UC Irvine
UC Irvine Previously Published Works

Title

A comparison of spatially-resolved drop size and drop velocity measurements in an isothermal chamber and a swirl-stabilized combustor

Permalink

Journal

ISSN

Authors

Mcdonell, VG
Wood, CP
Samuelsen, GS

Publication Date

DOI

Copyright Information

Peer reviewed

A COMPARISON OF SPATIALLY-RESOLVED DROP SIZE AND DROP VELOCITY MEASUREMENTS IN AN ISOTHERMAL CHAMBER AND A SWIRL-STABILIZED COMBUSTOR

MCDONELL, V. G., WOOD, C. P., SAMUELSEN, G.S.

UCI Combustion Laboratory
Mechanical Engineering
University of California
Irvine, California 92717

A liquid fuel air-assist atomizer is characterized in both an isothermal spray chamber and a swirl-stabilized combustor. The objective is to assess the extent to which the isothermal characterization represents atomizer performance under reacting conditions and in the presence of strong, aerodynamic swirl. The technique employed for the point measurements of droplet size and droplet velocity is phase Doppler interferometry. In the isothermal chamber, comparative measurements are conducted using laser diffraction (Malvern). To explain the differences in spray behavior observed in the combustor, the droplet measurements are complemented with laser anemometry measurements of the axial and azimuthal velocity fields, and thermocouple measurements of the temperature field. The results show that, except for initial Sauter mean diameter (SMD), the spray behavior in the combustor is substantially different than that observed in the isothermal chamber. In particular, (1) the spray field in the combustor has a hollow-cone structure, (2) the radial spread of the spray widens, (3) the number density decreases by at least an order of magnitude, and (4) the SMD at points displaced from the centerline is reduced. These differences are explained by the presence of heat release and the aerodynamically induced recirculation. In addition, the droplets and fuel vapor in the widened spray boundary are found to be important to combustor stability and performance. The results establish the importance and potential of characterizing sprays within the practical, operating environment.

Introduction

The performance of spray combustion systems is dependent upon the atomization quality of the spray and the spatial distribution of fuel.[1,2] Little is currently known about the interactions between a fuel atomizer spray and the aerodynamic and thermal environment of a combustion system. Because of the hostile environment and limited optical access of combustors, the characterization of sprays is presently performed in isothermal spray chambers[3,4] in the absence of the strong aerodynamic and elevated thermal environment into which a spray is injected in practical systems.

The objective of the present study is to characterize a liquid spray in both an isothermal spray chamber and in a swirl-stabilized combustor using the same air-assist atomizer operating under the same atomizing conditions. The overall goal is to assess the extent to which isothermal characterization relates to in-situ combustor atomizer performance.

Approach

The approach is to characterize an atomizer in an isothermal spray chamber using phase Doppler interferometry to measure droplet data rate, size, and velocity, and for comparitive purposes, laser diffraction (Malvern) to measure droplet size. The same atomizer is then characterized in a swirl-stabilized model combustor using phase Doppler interferometry. To explain the differences between the phase Doppler based data acquired in the two environments, spatially-resolved velocity maps are obtained in the combustor with two-component laser anemometry, and a temperature map in the combustor is established with a thermocouple probe.

Experiment

Atomizer

The air-assist atomizer used in this evaluation (Parker Hannifin Part No. 6830604) was designed to fill a requirement for a low-flow, two-phase nozzle with a high degree of atomization for use in an atmospheric, laboratory combustor. The atomizer consists of two principal components (Fig. 1). The outer body houses a set of swirl vanes and one complete air circuit. Within this, a fuel insert is fitted which contains a hollow tube surrounded by a set of swirl vanes on the outside surface. In conjunction with a shroud, the insert forms a second air circuit. Fuel is injected radially as high velocity jets through three discrete ports located 120 degrees apart in the tip of the hollow fuel insert. These jets impinge on the inner surface of the shroud that separates the two air circuits. The two atomizer swirlers and the combustor swirler each impart a counterclockwise tangential ve-
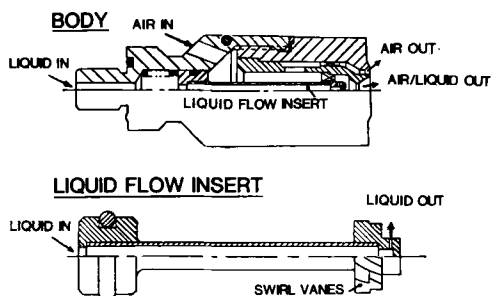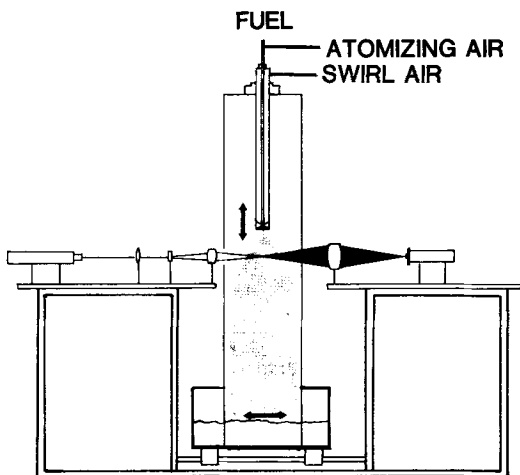

