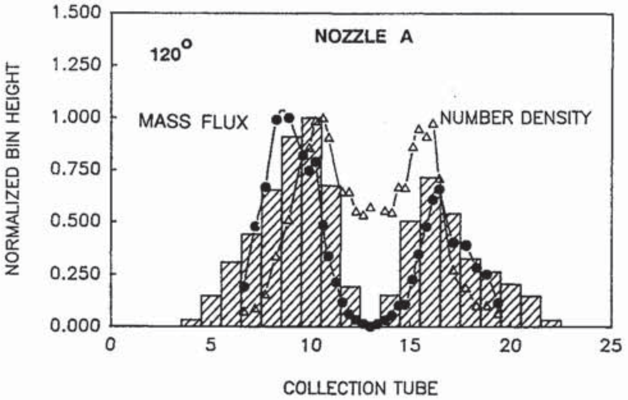

Fig. 10 Comparison of mass flux and number density (nozzle A: 120-deg orientation).

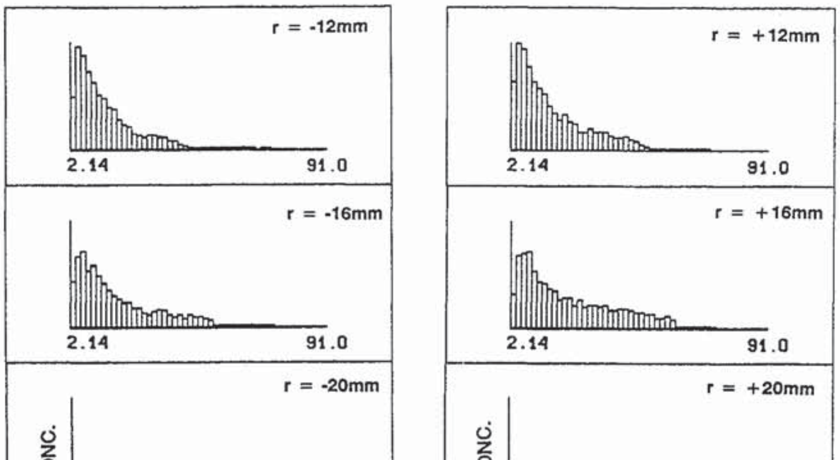

Fig. 11 Normalized concentration vs size (nozzle A: 120-deg orientation).

droplet-size distributions by the phase Doppler provides the information necessary to deduce the specific source of the volume flow asymmetry.

Additional Insight Provided by Phase Doppler

An additional attribute of the data acquired from phase Doppler is the capability to couple droplet velocity with droplet size. By coupling the velocity with the volume flux determined from the size distribution, a measurement of concentration can be deduced. Figure 10 presents the radial profile of normalized number density (#/cc) overlaid on the mass flux profiles shown in Fig. 7. Note that at the ± 16-mm location, an identical concentration of drops exists. Yet, Fig. 8 indicates that *more* drops, especially small drops, are present on the − 16-mm side. What Fig. 8 does not take into account is the velocity of the drops. As a result, a misleading view of the concentration of drops may be portrayed. This is especially pertinent because the concentration of drops may be more important than mass flux in consideration of problems associated with gas-turbine combustors.

Figure 11 presents the data in yet another fashion, concentration vs drop size, to provide additional insight into the issue of asymmetry. Note that the concentration of small drops is larger on the − 16-mm side, but that the concentration of large drops is larger on the + 16-mm side. Comparison of these data to those for the same radial locations presented in Fig. 8 shows that very little asymmetry in concentration exists. The reason that the asymmetry of concentration is less than for the number of drops is that the velocity of the drops on the − 16-mm side is greater than that of the drops on the + 16-mm side (this is true for drops of all sizes). The higher velocity tends to spread the drops out more on the − 16-mm side and, as a result, reduces the concentration at this location. Note that the velocity does not directly affect the mass flux.

Conclusion

The conclusions of this study are as follows:

1) The conventional and advanced techniques utilized in the present study are a) consistent with one another where comparable measurements can be made (e.g., patternator and phase Doppler mass flux) and b) consistent in revealing the relative quality of symmetry between the three nozzles interrogated.

2) Point, spatially resolved measurements of droplet velocity, size, number density, mass flux, and size distribution are required to fully assess the spray-field symmetry of an atomizer.

3) Two-component phase Doppler laser interferometry shows promise in the provision of the requisite data.

4) A thorough characterization requires a detailed survey of a myriad of both atomizer orientations and all locations. Such an effort is time intensive and data-storage intensive.

5) In the present study, an analysis of the phase Doppler data reveals that the asymmetry in mass flux is caused by a nonuniformity in the number of large drops produced by the injector.

For quality control of nozzle production, it is likely that patternation is sufficient, and the additional information provided by phase Doppler may not be of direct use nor the time needed to provide such information justified. In support of atomizer design, however, the information provided by phase Doppler may become more significant. Clearly, the information is desirable for the development of numerical models of atomization and spray evolution.

Further work in this area includes 1) the assessment of gas-phase flow symmetry on symmetry of sprays produced by twin-fluid atomizers,[11] 2) the assessment of the extent to which ambient characterization can be extrapolated to actual operation,[4] and 3) the assessment of atomizer symmetry on the performance of practical combustors.

Acknowledgments

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