FIG. 1. Atomizer

FIG. 2. Isothermal Spray Facility[4,5]

locity (looking into the face of the combustor and nozzle). For the present study, the same atomizer was operated in both the isothermal chamber and combustor at a liquid mass flow rate of 3.27 kg/hr of JP-4 and an atomizing air-to-liquid mass ratio of 1.5.

Isothermal Chamber

The spray facility (Fig. 2) is designed to characterize a liquid fuel atomizer under isothermal conditions.[4,5] The chamber consists of a 30.5 cm i.d. × 152 cm long plexiglas tube positioned vertically at the center of an optical platform. The tube rests in a fuel collection basin that is connected to an exhaust system via a fuel vapor trap. The chamber and basin assembly is mounted on a precision platform permitting movement with one degree of freedom in the horizontal plane for radial traverses of the spray.

The atomizer is centrally positioned within the chamber in a fixture that permits vertical movement for axial traverses. The atomizer is assembled in the end of a 19 mm o.d. fuel delivery tube that is plumbed to supply JP-4 fuel and atomizing air. Screen air is introduced into the top of the chamber and, coupled with the exhaust system in a push-pull manner, provides a bulk reference velocity of approximately 0.5 m/s to eliminate mist accumulation due to recirculation at the atomizer inlet plane and/or wall recirculation at the measurement plane.

Combustor

The swirl-stabilized combustor employed is a model laboratory complex flow combustor developed in a series of tests and previously described in detail.[6] The configuration is presented in Fig. 3a. The atomizer is plumbed to a fuel/air delivery tube which is identical to that in the isothermal chamber. For the results reported here, the combustor is operated at atmospheric pressure, a bulk reference velocity of 7.5 m/s, and an overall equivalence ratio of 0.3. Both swirl and dilution air are heated to 100°C prior to introduction into the combustor.

The environment into which the fuel is injected is characterized by laser anemometry measurements of the aerodynamic field and thermocouple probe measurements of the temperature (thermal) field. The details of these methods are provided in Reference 6. The results are presented in Fig. 3b. The presence of a recirculation zone is evident in the aerodynamic field at the 1 and 2 cm axial stations. This zone is established by the interaction of the fuel
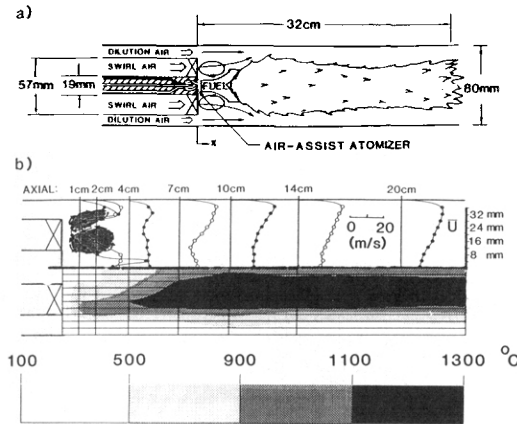
FIG. 3. Swirl-Stabilized Combustor
a) Configuration
b) Velocity and Thermal Environment

spray and surrounding aerodynamic swirl. The strength of the fuel spray momentum is sufficient in the present case to preclude the formation of an on-axis recirculation zone. The thermal field exhibits peak temperatures exceeding 1200°C. Note the relatively high temperatures (900–1100°C) located in the aerodynamically defined recirculation zone. These data confirm the location and size of the primary recirculation zone, and also reveal a relatively cool region (300–500°C) in the immediate vicinity of the atomizer and along the core of the combustor.

Diagnostics

Phase Doppler Interferometer. The principal measurement method used for droplet sizing and droplet velocity is phase Doppler (PD) interferometry. The technique determines droplet velocity by standard fringe mode laser anemometry, and establishes the droplet size by measuring the phase shift of light encoded in the spatial variation of the fringes reaching three detectors after traveling paths of different lengths through the drop. The phase shift is measured directly by the detectors, each looking at a spatially distinct portion of the collection lens. Although two detectors can provide the needed information, a third is used as a validation check and to extend the size range sensitivity.

Primary advantages of the phase Doppler technique are the capability to resolve a wide range of droplet sizes for a given optical configuration and relative insensitivity to changes in beam intensity and noise. The size range that can be measured with one optical configuration is potentially greater than 100:1. Detector gain

limitations and signal-to-noise considerations restrict this potential size range to an effective window of 35:1. This window can be electronically placed anywhere within the limits imposed by the optical configuration. If the size range of the spray exceeds 35:1, data splicing from separate windows is required. A detailed description of the technique is available.[7]

Different optical transmitters are used in the isothermal chamber and swirl-stabilized combustor although the manner by which the interferometric probes are formed is identical. Both are breadboarded by UCI Combustion Laboratory personnel using standard two-component laser anemometer optics. The transmitter in the isothermal chamber uses a 5mW Melles-Griot Helium-Neon (632.8 nm) laser, whereas the transmitter used for the combustor employs the green line (514.5 nm) at a power of 400mW from a 5W Model 165 Spectra-Physics Argon Ion laser. In each case, the laser beam is focused onto a diffraction grating where it is split into multiple modes. The two first-order beams are then collimated, focused, and crossed to form the probe volume. To allow the distinction between negative and positive velocities, frequency shifting is provided by rotating the diffraction grating. The beams are focused to a 95 μm diameter waist (to the $1/e^2$ intensity point) at the probe volume. The same receiver (Aerometrics Model 2100) and processor (Aerometrics Model 3100) are used in both experiments.

For droplet sizing purposes, the receiver is positioned 30° off the beam axis. For azimuthal velocity measurements, the 30° off axis position is used in the reacting case and a 7° off axis position is used in the isothermal case. The narrower angle for the isothermal case is required to maintain the structural integrity of the chamber. A 50 μm by 1 mm rectangular slit serves as a spatial filter with the long axis normal to the optical axis. The photodetector voltage in the receiver and filter settings for pedestal and high frequency noise removal are menu controlled via a microcomputer (IBM AT). The computer also provides data reduction and analysis. Both size and velocity distributions are produced, as well as Sauter mean diameter (SMD). The present paper focuses on the comparison of data rate, SMD, and mean azimuthal droplet velocity in the isothermal chamber and combustor.

Isothermal Chamber. In the isothermal chamber, the transmitter optics are configured to give a fringe spacing of 8.8 μm. With this configuration, a droplet sizing window is provided with ranges varying from 1.2-to-42 μm to 4.7-to-166 μm.

To verify the phase Doppler measurements, droplet size data are also acquired in the isothermal chamber using laser diffraction, a technique generally accepted in industry for the line-of-sight ensemble measurement of spray SMD. A commercial instrument is employed (Malvern Model ST2200) with an optical path in the same plane but directed 90° from that of the radial point measurements. The diffraction data are processed using both a two-parameter Rosin Rammler (RR) and a fifteen-parameter Model Independent (MI) algorithm.

The diffraction-based measurements of SMD represent a value deduced from a "snapshot" of the spray at an instant in time. Such a measurement can be biased. For example, if small droplets are moving slower than the large droplets, the SMD will encompass proportionately more small droplets and yield a size distribution biased to small droplets. This value of SMD is termed a "spatial-SMD" or "volume-sensitive" SMD. In contrast, the PD makes a continuous point measurement of single droplet realizations. A value of SMD derived in this fashion is termed a "temporal-SMD" or "flux-sensitive" SMD. However, because the PD acquires data in size-velocity pairs, a spatial-SMD can be calculated to compare the line-of-sight diffraction-based (spatial) measurements to the point interferometric (temporal) measurements. To this end, a data reduction protocol has been developed for the PD data to (1) generate spatial-SMD in addition to temporal-SMD, and to (2) integrate the PD point measurements across the spray to produce a comparable line-of-sight "composite SMD."[4]

Swirl-Stabilized Combustor. The optical configuration used for PD measurements in the swirl-stabilized combustor provides droplet sizing windows with ranges varying from 1.3-to-4.5 μm to 5.17-to-181 μm. The fringe spacing is 7.9 μm. Measurements are acquired in the absence of LA seeding to allow for the unambiguous discrimination of droplet velocity and size.

With increasing experience and the results from comparative tests in spray chambers, the verification of the PD technique (including the delineation of the limits of applicability) in isothermal sprays is progressing with satisfactory results.[4] Properly applied, PD can provide data in an isothermal spray chamber that can be quantitatively used for modeling and other forms of analyses with increasing confidence. The application to reacting flows, in contrast, is new and reservations are just now being established. The specific questions divide into two categories. First, with respect to the technique itself:

—What are the characteristics of the processor data rate transfer function; what is the effect of this transfer function on SMD and velocity?
—What are the response limitations of the technique, if any, to the imposition of frequency shift?

With respect to the reacting environment:

—What is the effect of variations in gas-phase index of refraction induced by thermal gradients?
—What is the effect of variation in droplet index of refraction imposed by selective evaporation of a practical fuel?
—What further limits on sensitivity are imposed by increased noise due to flame luminosity?

These and other questions remain subjects of active inquiry. The present measurements of droplet size and droplet velocity measured in the combustor are based on the protocol developed in exploratory tests.[8] As such, the accuracy is not yet established, but experience to date suggests the uncertainty associated with the droplet size and droplet velocity data presented here is conservatively within ±30%.

Results

Photographs of the spray in the two environments are presented in Fig. 4. The cone angles in both cases are visually identical, approximately 45° full angle. Otherwise, the spray in both cases is visually different. First, the axial extent of the spray is greater in the isothermal spray chamber. Second, the number density is higher in the isothermal case. Third, a hollow-cone shape is discernible in the combustion case. Hence, from the photographic documentation alone, the performance of the spray in the two environments is clearly different. To quantify these differences, laser diffraction and laser interferometry were applied to characterize the spray.

The first results presented are the comparison of diffraction based and interferometric based ensemble SMD. These results are followed by the results for the phase Doppler measurements of droplet data rate, droplet size, and droplet velocity in both the isothermal chamber and the swirl-stabilized combustor. At the conclusion of the section, the interferometric results are discussed relative to the performance of the spray in the swirl-stabilized combustor.

Comparative Measurements

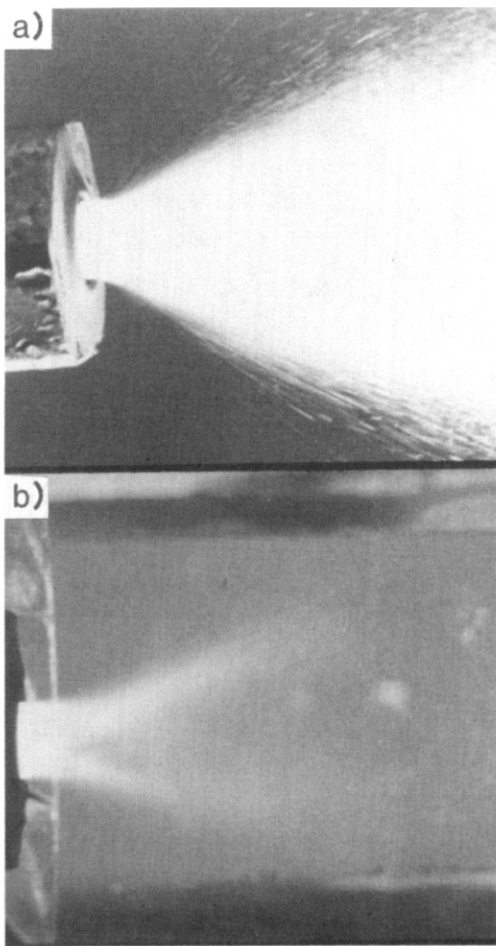The ensemble SMD data determined by laser diffraction are compared, in Figure 5, to the

FIG. 4. Spray Photographs
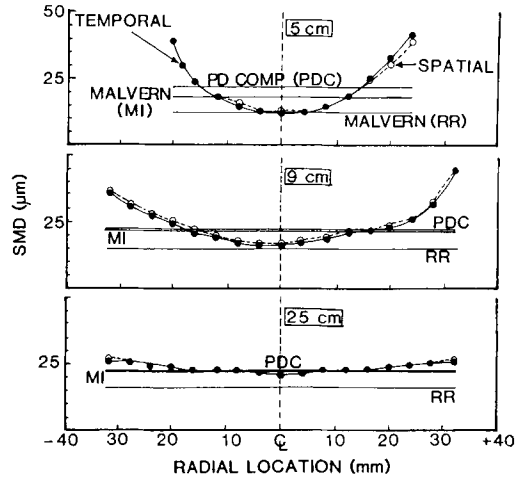a) Isothermal Chamber
b) Combustor

FIG. 5. Comparison of Laser Diffraction and Laser Interferometric SMD Measurements

difference is small in the present case because, by 5 cm from the atomizer, all droplet sizes present in the spray have assumed the dilute phase flow velocity.

Two important findings result from these comparative measurements. First, in regions of this practical spray field where neither instrument is limited, the correspondence is excellent. Second, in regions of this spray that are of primary interest to the present work (i.e., close to the nozzle), the phase Doppler technique provides the ability to make quantitative measurements whereas the diffraction technique becomes limited by obscuration.

Laser Interferometric Results

A characterization of the spray using phase Doppler interferometry is presented in Figs. 6–9 for both the isothermal chamber and swirl-stabilized combustor. Measurements made in 1 cm increments are presented from 2 cm (the first axial location at which ligaments did not affect the PD measurements) to 5 cm (the last axial location at which the droplet data rate in the combustor exceeds 25 Hz, a value arbitrarily selected to represent the boundary of the spray). At each axial location, data are acquired radially at 4 mm increments. Results for both droplet SMD and mean azimuthal velocity are reported at locations where the data rate exceeds 25 Hz.

Data Rate. The radial profiles of data rate are presented in Fig. 6a. Dashed lines are used in the region where the data rate exceeds 4000 Hz as the PD processor rolls off data rates above this value.[10] Hence, in the isothermal

composite SMD data produced by the phase Doppler. The data at 25.0 cm shows that, at a Malvern measured obscuration of 41%, the PD composite (PDC) spatial-SMD and MI spatial-SMD both yield a value of 22 μm. At 9.0 cm and an obscuration of 52%, a similar correspondence results. At 5.0 cm and an obscuration of 58%, both Malvern models fall short of the PD composite. This is consistent with findings that, for obscurations greater than 50%, multi-droplet scattering becomes significant with the net effect of biasing the diffraction measured SMD to lower values.[9] For this spray, the fifteen-parameter MI model compares consistently better to the PD composite than the two-parameter RR model.[4] Note that the difference between the spatial- and temporal-SMD at each radial point in the spray is also shown in Fig. 5. The

case, the peak data rate is higher than that reported and the precise shape of the data rate profile cannot be established above 4000 Hz. Clearly, however, the isothermal data rate is at least an order of magnitude higher in most regions of the spray compared to the combustor case. These data also suggest that, in the isothermal chamber, the initial hollow cone nature of this spray collapses within two centimeters of the nozzle to a solid cone spray.

The data rate profiles in the combustor indicate that droplets are not present in the core of the spray at 4 and 5 cm. Hence, the hollow cone nature of the spray is preserved in this environment. Visual observations of beam scattering through the spray confirm this structure. The data rate profiles in the combustor also indicate an increased angle of injection (~60° compared to ~45° in the isothermal chamber). This difference is again confirmed by visual observations of beam scattering through the spray. This result is in apparent contradiction to the injection angles derived from the photographs (Fig. 4) where the angle appears to be the same in both environments. The explanation for these contrasting results rests with the number density associated with those droplets that extend beyond the 45° cone angle in the combustor environment. The number density is clearly too low to be photographically recorded in this region.

It is noteworthy that the 2 cm profile in the combustor reveals a mass flow asymmetry. The asymmetry, attributed to the discrete fuel jets within the air-assist circuit,[11] is further illustrated by the data rate isopleths presented in Fig. 6b.

Temporal-SMD. Measurements of temporal-SMD are presented in Fig. 7. In general, the data show the extent to which the spray SMD is symmetric about the centerline in both environments. In both cases, the temporal-SMD increased radially outward. In the isothermal case the increase is greater, approaching 4-to-1. The extent of the radial spread is significantly greater in the case of the combustor, as noted above.

Azimuthal Velocity. Azimuthal mean velocity data (Fig. 8) are selected for presentation in order to characterize (1) the effect of the two nozzle swirlers and (2) the added influence of the aerodynamic swirler in the combustor. (Note that, for the optical configuration required for the measurement of azimuthal velocity, PD measurements were not possible at axial positions of 2 and 3 cm in the isothermal chamber due to high number density. In the combustor, the number density was not a limiting factor at these axial positions.) The
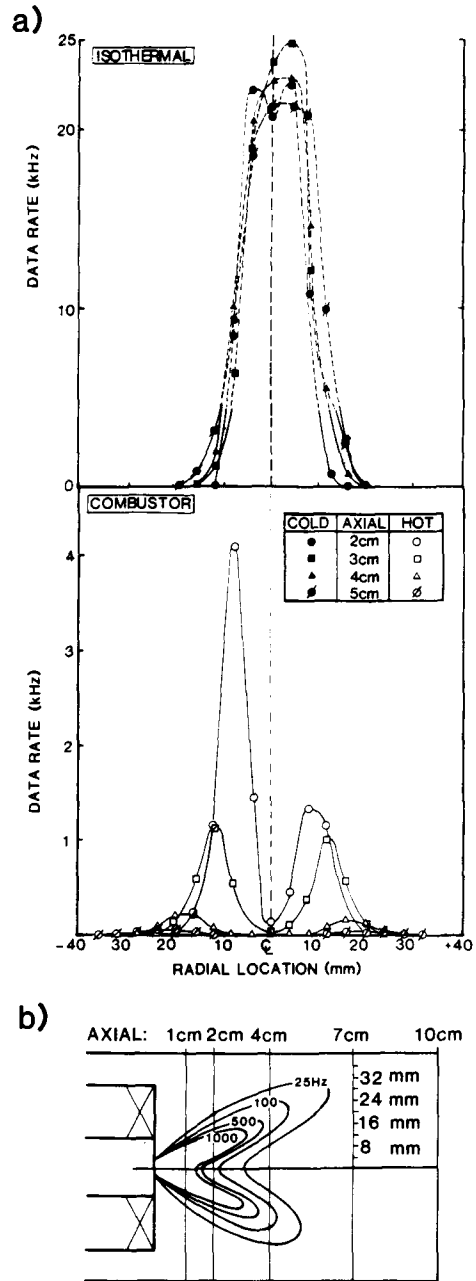
FIG. 6. Laser Interferometric Results: Data Rate
a) Radial Profiles for Isothermal (Cold) and Combustor (Hot)
b) Isopleths for Combustor

azimuthal velocities for the isothermal case (1) do not exceed 1.25 m/s, and (2) are reasonably symmetric about the centerline. The profiles for the combustor case also reflect a general symmetry of droplet azimuthal velocities about
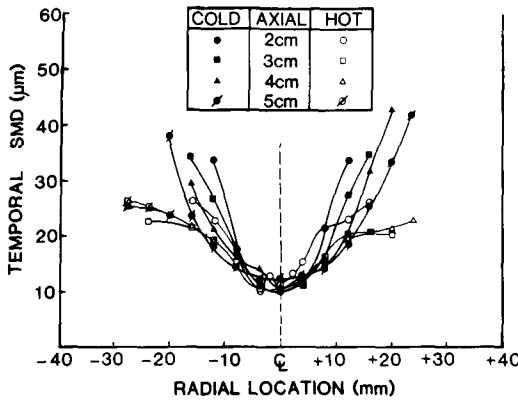
FIG. 7. Laser Interferometric Results: Temporal-SMD for Isothermal (Cold) and Combustor (Hot)

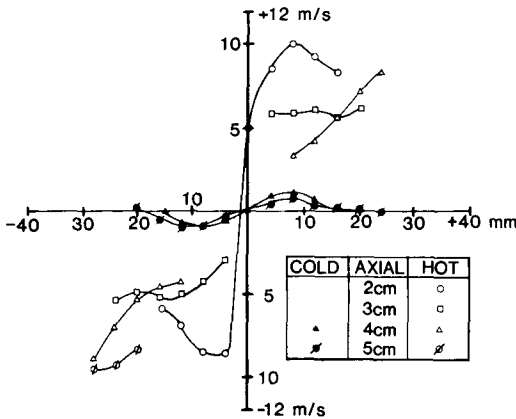FIG. 9. Relationship of Spray Field to Combustor Environment

FIG. 8. Laser Interferometric Results: Azimuthal Velocity for Isothermal (Cold) and Combustor (Hot)

the geometric centerline of the combustor. However, the azimuthal velocities are higher in the combustor by almost an order of magnitude due to the strong swirl field imposed by the combustor swirler. (LA measurements of the dilute phase indicate azimuthal velocities of 5 to 10 m/s in the region of the spray field.)

Relationship of Spray Field to Combustor Environment. The data acquired in the combustor are significantly different from those acquired in the isothermal chamber. The explanations for these differences can be deduced by the superposition of the droplet data rate isopleths (Fig. 6b) on the thermal and aerodynamic fields of the combustor (Fig. 3b). The result is presented in Fig. 9. (Note that the data rate isopleths from the lower half plane of Fig. 6b have been mirror imaged in Fig. 9 and represent, as a result, an apparent symmetry that
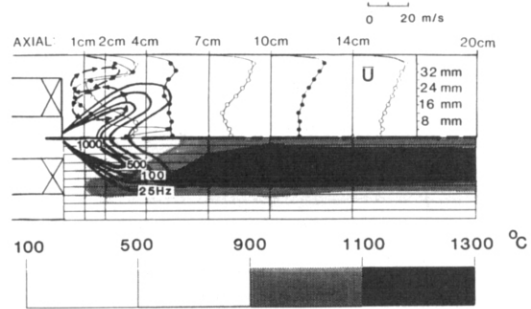
does not in fact exist.) The size and location of the recirculation zones, inferred from the axial velocity measurements, are shown as regions bounded by arrows.

The outer portion of the spray field is seen to traverse the interior recirculation zone. The data rate drops rapidly as the spray is directed outward and droplets traverse the steep thermal gradient toward higher temperatures. The relatively wider spread (Fig. 6a) and lower SMD (Fig. 7) of the spray in the combustor is attributed to the outward radial momentum imparted to the spray by the interior recirculation zone and elevated azimuthal velocities. The small droplets are preferentially accelerated outward and, hence, the SMD is lower. This preferential acceleration is confirmed by the size-velocity correlations deduced from the PD measurements in the combustor. The rapid evaporation in the reacting environment further enhances the reduction in SMD.

Figure 9 also suggests the sequential path which the combustor is stabilized. First, small droplets, along with fuel vapor, are entrained from the spray field into the inner recirculation zone and reacted with air captured by the outer recirculation zone. This reaction region corresponds in locale to the high temperature region indicated by the thermal field. Second, combustion intermediates and products are transported back into the spray field by the interior recirculation zone, leading to the rapid evaporation (and hence, lower data rate) observed in the combustor environment. Finally, this evaporation produces the fresh fuel vapor and small droplets which are then available for entrainment in the manner first stated. As a result, the interaction of the aerodynamically induced recircuation zones and the small droplets and fuel vapor in the boundary of the spray are pivotal to the stabilization of the combustor.

Conclusions

The present study compares the characterization of a spray in an isothermal chamber and a swirl-stabilized combustor. The following conclusions have resulted from this study:

1. Spray performance under reacting conditions in a swirl-stabilized combustor is substantially different than the performance in an isothermal spray chamber. Except for the initial SMD, no correlation is evident between the two environments.

2. The interaction between the spray and combustor aerodynamics substantially affects the spray performance. Hence, spray performance in a reacting flow is a function of combustor design and operating conditions as well as nozzle design and operating conditions.

3. In the present study, the spray structure is transformed from solid cone in an isothermal chamber to hollow cone in a swirl-stabilized combustor. The radial spread and variation in SMD is markedly influenced by the presence of heat release and aerodynamically induced recirculation. The photographically deduced cone angle in the combustor is not indicative of the radial spread of the spray. The droplets and fuel vapor in the widened boundary of the spray are, in the case of the present experiment, important to combustor stability and overall performance.

4. In-situ measurements of droplet size and droplet velocity in a practical combustion environment are required to characterize the performance of a atomizer. Phase Doppler interferometry, along with photographic analyses, show promise for providing the required data. Outstanding questions remain, however, and the technique awaits additional verification under reacting flow conditions.

Acknowledgments

REFERENCES

1. WOOD, C.P. AND SAMUELSEN, G.S.: *J. Engr. Gas. Turb. Pwr.,* 107, 38 (1985).
2. KRAMLICH, J.C., HEAP, M.P., SEEKER, W.R., AND SAMUELSEN, G.S.: *Twentieth Symposium (International) on Combustion,* p. 1991, The Combustion Institute, 1984.
3. RIZK, N.K. AND LEFEBVRE, A.H.: *J. Propulsion,* 1, 200 (1985).
4. JACKSON, T.A. AND SAMUELSEN, G.S.: Proceedings of the SPIE-The International Society for Optical Engineering, 573, p. 73, Society of Photo-Optical Instrumentation Engineers, 1985.
5. JACKSON, T.A. AND SAMUELSEN, G.S.: *J. Engr. Gas Turb. Pwr.,* 108, 1 (1986).
6. WOOD, C.P., SMITH, R.A., AND SAMUELSEN, G.S.: *Twentieth Symposium (International) on Combustion,* p. 1083, The Combustion Institute, 1985.
7. BACHALO, W.D. AND HOUSER, M.J.: *Optical Engineering,* 23, 583 (1984).
8. SAMUELSEN, G.S., WOOD, C.P., BACHALO, W.D., AND RUDOFF, R.C.: In-Situ Measurements of Drop Size and Drop Velocity in a Spray Combustor, Report ARTR-85-10, UCI Combustion Laboratory, University of California, Irvine, 92717, 1985.
9. DODGE, L.G.: *Optical Engineering,* 23, 626 (1984).
10. BACHALO, W.D.,, Aerometrics, Incorporated: Private communication, 24 February, 1986.
11. JACKSON, T.A. AND SAMUELSEN, G.S.: Detailed Characterization of an Air Assist Atomizer and Its Use In a Swirl-Stabilized Combustor, AIAA-85-1181, 1985.

COMMENTS

S. R. Gollahalli, University of Oklahoma, USA. To what extent are the differences between the characteristics of the burning and nonburning sprays you observed specific to your combustion system (atomiser and chamber design)?

Author's Reply. The spray chamber design is typical of those used to characterize sprays isothermally, where the objective is to establish a well behaved environment into which the spray is injected. In principle, then, the isothermal characteristics is not

specific to the facility. This has been confirmed to a limited extent in comparative measurements between two independent facilities at Carnegie-Mellon University and Parker Hannifin Corporation.[1]

In contrast, the combustor results are likely specific to the system. Swirl stabilized, centrally injected combustors will yield flowfield features that are peculiar to the combination of nozzle and combustor designs employed as well as operating conditions. The characterization of a spray must include measurements of droplet size and velocity in the specific combustor environment in which the nozzle is scheduled for use. (See Conclusions 2 and 4 in the text).

REFERENCE

1. MUNROE, M.E., AND SAMUELSEN, G.S.: Parker Hannifin Clone Nozzle: Malvern and Laser Interferometric Measurements, UCI Combustion Laboratory Report, UCI-ARTR-85-8, Department of Mechanical Engineering, University of California, Irvine, CA, 92717, 1985.

●

T. Niioka, National Aerospace Laboratory at Japan. It appears to me that the width of your combustion chamber is too small to generalize your experimental results. Do you have any proof or experimental evidence to describe that there is no wall effect?

Author's Reply. The response to Gollahalli addresses the specificity of the results. A discussion of the specificity of results of this type is readily available.[1] With respect to "wall effect," the wall conditions do influence the flowfield and contribute markedly to the specificity of any combustor. First, the walls dictate the degree of confinement, the latter of which is influential to flowfield structure. Second, the temperature of the wall affects the radiative flux and hence the thermal field of the combustor. Third, any geometrical perturbations in the wall will affect the flow locally and, if the perturbation is large, the bulk flow as well. In the present case, the interior of the wall is smooth and void of geometrical steps. In addition, the "dilution air" steam serves to buffer and isolate the bulk flow region of turbulent mixing and heat release from the physical wall.

REFERENCE

1. CHARLES, R.E., EMDEE, J. MUZIO, L.J., AND SAMUELSEN, G.S.: Twenty First Combustion (International) on Combustion, The Combustion Institute, 1986.

●

A. D'Allessio, Univ. of Naples, Italy. The technique used for the determination of the droplets size is based on the assumption that the droplets are transparent. The sprays in combustion regime may contain droplets which are partially absorbing for pyrolysis in liquid phase.

May the authors comment on the influence of the optical properties of the droplets on the measurement method?

Author's Reply. The droplet is only required to be spherical. The measurement is then based upon various parameters such as collection angle, detector separation, and the index of refraction of the drop. The real part of the index of refraction denotes an actual phase shift, and the imaginary part denotes a decay of the amplitude.[1] Changes in the real part of refractive index will affect the measurement. These types of changes were taken into consideration in the work presented. For example, both selective evaporation effects for the multicomponent fuel and beam steering were investigated. The beam steering investigation is described in the response to Mularz. Our analysis of selective evaporation effects indicates that, for this particular fuel, these effects should result in an error of less than 2%.

Pyrolysis, and hence the introduction of an imaginary component to the total droplet index of refraction, does not affect the size measurement. Pyrolysis will only reduce the detectability of the droplets, which is compensated for by an increase in the voltage of the photomultiplier tube. For a fully opaque particle, the measurement must be transformed from refraction to reflection.

REFERENCE

1. VAN DE HULST, H.C.: Light Scattering by Small Particles, Dover Publication, Newark, 1981.

●

T. Hirano, University of Tokyo, Japan. Would you explain why in your study you used data rate for the presentation of data rather than number density?

Author's Reply. The data rate reported in this paper is the total number of events divided by the total sample time at a given location. The number density must be calculated from this value, and includes as well the geometrical dimensions of the probe volume, the velocity of droplet event, and the probe volume correction. At this juncture, the level of confidence in the calculation of number density in highly swirling flows with the present hardware and software capabilities of the phase Doppler instrument is not sufficient to warrant its use. In addition, highly dense regions in the isothermal spray exist where even the measured data rate does not accurately reflect the actual data rate. Hence, in such regions, the use of data rate is qualitative and the calculation of number density will result in substantial error. The calculation

of number density in highly swirling flows and in dense spray fields depends on further hardware and software developments, and appropriate verification. The probability of success is high.

●

C. Hassa, DFLR-Cologne, Germany. I noticed that you used the term "data rate" throughout your talk. Does that mean that you make a distinction between "data rate" and "droplet rate", or are those terms used as synonyms?

Author's Reply. In this work, these terms are synonymous.

●

E. J. Mularz, NASA-Lewis Research Center, USA. In your combustion experiment, did you notice any "Beam Steering" in the laser measurements due to the high temperature gradients?

Author's Reply. The degree to which the beam is affected by the high temperature gradient was evaluated by projecting a single laser beam through the full width of the combustor duct and observing the motion of the beam on a wall far (10 meters) from the combustor. No discernable motion of the beam was observed, indicating that beam steering was not a factor in the 80mm diameter combustor employed in the present experiment. Larger duct diameters will be more susceptible to beam steering.